Application of Fuzzy FMEA to Indian Railway Signalling Systems

[1]Subhash Chandra Panja [2]Ramakrishna P Chakraborty [3]Deashis Sarkar [4]Ratri Parida [5]Sankar N Patra
[1]Professor [2,3]Principal [4,5]Assistant Professor
[1,5]Jadavpur University, Kolkata - 700 032, India [2]K.K.Das College GRH -17, B.P.Township, P.O. Garia Kolkata 700084, India [3]Asansol Engineering College, Asansol, India [4]IIM Sambalpur Odisha, India – 768200

Abstract

The paper deals with the failure analysis of railway signalling systems, in general, and Indian Railway signalling systems, in particular. It is worth mentioned that failure of railway signalling subsystems and systems hampers the safe running of rolling stock and thus, sometime reduces productivity. Both traditional and fuzzy logic-based failure mode and effect analysis (FMEA) are considered here to analyse the railway signalling failures. It is observed that on the basis of risk priority numbers (RPN) of railway signalling subsystem's failure, fuzzy logic-based FMEA is better than the traditional FMEA. Also, one hundred and twenty five rules have been generated with the help of fuzzy logic-based FMEA by considering different levels of severity, occurrence, and detectability. Twenty rules out of one hundred and twenty five are taken into account as very significant as far as operation and failure analysis of signalling system is concerned.
Keyword- FMEA, Fuzzy Logic, Railway Signalling Systems, RPN

I. INTRODUCTION

A transportation system is needed to transport human beings and goods from one place to another. Doing so, it occupies a distinct place in the social and cultural fabric of a nation. The trade and commerce of a country depend on its efficient transportation that may be considered to be an index of social and economic progress of a country. One of the important and essential aims of a country is to design and develop an improved and efficient mode of transportation systems of different types, such as railways, roadways, waterways, and airways. In this context, it is stated that being the second largest transport system, Indian Railways (IR) plays efficiently all the above-mentioned critical roles in India over the last few decades.

IR, being a multi-gauge, multi-traction system and covering 63,028 route kilometers, runs around 11,000 trains everyday out of which 7,000 are passenger trains [Indian Railways website, 2007]. Doing so, it is a very large and complex system. Thus, the movement of rolling stock is a prime necessity with smooth operations of other different railway systems, such as track, control arrangements, system of working, and signalling systems.

Signalling systems consists of a number of fail-safe subsystems, viz. panel, point-and-point-machine, signal-unit, track circuit, cable, relay, back indication, signal- and point-drive cards, level crossing gate, and power supply and it is responsible for safe and reliable movement of trains on flanged-rails [1]. Though all the mechanical and electrical devices work with fail-safe design and mode, most signalling devices must work in wide range of temperature, vibration, varying soil-conditions, and all possible dynamic combinations of these variables [2]. In this regards, railway signalling subsystems are to be critically monitored constantly and its improvement of operational activities is to be analyzed on regular basis. Keeping this in mind, it is worth mentioned that failure mode and effect analysis (FMEA) is one of the important tools by which present working condition may be determined and subsequently, improvement of operational activities of the railway signalling subsystems and components may be suggested. The basic objective of traditional FMEA is to determine how an item can fail and assess the effect of that failure on the system on the basis of the ranking of Risk Priority Numbers (RPN), which is calculated by the multiplication of three factors, viz. severity (S), delectability (D), and probability of occurrence (O) [3].

The RPN is calculated as the product of ranking from 1 to 10 of each factor [4, 5] and given as follows:

RPN = Occurrence ranking   Severity ranking Detection ranking

Thus, the range of RPN is 1 to 1000. It is observed that there are some deficiencies in traditional FMEA, though it is successfully applied in many engineering systems for improving the design and other operational activities. According to Garcia et al[6] a failure mode with an occurrence index, a severity index, and a detection index equal to 4, would have a RPN equal to 64, while another, whose indices are 2, 10, and 1, respectively, would have a RPN equal to 20. A careful analysis of the failure modes and effects, considered, show that the first one is not catastrophic whereas second one is. Moreover, it is also seen that a same RPN can be generated in a number of ways and out of 1000 possible numbers only 120 cases of RPN may be investigated [7]. In this context, a fuzzy logic approach may be adopted to capture the subjectivity of the experts in linguistic forms and address innumerable possibilities of RPN values in a range of 0 to 1.

Moreover, Panja and Ray [8] applied traditional FMEA to analyze the failure occurrences of railway signalling systems. It is observed in their paper that severity and detection index of all railway signalling subsystems are same. It seems that the typical subjectivity is present in their modelling and analysis.

Keeping this in mind, the subjectivity of experts of IR signalling may be eliminated to FMEA and with the help of rules and operations of Fuzzy Logic the Fuzzy RPN may be estimated. The RPN, so estimated, helps suggest the improvement of operational activities as well as design requirements of Railway signalling systems, in general, and IR, in particular.

Describing the operational details of the IR Signalling subsystems, this paper identifies different operations and rules of FMEA and fuzzy logic, and explains the procedures of expert-based analysis in this context. On the basis of data analysis, the paper discusses the results and suggestions for improvement of the IR signalling subsystems.

II. Subsystems of Railway Signalling

'Signalling system' of railways consists of a group of devices and methods with which the movement of a train is controlled on the flanged steel rails so as to prevent the occurrence of accidents, ensuring the safety of the passengers, the operating personnel, and the rolling stock [9] and a 'signal' is defined as a medium, which conveys a particular pre-determined meaning in non-verbal form.

A signalling system consists of a number of subsystems, viz. panel, point-and-point-machine, signal-unit, track circuit, cable, relay, back indication, signal- and point-drive cards, and power supply [9]. These railway signalling subsystems are described in brief in following sections.

A. Panel

Panel is used to operate signals for setting up the routes of train movement and other signalling subsystems manually and kept either in the cabin of Station Master or beside the station.

B. Point-and-Point-Machine

Point-and-point-machine is one of the very important signalling subsystems and used to divert trains from one line to another line.

C. Signal-Unit

In railways, different types of visual and audible signals, such as fixed, hand, detonating, and flare, are used to indicate the condition affecting the movement of trains. Among these signals, fixed signal is the most popular and common in IR. Fixed signals, also known as signal-unit, consists of several components, viz. signal lamp, lens, frame, bracket, lamp holder unit, relay, transformer, cables, and power supply. In IR, signal-units are two-, three-, and four-aspect and out of these, three- and four-aspect colour light signal are mostly used.

D. Track-Circuit

Track-circuits are devices, which detect the presence of vehicle on the rails. The track-circuits are used to control signal-units, point-and-point-machines, and block instruments so as to reduce the human interaction and to make train running safer.

E. Cable

PVC insulated, PVC sheathed and armoured signalling cables are used for signalling circuits in IR.

F. Relay

Relays are devices which open and close electric circuits when their own feed circuits are suitably controlled and communicate certain information from one circuit to another. These sophisticated switchgears are used for remote and succession control of various electrical equipment's.

G. Back indication

The 'back indication' is also known as feedback indication. In IR signalling systems, a separate circuit is provided for each of the signalling subsystems, and connected and represented to panel in such a way that the panel operator can identify its working condition.

H. Signal- and Point-Drive Cards

The solid state interlocking SI-based signalling system combines the software and microprocessor-based input/output (I/O) cards with the railway signalling subsystems. With the help of these cards the modes of operations as well as failures of signals and points can be identified and according to the information available the decisions are to be taken.

I. Level-Crossing Gate

Level-crossing gates are either of the swing type with one or two leaves on each side depending on the width of roadway, or the barrier type. As movable barriers are obsolete, the use of lifting barriers constitutes the best arrangement from the point of view of quick clearance and the control can be local or remote or automatic as required.

J. Power Supply

25 KV AC 50 Hz single phase power supply for electric traction is derived from the grid systems of the State Electricity Boards through traction substations located at the route of the electrified sections at distances of 45 to 50 kilometers.

In the railway signalling, all the subsystems are connected together and inter-linked. Thus, failure of one subsystem shows the most restrictive aspect of signals and hence, the movement of rolling stock is stooped.

III. DESCRIPTION ON TRADITIONAL AND FUZZY LOGIC-BASED FMEA

In case of traditional FMEA, ten-grade scale of Severity, Occurrence and Detectability is used to find out the risk priority number (RPN), which is used to rank the order of the potential design concerns [10]. On the other hand, fuzzy logic-based approach categorizes the same ten grade scale of Severity, Occurrence and Detectability into five linguistic variables, viz. remote (R), low (L), moderate (M), high (H), very high (VH). It may be mentioned that with this linguistic variables data are easy and convenient to collect. Then these data are transformed in terms of rating as mentioned in the second column of Table 1. Without the loss of generality we have chosen the fuzzy membership values corresponding to R, L, M, H, and VH as 0.17, 0.33, 0.5, 0.67, and 0.83, respectively, as shown in third column in Table 1 [11, 12]. In this representation, the most ambiguous point (i.e. 0.5) is considered as Moderate. Then two more or less equal divisions between 0 to 0.5 and 0.5 to 1 have been selected. It can also be stated that two values, i.e. 0 and 1 are not taken, which are analogous to crisp set. Table 1 represents the linguistic variables, traditional index values, and fuzzy membership values as follows:

Occurrence (O) Severity (S) No Detection (D)	*Rating*	*Possible failure rate (operating days)*	*Fuzzy Membership Values*
Remote(R)	*1*	*<1:20,000*	*0.17*
Low(L)	*2/3*	*1:20,000/1:10,000*	*0.33*
Moderate(M)	*4/5/6*	*1:2000/1:1000/1:200*	*0.50*
High (H)	*7/8*	*1:100/1:20*	*0.67*
Very High(VH)	*9/10*	*1:10/1:2*	*0.83*

Table 1: Traditional and Fuzzy FMEA scales for RPN

IV. METHODOLOGY

The step-wise methodology of Fuzzy FMEA for IR signalling systems are described as follows:

A. Step I: Data Collection

The primary and most important step of Fuzzy FMEA for IR signalling is the data collection, because the entire analysis depends on its accuracy. The time period of data collection is to be specified first based on number of samples and type of data required. In this context, it is worth mentioned that the sampling decisions and objectives of analysis are to be described. Moreover, the unit of analysis is to be identified in such a way that it can address system requirements, sampling methods, and sampling frequency.

In case of Fuzzy FMEA, the whole analysis is based on Experts. Thus, the experts should be selected in such a way that they must have wide and hands-on experience of railway signalling systems. In this regards, it is stated that more than one expert may be chosen to average out the variability of data and hence, minimize the error.

The parameters of data collection of railway signalling subsystems and systems are as follows:

1) Different Functional Relationships
2) Failed Systems
3) Types of Failures, Frequency of Failure
4) Failure Modes
5) Failure Consequences

B. Step II: System-Level Traditional and Fuzzy FMEA

After completion of data collection, the system-level analysis may be started. In this step, the primary data, as collected, is changed in terms of traditional as well as fuzzy scales of severity, occurrence and detectability. The system-level analysis may be carried out in two ways. In case of traditional FMEA, the RPN is calculated by multiplying of severity, detectability and occurrence and rankings. Equation 1 represents the formula of RPN calculation of signalling subsystems.

$$\text{Traditional RPN} = O \times S \times D \qquad (1)$$

In case of Fuzzy FMEA, the fuzzy RPN is calculated on the basis of fuzzy scales of severity, detectability, and occurrence with the help of operations and rules of fuzzy logic and rankings of fuzzy RPN is listed. Formulae, which are considered on the basis of weighted average, in this regards, are mentioned as follows:

$$\text{Index values of O, S, D} = \Sigma(w_i\mu_i)/\Sigma w_i \quad (2)$$

Where, w_i be the weight of expert, Σw_i is the sum of weights and equal to 1, and µi be the fuzzy membership value corresponding to linguistic response of experts.
RPN is calculated as follows:

$$\text{Fuzzy RPN} = \text{Average of O, S, and D} \quad (3)$$

Where values of O, S, D are estimated by equation 2.

C. Step III: Comparison and Suggestions for Improvement
At this stage, the rankings of RPN values of traditional and Fuzzy FMEA are compared. On the basis of this comparison, the suggestions are to be made to improvement of railway signalling operations, in general, and IR, in particular.
The steps, as described, are shown below as a framework in Figure 1.

V. RESULTS AND DISCUSSIONS

In this research work, the data have been collected from five knowledgable experts in the rank of operator, maintainer, and officer depending upon their availability and willingness of participation with prior permission having wide experience of 8 to 24 years in railway signalling department of Eastern Railway, IR. The experts are assigned weight depending upon their position held in IR and duration of their experience, provided sum of these weight values is one. The experts have asked for the linguistic data for each factor of FMEA and each railway signalling subsystems. The linguistic data, termed as R, L, M, H, and VH, are transformed into 1, 3, 5, 7, and 9 in case of traditional FMEA and 0.17, 0.33, 0.5, 0.67, and 0.83 in case of fuzzy logic-based FMEA.

The data, as supplied by the experts, are converted with respect to Table 1and analysed with the help of the weights and formulae 2 and 3. The values of S, O, D, so transformed, and values of RPN of railway signalling subsystems in the context of traditional FMEA are represented in the Table 2

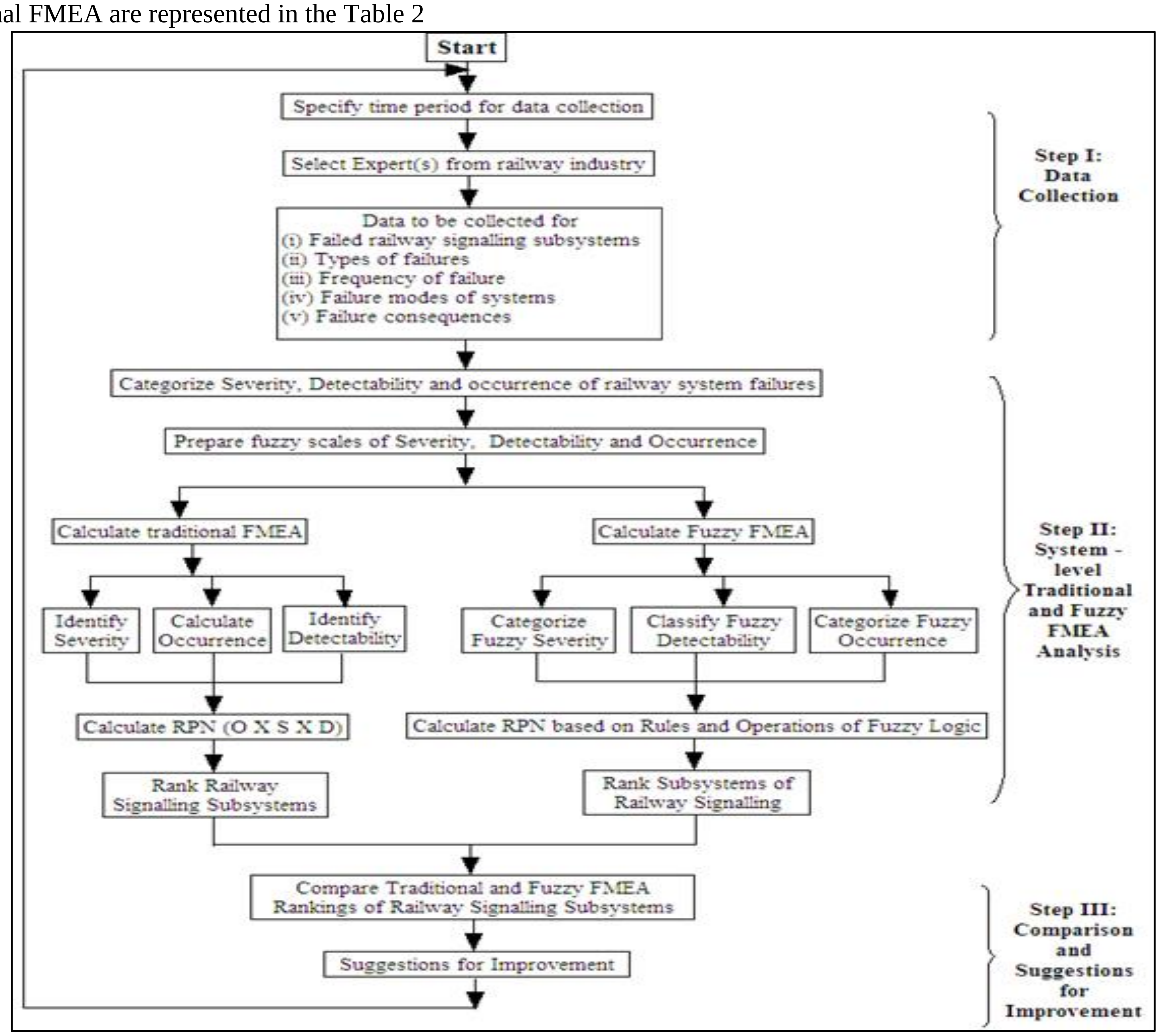

Fig. 1: Framework of traditional and fuzzy FMEA of railway signalling systems

Railway Signalling Subsystems	*S*	*D*	*O*	*RPN*
Panel	*4*	*1*	*2*	*8.00*
Cable	*4*	*5*	*6*	*120.00*
Relay	*4*	*3*	*4*	*48.00*
Point-and-Point-Machine	*4*	*2*	*4*	*32.00*
Track - circuit	*3*	*4*	*7*	*84.00*
Back Indication	*4*	*4*	*4*	*64.00*
Signal-Unit	*4*	*1*	*3*	*12.00*
Point-drive Card	*4*	*3*	*1*	*12.00*
Signal-drive Card	*4*	*3*	*1*	*12.00*
Power Supply	*5*	*2*	*5*	*50.00*
Level Crossing Gate	*4*	*2*	*5*	*40.00*

Table 2: Calculation for traditional FMEA

Similarly, same data have been transformed to fuzzy membership values and RPN is calculated by applying equation 2 and 3. These values are demonstrated in Table 3.

Railway Signalling Subsystems	*S*	*D*	*O*	*Average of (O, S, D)*
Panel	*0.47*	*0.19*	*0.25*	*0.30*
Cable	*0.39*	*0.48*	*0.55*	*0.47*
Relay	*0.45*	*0.29*	*0.43*	*0.39*
Point-and-Point-Machine	*0.47*	*0.22*	*0.17*	*0.37*
Track - circuit	*0.33*	*0.39*	*0.50*	*0.45*
Back Indication	*0.37*	*0.39*	*0.50*	*0.39*
Signal-Unit	*0.4*	*0.2*	*0.17*	*0.30*
Point-drive Card	*0.4*	*0.37*	*0.17*	*0.31*
Signal-drive Card	*0.4*	*0.37*	*0.17*	*0.31*
Power Supply	*0.52*	*0.25*	*0.50*	*0.42*
Level Crossing Gate	*0.42*	*0.23*	*0.47*	*0.37*

Table 3: Calculation for fuzzy logic-based FMEA

Comparing Table 2 and 3, the ranks of the railway signalling subsystems are developed by considering descending order of RPN values. The ranks, so developed, by traditional and fuzzy logic-based FMEA are shown in Table 4 as follows:

Railway Signalling Subsystems	*Traditional FMEA Ranking*	*Fuzzy FMEA Ranking*
Cable	*1*	*1*
Track - circuit	*2*	*2*
Back Indication	*3*	*4*
Power Supply	*4*	*3*
Relay	*5*	*4*
Level Crossing Gate	*6*	*5*
Point-and-Point-Machine	*7*	*5*
Signal-Unit	*8*	*7*
Point-drive Card	*8*	*6*
Signal-drive Card	*8*	*6*
Panel	*9*	*7*

Table 4: Comparison between traditional and fuzzy FMEA rankings

It is clear from the Table 4 that ranks 1 and 2 are same for both the approaches. Although power supply is an external subsystem, it can play vital role to run all other signalling subsystems. Thus, it should have better rank, i.e. 3, and that represented in fuzzy logic-based FMEA. It is known to railway practitioner that all the railway signalling subsystems and components are run satisfactorily by interlocking, which is primarily dependent on back indication. Thus, back indication is having better rank, i.e. 4, in fuzzy logic-based FMEA. In this way, it may be observed that fuzzy logic-based FMEA ranks overall shows better results compared to traditional FMEA.

In this research work, fuzzy rules are also generated. As each of the railway signalling subsystems follows five categories of linguistic variables of three parameters of FMEA the maximum possible rules may be one hundred twenty five for each subsystems. It is observed that out of one hundred twenty five rules, twenty rules are having fuzzy membership values more than 0.66, which is near to high. These twenty rules, by considering “vital few and trivial many”, are summarized as follows:

1) If all the parameters are very high then the RPN is Very High
2) If any two parameters are very High and other one is High then the RPN (.77) is above high
3) (1) If all the parameters are high then the RPN (.67) is High (2) If any two parameters are High and other one is Very High then the RPN (.72) is close to but greater than high.
4) If all the parameters are high then the RPN (.67) is High
5) If the parameters are a combination of very high, high, and medium then the RPN (0.66667) is close to but less than High
6) If any two parameters are very High and other one is Low then the RPN (.66333) is above high

Some examples of the 20 rules are mentioned below:

- If severity is very High , delectability is very High and occurrence is very High then RPN is very High

- If severity is very High , delectability is very High and occurrence is High then RPN(.77) is above High
- If severity is very High, delectability is very High and occurrence is medium then the RPN (.72) is close to but greater than high (2) If severity is High, delectability is High and occurrence is very High then the RPN (.72) is close to but greater than high.
- If severity is High , delectability is High and occurrence is High then RPN is High
- If severity is Very High , delectability is High and occurrence is Medium then the RPN (0.66667) is close to but less than High
- If severity is Very High , delectability is Very High and occurrence is Low then the RPN (.66333) is above high

It is recommended that if one of the twenty rules are being followed by a railway signalling subsystems there is a high possibility to its failure, in particular, and whole railway signalling system, in general.

VI. CONCLUDING REMARKS

This research work considers the failure study of railway signalling systems. FMEA is used in this regards. The necessary data required to calculate RPN of FMEA have been collected from Indian Railways. Both traditional FMEA and fuzzy logic-based FMEA are applied and it is seen from the results that fuzzy logic-based FMEA can be better that other as far as minimization of subjectivity is concerned. Moreover, different levels of severity, occurrence, and detectability are taken into account to generate the rules and it is observed that twenty rules out of one hundred and twenty five rules show critical. The designers and practitioners are required to keep in mind the conditions of these twenty rules to enhance the operational activities of railway signalling components, subsystems, and systems by minimizing its failures. It is recommended that the study can be improved if more number of experts and levels of fuzzy linguistic variables can be generated and considered. Moreover, this study may be done at the component-level of railway signalling to study in better manner.

REFERENCES

[1] Kumar, K.V. and Chandra, V.Transputer-based fault-tolerant and fail-safe node for dual ring distributed railway signalling systems. Microprocessors and Microsystems, 1994, 18 (3), 141-150
[2] Lee, J.-H., Hwang, J.-G., and Park G.-T. Performance evaluation and verification of communication protocol for railway signalling systems. Computer Standards and Interfaces, 2005, 27, 207-219
[3] Bowles, J.B. and Pelaez, C. E. Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis, Reliability Engineering and System Safety, 1995, 50, 203-213
[4] Pelaez, C. E. and Bowles, J.B. Using fuzzy cognitive maps as a system model for failure modes and effects analysis", Information Sciences, 1996, 88 (1-4), 177-199
[5] Misra, K.B.Reliability analysis and prediction: a methodology oriented treatment. Elsevier Science Publishers B.V., Amsterdam, the Netherlands, 1992
[6] Garcia, P. A. A., Schirru, R. and Melo, P. F .F .E. A fuzzy data envelopment analysis approach for FMEA. Progress in Nuclear Energy, 2005, 46 (3-4), 359-373
[7] Guimaraes, A.C.F. and Lapa, C.M.F. Fuzzy FMEA applied to PWR chemical and volume control system. Progress in Nuclear Energy, 2004, 44 (3), 191-213
[8] Panja, S. C. and Ray, P.K. Failure mode and effect analysis of indian railway signalling system. International Journal of Performability Engineering, 2008, 4 (3), 3-14
[9] Saxena, S.C. and Arora, S.P. A text book of railway engineering, Sixth Revised and Enlarged Edition, DhanpatRai Publications (P) LTD., New Delhi, India, 2003
[10] Liu, H.C., Liu, L. and Liu N. Risk evaluation approaches in failure mode and effects analysis: A literature review. Expert Systems with Applications, 2013, 40 (2), 828-838
[11] Lin, Q.L., Wang, D.J., Lin W.G., and Liu H.C. Human reliability assessment for medical devices based on failure mode and effects analysis and fuzzy linguistic theory. Safety Sciences, 2014, 62, 248-256
[12] Chen P.S. and Wu M.T. A modified failure mode and effects analysis method for supplier selection problems in the supply chain risk environment: A case study. Computer and Industrial Engineering, 2013, 66 (4), 634 – 642

