MANAGING SUPPLY CHAIN RISKS: A FUZZY-FAILURE MODE AND EVALUATION APPROACH FOR RANKING THREATS

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Abstract: On the backdrop of lower transportation cost, outsourcing paved the way for borderless production activities and ushered in the era of Supply Chain Management (SCM). For many organizations, achieving the goals of their Supply Chain (SC) is constantly threatened by increased competition and disruption. In this study, the aim is to identify, and rank, SC threats in a developing country using Failure Mode and Effects Analysis (FMEA) with Fuzzy Logic (FL). FMEA parameters were derived for 44 supply chain threats (SCT1 – SCT44) and their Risk Priority Number (RPN) determined. Subsequently, the Mamdani Fuzzy Inference system was utilized to arrive at a Fuzzy-RPN with 125 rules using severity as a determining factor. The rules were ranked to prioritize SC threats. From the conventional FMEA, demand variation (SCT42) and long-distance sourcing (SCT27) had the highest and lowest RPN, respectively. After fuzzification and defuzzification, Fuzzy-RPN identified raw material delay (SCT1), government policy (SCT11), poor transport infrastructure (SCT18) and political instability (SCT19) as threats with the highest Fuzzy-RPN (210) and product recalls (SCT28) with the lowest Fuzzy-RPN (99). Based on these results, it is concluded that a Fuzzy-FMEA approach can identify and rank SC threats with the use of an RPN devoid of sentiments and inaccuracies.

Keywords: supply chain, fuzzy-logic, threats, risk priority number, disruption

1. INTRODUCTION

Before the 1990s, the approach of many organizations to customer fulfilment was vertical integration with little or no emphasis on core competencies. On the backdrop of lower transportation cost, outsourcing paved the way for borderless production activities and ushered in the era of Supply Chain Management (SCM). SCM coordinates decisions on production, inventory, location and transportation among the firms in a Supply Chain (SC) to reduce operating and inventory costs [1].

SC as a network of relationships aligns firms and the required chain drivers to deliver products and services [2-4]. From a system view, SC drivers include production facilities, material suppliers, distribution and retailing services, location, transporters, and customers connected to exchange materials and share information [1]. While one of the goals of an SC is to ensure virtual integration among participating companies, a robust SC system should possess the ability to maintain a balance between responsiveness and efficiency. Such a system can increase the efficiency of different business process through integration and proper coordination. On responsiveness, an excellent decision-making structure will enable an organisation respond to disruptions from increased competition, globalisation, global pandemic, and technological advancement. Invariably, failure events characterized by the

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termination of the ability to exchange resources and information in the chain will occur if disruptions and risks are poorly managed.

Supply chain risks are events (or conditions) at macro and micro levels with the potential to negatively influence core drivers in the chain leading to failures [5]. Micro-risk considers recurrent events which have their root cause from components within the network. Macro-risk includes external and man-made events. Harington [6] commented that 90% of firms do not formally measure risk and about 47% do not possess any backup plan in the event of unexpected disruptions. Based on the multiplicity and diverse risky events among chain drivers, Supply Chain Risk Management (SCRM) should be a collaboration effort. SCRM should consider environmental, social, and economic risks at macro and micro levels, and propose a contingency approach to increase SC resilience. The resilience of an SC describes the internal and external capability of the system elements to manage inevitable disruptions and revert to pre-disruption status. This ability will mitigate (or ameliorate) against the ripple effect of disruptions; for example, Peck [7] sighted SC disruptions of two Finnish phone makers Nokia and Ericsson in 2000. The disruption caused Ericsson about $400 million loss in new product sales. In addition, UPF-Thompson, a major supply of chassis to Land Rover became insolvent in 2001. These events and others opened a new era in SCRM research as interests in creating a resilient supply chain increased.

Singhal et al. [8] reviewed research articles on SCRM and concluded that a large proportion of the methods appeared disjointed despite growing diverse techniques and applications. Similarly, lack of understanding of SCRM and an all-inclusive SCRM technique are barriers to effectively manage SC risks [5, 9]. Tang and Musa [10] commented that quantitative models in SCRM are lacking despite a significant rise in intellectual understanding of SCRM. Ghadge et al. [11] used Failure Mode and Effects Analysis (FMEA) to identify and access SC risks. Cankabis et al. [12] utilized FMEA with Analytic Hierarchy Process (AHP) to model risk assessment for SC system. Their study indicated that a prioritized sub-risks in SC can be obtained using FMEA despite its limitations. However, the limitations of the conventional FMEA [13-15] can be enhanced when integrated with other techniques e.g. Analytic Hierarchy Process (AHP), Fuzzy Logic (FL), Value Analysis, etc. [16]. In this study, the aim is to develop a quantitative knowledge repository to rank, prioritize and manage supply chain threats in a developing country using Failure Mode and Effects Analysis (FMEA) with Fuzzy Logic (FL).

1.1. Supply chain risk management

The quest to identify, manage and minimize the vulnerability of the elements of a supply chain via a structured approach is the goal of SCRM [8]. As a background for this research work, previous methods used in SCRM are presented in Table 1.

Table 1. Past research efforts on SCRM.

S/N	Author(s)	Year	Keywords	Approach/Method
1.	Juttner et al. [17]	2003	Risk management. Supply chain risk management	Qualitative
2.	Juttner [18]	2005	Supply chain risk management, supply chain	Qualitative focus group and quantitative survey and
3.	Tang [19]	2006	Supply chain, risk management	Qualitative literature review
4.	Peck [7]	2006	Supply chain, vulnerability, supply chain management	Qualitative
5.	Manuj and Mentzer [20]	2008	Supply chain risk management	Integrated literature review
6.	Tang and Musa 10]	2011	SCRM, risk management	Literature survey and citation analysis
7.	Singhal et al. [8]	2011	SCRM, risk, uncertainty, literature review	Multi-layered top town taxonomy for classifying literature
8.	Sodhi et al. [21]	2012	Supply chain, SCRM	Qualitative
9.	Sakli et al. [22]	2014	Manufacturing systems, SC, performance analysis, Time series analysis risk, Performance indices	Stochastic model of product flows
10.	Ho et al. [5]	2015	SCRM, risk types, risk factors literature review, risk management methods	Literature review

11.	Ghadge et al. [11]	2017	Supply chain risk management, Product safety and security, Fuzzy, FMEA	Fuzzy, FMEA
12.	Canbakis et al. [12]	2018	Risk management, Supply Chain, AHP, FMEA, WP	FMEA, AHP, WP
13.	Bier et al. [23]	2019	Supply chain, Disruptions, Risk management	Systematic literature review
14.	Hudin et al. [9]	2019	SCM, Risk management, Supply chain risk management, Barrier automotive	Qualitative case study method

1.2. Failure mode and evaluation analysis and Fuzzy logic

FMEA is a subjective human thinking used to identify and analyse failure modes and their causes in components and systems [24, 25]. As a bottom-up framework, each potential failure mode in FMEA; severity (S), occurrence (O) and detectability (D) are identified and assigned values between 1 and 10. Thereafter, a risk priority number (RPN) between 1 and 1000 will be obtained for each failure mode.

FL possess a high tolerance for inaccurate data and allows the modelling of intricate non-linear situations within little time [26]. An FL system has the following components: fuzzifier rules, inference engine, and defuzzifier. The FL process combines a set of crisp input, transformed into a fuzzy set through fuzzy linguistic variables, fuzzy linguistic terms and membership functions. Fuzzification allows an inference to be made based on set of rules. Using membership functions, the result can be presented as a crisp output in what is known as defuzzification [27, 28].

1.3. Fuzzy-FMEA

In Fuzzy-FMEA, the failure modes in FMEA are fuzzified with their respective membership function to obtain a degree of importance for each parameter. The technique of Fuzzy-FMEA as described by Balaraju et al. [28] is described in Figure 1.

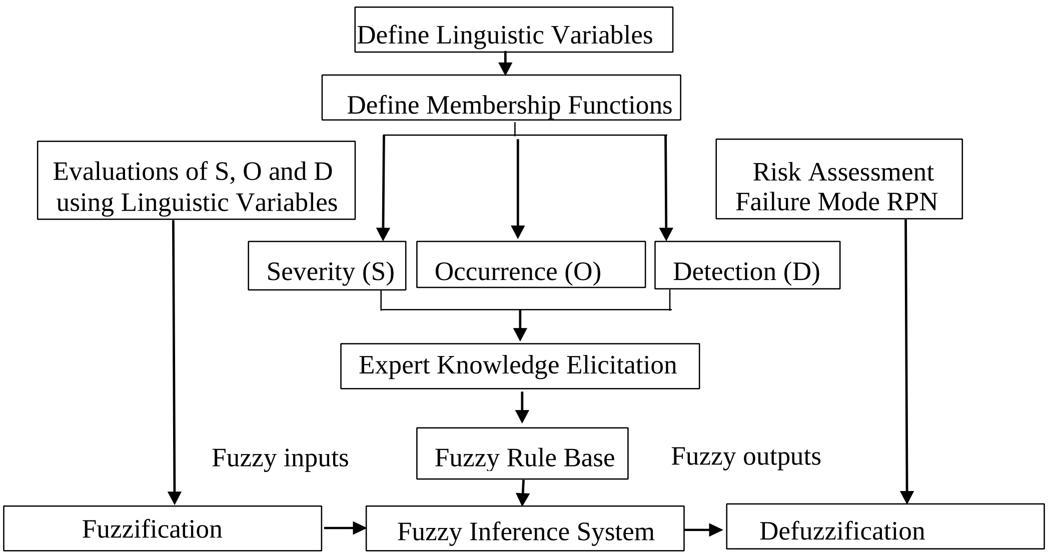

Fig. 1. Fuzzy-FMEA technique.

2. METHODOLOGY

2.1. Primary and secondary data collection

Primary data obtained through interviews and questionnaire distributed among 7 organisations are presented in Table 2.

Table 2. Summary of sources of data collected.

S/N	Organisation	Experts	Sector	Data Collection Type
1	Company A	Field Service Engineer	Telecommunication	Questionnaire/Interview
2	Company B	Supply chain personnel	Construction	Questionnaire
3	Company C	Project Administrator	Real Estate	Questionnaire/Interview
4	Company D	Account officer	Construction	Questionnaire/Interview
5	Company E	Architect	Construction	Questionnaire
6	Company F	Project Engineer	Maintenance	Questionnaire/Interview
7	Company G	Business Development officer	Oil and gas	Questionnaire

From Rwakira [29], 44 SC threats were adopted to capture relevant aspects threats within the context of developing countries. The threats with their representative codes are shown in Table 3.

Table 3. Supply chain threats.

Code	Threat Description	Code	Threat Description
SCT1	Raw materials delay	SCT23	Outsourcing
SCT2	Financial difficulties	SCT24	Communication barriers
SCT3	Poor customer delivery performance	SCT25	In-transit material theft
SCT4	Poor quality products	SCT26	Natural disasters e.g. flood, drought etc.
SCT5	Product counterfeiting	SCT27	Long-distance sourcing
SCT6	Machine breakdowns	SCT28	Product recalls
SCT7	Customer dynamism	SCT29	Demand forecasting
SCT8	Unfair competition	SCT30	Exchange rate fluctuations
SCT9	Payment threat	SCT31	Unstable taxation
SCT10	Risk communication	SCT32	Geographic location
SCT11	Government policy	SCT33	Weak legal system
SCT12	Corruption	SCT34	National politics
SCT13	Effective contracting	SCT35	Economic policies
SCT14	Limited local supply market	SCT36	Market dynamics
SCT15	Order cancellation	SCT37	Stock theft
SCT16	Supplier delivery failure	SCT38	Manufacturing flexibility
SCT17	Dishonest suppliers	SCT39	Exclusive sourcing
SCT18	Poor transport infrastructure	SCT40	Distributor complacency
SCT19	Political instability	SCT41	Raw materials shortages
SCT20	Procurement risks	SCT42	Demand variations
SCT21	Power shortage	SCT43	Reputational risk
SCT22	Insufficient skilled manpower	SCT44	Poor internal coordination

2.2. Fuzzy-FMEA method

In this study, the Mamdani Fuzzy Inference System (MFIS) will be adopted. MFIS considers the Fuzzify input variables (i.e. S, O and D), the Fuzzy operator (AND / OR), Implication method (IF-THEN rule), Aggregation method (Max Function), and Defuzzification. The MFIS used in this research is presented in Figure 2. In Table 4, the linguistic variables, term sets and membership functions required to convert FMEA into equivalent FIS are highlighted. Membership functions map non-fuzzy inputs to fuzzy linguistic variable and vice-versa in the Fuzzification and Defuzzification process. In essence membership functions are used to quantify linguistic terms. A total of 125 rules combination were obtained from the membership functions.

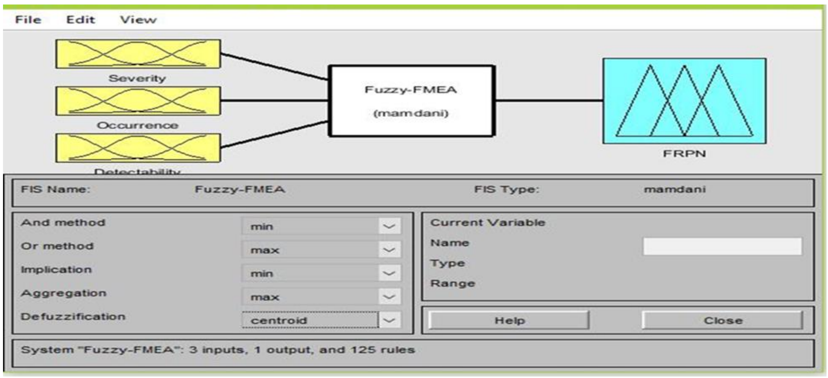

Fig. 2. Fuzzy risk priority number using Mamdani Fuzzy Inference System.

Table 4. Linguistic variable, term sets and membership functions.

Linguistic Variables	Term sets	Membership functions
	None	trapmf
	Low	trimf
INPUT 1: SEVERITY	Moderate	trimf
	High	trimf
	Hazardous	trimf
	Unlikely	trapmf
INPUT 2: OCCURRENCE	Low	trimf
	Moderate	trimf
	High	trimf
	Very-high	trimf
	Excellent	trapmf
	High	trimf
INPUT 3: DETECTABILITY	Moderate	trimf
	Low	trimf
	Remote	trimf
	Very-low	trapmf
	Low	trimf
OUTPUT: FRPN	Moderate	trimf
	High	trimf
	Very-high	trimf

In Figure 3, a sample screenshot of the developed FIS based fuzzy rules is presented. Using the Fuzzy Logic toolbox in MATLAB software, Fuzzy RPN (FRPN) value was obtained for each threat.

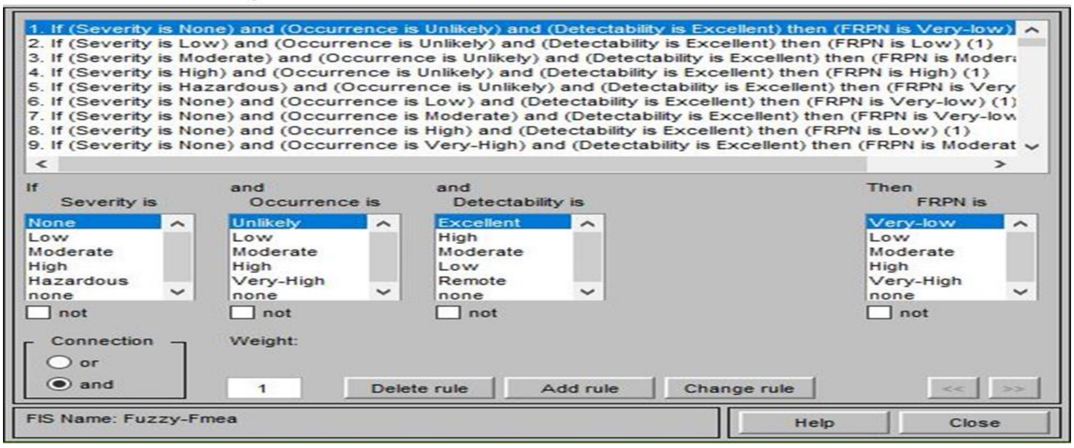

Fig. 3. FIS based fuzzy rules.

3. RESULTS

From the conventional FMEA, RPN value for each threat is presented in Table 5. Demand variation (SCT42) and long-distance sourcing (SCT27) had the highest and lowest RPN, respectively.

Table 5. RPN for SC Threats and ranking using FMEA.

SC Threats	Severity	Occurrence	Detectability	FMEA RPN	Ranking
SCT1	8	8	3	192	6
SCT2	8	7	4	224	2
SCT3	7	7	3	147	12
SCT4	8	6	3	144	13
SCT5	7	6	3	126	19
SCT6	8	8	1	64	38
SCT7	5	3	6	90	29
SCT8	6	8	3	144	13
SCT9	5	3	8	120	23
SCT10	6	4	8	192	6
SCT11	8	7	2	112	27
SCT12	8	5	5	200	5
SCT13	6	3	7	126	19
SCT14	5	4	8	160	10
SCT15	4	3	6	72	36
SCT16	4	3	7	84	31
SCT17	6	3	7	126	19
SCT18	8	8	2	128	17
SCT19	8	8	2	128	17
SCT20	7	8	4	224	2
SCT21	7	8	3	168	8
SCT22	3	2	8	48	42
SCT23	3	3	7	63	39
SCT24	4	3	7	84	31
SCT25	5	4	7	140	16
SCT26	8	7	1	56	41
SCT27	6	5	1	30	44
SCT28	7	2	3	42	43
SCT29	5	5	6	150	11
SCT30	6	4	5	120	23
SCT31	5	5	5	125	22
SCT32	4	4	5	80	35
SCT33	5	3	7	105	28
SCT34	5	3	6	90	29
SCT35	6	5	7	210	4
SCT36	6	4	6	144	13
SCT37	4	3	5	60	40
SCT38	4	3	7	84	31
SCT39	5	3	8	120	23
SCT40	4	3	7	84	31
SCT41	8	5	3	120	23
SCT42	8	6	5	240	1
SCT43	3	3	8	72	36
SCT44	6	4	7	168	8

The membership function editor, the Fuzzy-FMEA viewer, and the Fuzzy-FMEA editor from the Fuzzy Logic toolbox in MATLAB are presented in Figure 4, Figure 5 and Figure 6, respectively.

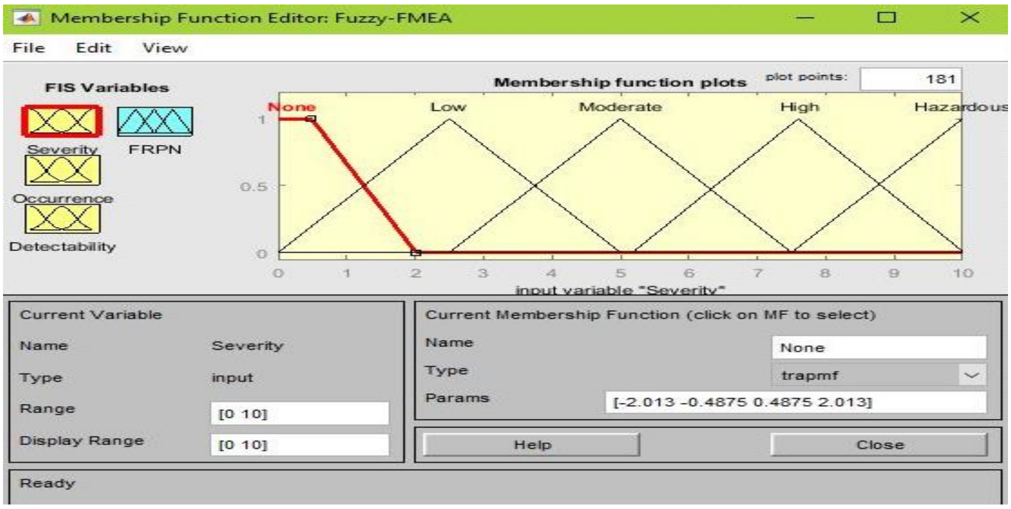

Fig. 4. Membership function editor.

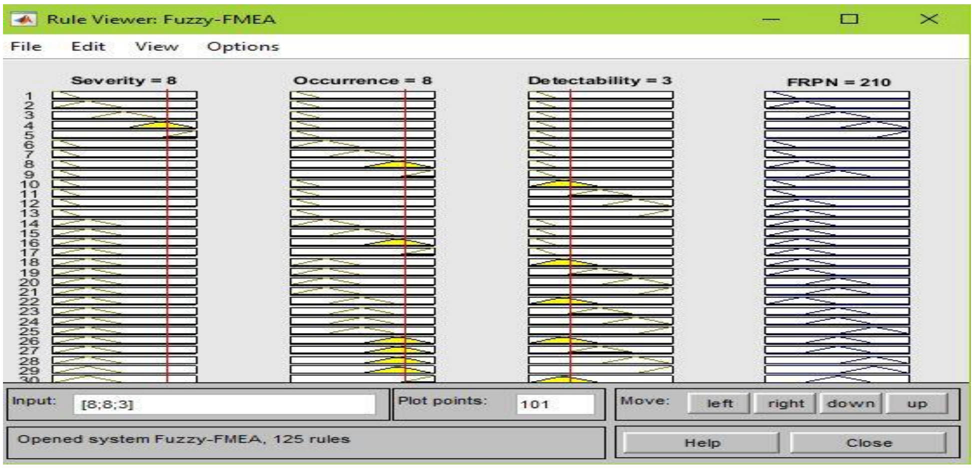

Fig. 5. The Fuzzy-FMEA viewer.

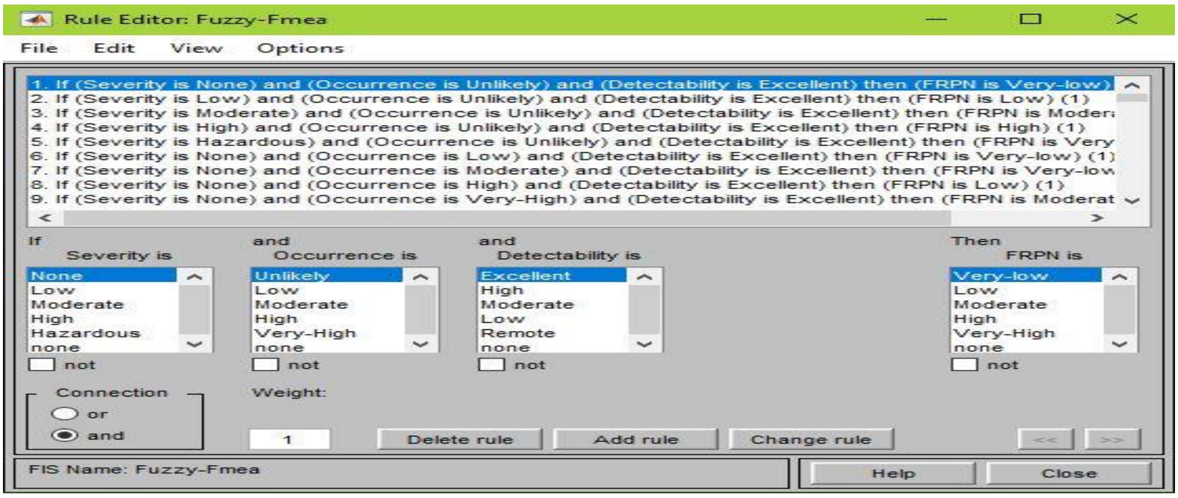

Fig. 6. Fuzzy-FMEA editor.

After fuzzification and defuzzification, the Fuzzy RPN for each threat is presented in Table 6. Fuzzy-RPN identified raw material delay (SCT1), government policy (SCT11), poor transport infrastructure (SCT18) and political instability(SCT19) as threats with the highest Fuzzy-RPN (210) and product recalls (SCT28) with the lowest Fuzzy-RPN (99).

Table 6. RPN for SC threats and ranking using Fuzzy- FMEA.

SC Threats	S	O	D	FMEA RPN	Ranking	FRPN	FRPN Ranking
SCT1	8	8	3	192	6	210	1
SCT2	8	7	4	224	2	207	5
SCT3	7	7	3	147	12	185	19
SCT4	8	6	3	144	13	193	6
SCT5	7	6	3	126	19	176	22
SCT6	8	8	1	64	38	193	6
SCT7	5	3	6	90	29	151	31
SCT8	6	8	3	144	13	152	30
SCT9	5	3	8	120	23	189	10
SCT10	6	4	8	192	6	189	10
SCT11	8	7	2	112	27	210	1
SCT12	8	5	5	200	5	189	10
SCT13	6	3	7	126	19	171	24
SCT14	5	4	8	160	10	189	10
SCT15	4	3	6	72	36	125	41
SCT16	4	3	7	84	31	144	34
SCT17	6	3	7	126	19	171	24
SCT18	8	8	2	128	17	210	1
SCT19	8	8	2	128	17	210	1
SCT20	7	8	4	224	2	181	21
SCT21	7	8	3	168	8	185	19
SCT22	3	2	8	48	42	140	39
SCT23	3	3	7	63	39	125	41
SCT24	4	3	7	84	31	144	34
SCT25	5	4	7	140	16	171	24
SCT26	8	7	1	56	41	193	6
SCT27	6	5	1	30	44	149	33
SCT28	7	2	3	42	43	99	44
SCT29	5	5	6	150	11	187	18
SCT30	6	4	5	120	23	161	28
SCT31	5	5	5	125	22	188	16
SCT32	4	4	5	80	35	133	40
SCT33	5	3	7	105	28	172	23
SCT34	5	3	6	90	29	151	31
SCT35	6	5	7	210	4	188	16
SCT36	6	4	6	144	13	161	28
SCT37	4	3	5	60	40	115	43
SCT38	4	3	7	84	31	144	34
SCT39	5	3	8	120	23	189	10
SCT40	4	3	7	84	31	144	34
SCT41	8	5	3	120	23	189	10
SCT42	8	6	5	240	1	193	6
SCT43	3	3	8	72	36	142	38
SCT44	6	4	7	168	8	171	24

4. CONCLUSIONS

In this study, the integration of FMEA with Fuzzy Logic was utilized to rank supply chain threats. A Mamdani-FIS was developed with 3 inputs of severity, occurrence, and detectability. The output was a FuzzyRPN with a total of 125 rules. These rules were formed with severity as the most important factor to adequately rank the threats. With the use of fuzzy logic, subjectivity, vagueness, and incompleteness associated with the supply chain threats were made clearer. Based on these results, it is concluded that a Fuzzy-FMEA approach can identify and rank SC threats with the use of an RPN devoid of sentiments and inaccuracies.

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