The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/0265-671X.htm

Power distribution operational risk model driven by FMEA and ISM approach

Pallawi Baldeo Sangode
Symbiosis Institute of Business Management, Nagpur, India, and
Sujit G. Metre
Principal, S.B. City College, Nagpur, India

Received 12 August 2019
Revised 16 October 2020
Accepted 7 December 2020

Abstract

Purpose – The purpose of this paper is to identify various risks in the power distribution supply chain and further to prioritize the risk variables and propose a model to the power distribution industry for managing the interruptions in its supply chain. To accomplish this objective, a case of a major power distribution company has been considered.

Design/methodology/approach – Failure mode and effects analysis (FMEA) analysis has been done to identify the potential failure modes, their severity, and occurrence and detection scores. Then an interpretive structural model (ISM) has been developed to identify and understand the interrelationships among these enablers followed by MICMAC analysis, to classify the risk variables in four quadrants based on their driving and dependency powers.

Findings – The results of this study exhibit that technical failure in the information and technology system, the use of improper equipment, poor maintenance and housekeeping in the internal operations are the major risk drivers. Exposure to live wires and commercial loss in power supply has strong dependence power.

Research limitations/implications – This study is limited to a single power distribution company and not the whole power distribution sector.

Practical implications – This study suggests the managers of the power distribution company develop an initial understanding of the drivers and the dependent powers on the supply chain risks.

Social implications – Through prioritization, identification of drivers and the dependent risks, the losses in the power distribution supply chain can be minimized.

Originality/value – Various failures in the power distribution have been studied in the past, but they have not investigated the supply chain risks in the power distribution of a power distribution company.

Keywords Failure mode and effects analysis (FMEA), Interpretive structural modeling (ISM), MICMAC analysis, Supply chain

Paper type Research paper

Introduction

Power distribution is a crucial connection between the power supply company and the end-user. Proper distribution of power provides customer satisfaction and further proper revenue in the whole supply chain. The power distribution supply chain begins from the electricity producers who generate electricity through the sources of thermal, hydro or renewable sources. This power is supplied to the transmitters and finally, the distribution is done. Various drivers aid smooth functioning in this distribution supply chain. These drivers are those process functions that can impact the whole chain thereby resulting in the economic and financial condition of the firm.

Hence the failures or risks that can arise at any level in the execution of these process functions must be identified, prioritized and treated as they can not only cause financial and commercial losses, but the service quality loss and further loss of the company goodwill can surface. Hence risk management has to be aimed to safeguard the organization from the adverse effects and improve the overall performance (Maheshwari and Jain, 2014). Past

International Journal of Quality & Reliability Management

0265-671X
DOI 10.1108/IJQRM-06-2019-0206

studies have shown various models developed by the researchers to analyze and model the supply chain risks. (Pandey and Sharma, 2017) developed an interpretive structural model (ISM) for assessing the risks in the supply chain that can help the supply chain managers to take decisions on treating the risk effects. Sharma and Bhat (2014) developed an ISM model for the agile supply chain and identified various enablers involved in the agile supply chain and their relative importance to the decision-makers.

Literature review

Researches in the field of supply chain risks have prominently discussed the risks associated with the supply chain networks and also have formulated the models to interrelate these risk variables. These studies have identified various gaps and future scopes for modification, updating and expanding their models. These research gaps derived from the literature review of the reviewed papers of supply chain risks of the power distribution sector are presented in Table 1.

The study of the existing literature has revealed multiple variables influencing the power distribution supply chain. Figure 1 describes the same in the form of a fishbone diagram.

Research methodology

A case of a major power distribution company has been undertaken to study the risks associated with it. The author developed a framework on failure mode and effects analysis (FMEA) to identify, analyze and model the risks. Further structural equation modeling (SEM) is used to identify and represent the interrelationships among the various risks in the power distribution company. The author collected the data in two phases. In the first phase, a detailed review of the literature was done to study the various risks in the execution of the core functions of the power distribution company. The experts from the power distribution industry were consulted to validate the risk variables and their quantification. Two experts holding the managerial position in the company agreed to validate the risk variables and further rate the risk variables for its severity, occurrence and detectability. The FMEA sheet, composing of 17 risk elements, was filled through the common censuses of the experts (see Table 2).

In the next phase, based on the risk priority number (RPN) generated by the FMEA model, 11 top risk elements were selected for further analysis of their structural relationships. ISM is used to understand the structural interrelations among these risk elements. This process was also based on the same expert's judgment. The experts were given eight days to understand the ISM model and further derive the relationships among the risk elements through common consensus. Structural self-interaction matrix represented in Table 3, shows these interrelationships. The researcher's perspectives that compelled the implementation of FMEA and ISM and their method of implementation are explained as under. Further the complete flow of the proposed model is represented in Figure 2.

What is failure mode and effect analysis?

FMEA is a systematic and qualitative tool used to identify the possible failure modes in a process, causes of failures and the effects of the failure on the whole system. It begins during the earliest conceptual stages of design and continues throughout the life of the product or service. FMEA is a tool that identifies the risks in the products or the processes that are designed, and further begins the risks reducing actions through the highest potential impact (Beyene *et al.*, 2018). It excludes the prospective risks or failures from the system to boost the reliability and safety of the complex systems. This supports proper information provision for decision-making in risk management. Thus it helps to prioritize the risks in the process

Author	Research objectives	Possible gaps
Ahsen (2008)	The author aimed at developing an improved approach to prioritizing failures within the procedure of the FMEA	The author suggested that focusing on the possibilities of including interdependencies among the failure modes identified through FMEA
Moja *et al.* (2016)	The authors aimed at identifying and assessing the risks associated with the electricity sector through the operations department of a Swaziland Electricity Company	The authors recommended that further study can be undertaken to determine the risks and their magnitudes
Liu *et al.* (2010)	The authors have introduced the risk management techniques adopted by the electricity market	The authors suggested developing specific techniques of risk management to be applied to electricity markets
Holmukhe (2016)	The author studied various challenges faced by the electricity distribution sector in India and suggested possible solutions to the problems	The author suggested several measures for utility infrastructure as drivers to the successful transition of the power sector, which can be further studies
Narayanagounder and Gurusami (2009)	This paper demonstrates the new approach to prioritize failure modes and resolved the limitations of the traditional FMEA technique	The authors suggested the other possible methods can further be studied to drain away from the limitation of traditional FMEA
Dewangan *et al.* (2015)	The authors used interpretive structural modeling (ISM) to identify the enablers that play a vital role in enhancing the competitiveness of the manufacturing industry	The future scope of the study expands to identifying the enablers of the manufacturing competitiveness of the industries in India and abroad
Prabu *et al.* (2015)	The authors established the interdependency of the supply chain intricacy drivers using interpretive structural modeling (ISM) and impact matrix cross-reference multiplication (MICMAC)	The author suggested future work for identifying the industry-specific intricacy drivers
Dube and Gawande (2016)	The authors aimed at identifying the enablers for the implementation of green supply chain and the interrelationships among them using ISM model and MICMAC analysis	The authors suggested the need to develop model specific to the industries like automobile, electrical, electronic and chemical
Maheshwari and Jain (2014)	The authors reviewed the past studies from various authors which addressed the supplier's perspective risks in the supply chain	The authors suggested future research for the validation of various risk models and the development of algorithms for certain situations
Rogers *et al.* (2015)	The authors studied works of literature to identify, discuss and elaborate on the impact and origin of focal supply chain risk factors in the Indian concept	The authors suggested future study on various supply chain risks in the Indian business environment and future scope of improvement

Table 1. Literature review detailing the research gaps

thereby aiding proper risk treatment (Liu *et al.*, 2013). For evaluating the performances of different risk modes, that are categorized as occurrence (*O*), severity (*S*) and detection (*D*), FMEA uses the method of calculating the RPN. Integer scale of 1–10 is used for the estimation of the values of *O*, *S* and *D*. Further, RPN value is calculated by multiplying these three values. The risks are then prioritized based on the value of RPN. The higher the RPN, the higher is the risk. Thus, the risk estimation in FMEA with the RPN method is said to be the most effective method for the prevention of risks in advance (Lv *et al.*, 2019).

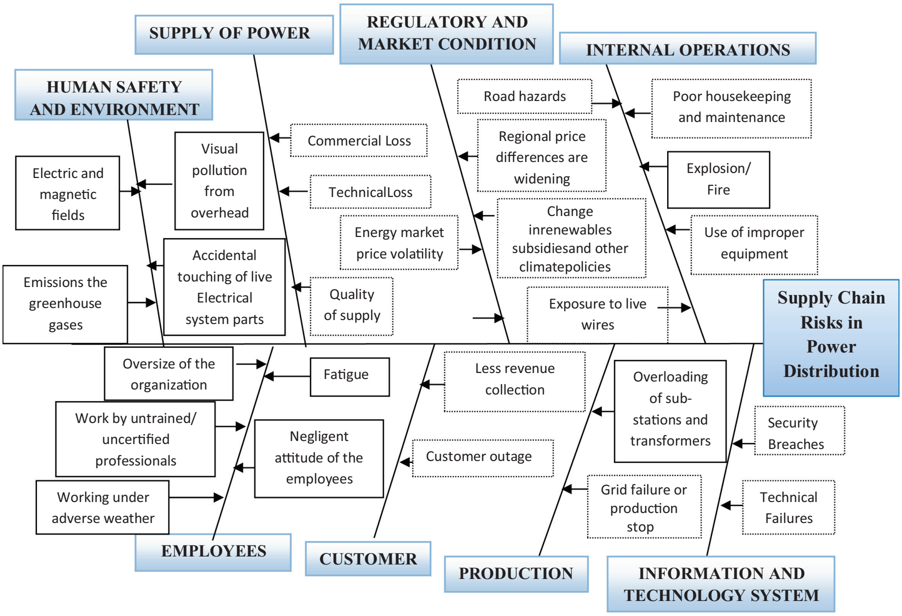

Figure 1.
Fishbone diagram for the supply chain risks in power distribution as derived from literature

In this research work, the issues or the risks in the process functions of the power distribution supply chain are categorized as:

(1) Internal operations risks;

(2) Production risks;

(3) Information and technology systems-related risks;

(4) Market and regulatory risks;

(5) Human resources-related issues;

(6) Risks at the customer level;

(7) Issues in the supply of power.

Internal operations risk in power distribution is those that may arise while the distribution operations are active. These were identified as road hazards, the use of improper equipment, exposure to live wires, poor housekeeping and maintenance, explosions/fire, grid failure. Production-related risks are the risks of a grid failure or production stoppage. Information and technology systems-related risks relate to the security breaches and technical failures in the use of computers and software for managing the data, distribution flow, etc. Market and regulatory framework issues that are identified change in renewables subsidies and other climate policies, energy market price volatility, rising energy prices and widening regional price differences. Human resources-related issues relating to the power distribution company were the oversizing of the company. Risks at the customer level that can occur are less revenue collection from the customer and customer outrage due to the power supply cut. Issues in the supply of power are the risks of technical and commercial failure and degradation in the quality of power supply.

Table 2. Application of FMEA to power distribution supply chain

Supply chain process function	Potential failure mode	Potential effect(s) of failure	Severity (*S*)	Potential cause(s) of failure	Occurrence (*O*)	Current process controls	Detectability (*D*)	Risk priority number (RPN)
Internal operations	Road hazards	Supply failure	3	Road excavation works damaging cables, dash by vehicles to poles	3	Proper cable markers in place/coordination with agencies/alternate power feeding arrangement	1	9
	Use of improper equipment	Equipment failure leading to a threat to operator life, failure to supply power	7	Overloading, substandard equipment	4	Monitoring equipment, factory testing, routine maintenance, plan for up gradation/modernization	3	84
	Exposure to live wires	Risk of accidents to outsiders, animals	5	Electrocution	2	Awareness of safety, identifying and correcting loose span, tilted poles	9	90
	Poor housekeeping and maintenance	Equipment failure, frequent breakdowns, loss of revenue, customer complaints	5	Earth faults, tree branches touching lines, tilted poles, loose contacts, poor workmanship	8	Timely maintenance	7	280
	Explosions/fire	Risk of accidents to outsiders/employee	6	Poor maintenance, poor quality equipment	2	Training for fire hazards	9	108
Production	Grid failure or production stop	Total supply failure	10	Demand generation gap, failure of islanding system	2	Preventive maintenance/effective islanding mechanism for generators. Redundancy of power evacuation lines	6	120

(*continued*)

Supply chain process function	Potential failure mode	Potential effect(s) of failure	Severity (*S*)	Potential cause(s) of failure	Occurrence (*O*)	Current process controls	Detectability (*D*)	Risk priority number (RPN)
Information and technology system	Security breaches	Risk of mal-operation may lead to accidents/no supply, equipment failure/data corruption	7	Phishing, application vulnerabilities	1	Technical training the employees to remain vigilant and identify suspicious links, all software and applications receive regular updates. The impact depends upon the degree of automation and no of control centers. At present automation is less. However, billing is fully IT-based. The provision of back up data at the separate server at a different location	7	49
	Technical failures	Operational activity/control problems	5	Hardware failure or severe software issues	2	No control mechanism	10	120

(*continued*)

Table 2.

Supply chain process function	Potential failure mode	Potential effect(s) of failure	Severity (*S*)	Potential cause(s) of failure	Occurrence (*O*)	Current process controls	Detectability (*D*)	Risk priority number (RPN)
Regulatory and market condition	Change in renewables subsidies and other climate policies	Average billing rate lowers affecting cash flow	6	More focus on renewable energy. Limited coal availability	2	Increase operational efficiency, being regulated business, regulator takes necessary steps	4	48
	Energy market price volatility	Has to spare more money for additional power/sale of power at a lower rate, power surplus/shortage scenario	5	Disturbances insource of power via water, coal, gas	4	Early steps to cover shortages. Accuracy in demand prediction. Close watch on happenings worldwide	7	140
	The rising energy prices and regional price differences are widening	Migration of industrial consumers, affecting cash flow and demand growth	5	Every state tries to attract industry with sops	3	Better quality and uninterrupted supply to be maintained. Ease in doing business	8	120
Human resource function	Oversize of the organization	Lack of effective control, coordination and proper communication	4	Poor supervision	4	No control mechanism	10	160

(continued)

Table 2.

Table 2.

Supply chain process function	Potential failure mode	Potential effect(s) of failure	Severity (*S*)	Potential cause(s) of failure	Occurrence (*O*)	Current process controls	Detectability (*D*)	Risk priority number (RPN)
Customer	Less revenue collection	Financial condition weak, no provision for *R* and *M* work	2	Theft of electrical energy	7	Prompt collections implementing, Surprise inspections are carried out by vigilance squads. The energy meter is housed in a separate box sealed and made inaccessible to the consumers. Multicore PVC cables are used as service mains instead of single core VIR wires. Heavy fines are imposed on consumers found committing theft of energy	3	42
	Customer outage	Less revenue collection	9	Grid failure or production stop	2	No control mechanism	10	180

(*continued*)

Table 2.

Supply chain process function	Potential failure mode	Potential effect(s) of failure	Severity (*S*)	Potential cause(s) of failure	Occurrence (*O*)	Current process controls	Detectability (*D*)	Risk priority number (RPN)
Supply of power	Technical loss	Distribution loss	5	The energy dissipated in the conductors, transformers and other equipment used for transmission, transformation, subtransmission and distribution of power	5	Anti-theft drive, meter shifting, mass meter replacement project/ balancing of load, maintaining power factor, avoid overloading, proper earthing	2	50
	Commercial loss	Distribution loss	5	Nonperforming and underperforming meters, wrong applications of multiplying factors, defects in CT and PT circuitry, meters not read, pilferage by manipulating or bypassing of meters, theft by direct tapping	5	Accurate metering, appropriate range of meter concerning connected load, electronic meters with (TOD, tamper-proof data and remote reading facility) for HT and HV services, intensive inspections by pooling up staff members, reduce meter exceptionally, use energy audit as a tool to pinpoint areas of high losses. Eradication of theft. AMR systems. With IT support, analyze data of consumption at the micro level	3	75
	Quality of supply	Power not supplied, supply at low voltage, fluctuating frequency or voltage, high harmonics	3	Revenue caps are adjusted in accordance with the customers' interruption costs. Improper load centre, demand supply mismatch. Poor workmanship in joints. High use of harmonics generation appliances	2	Proper planning and implementation of system improvement works, use of harmonic filters, proper crimping at joints	8	48

Table 3.
Structural self-interaction matrix (SSIM)

S. no.	SSIM	1	2	3	4	5	6	7	8	9	10	11
1	Poor housekeeping and maintenance risk	*X*	0	0	0	0	*V*	*V*	*V*	*V*	0	*X*
2	Customer outrage risk		*X*	0	0	*A*	*A*	0	0	0	*V*	0
3	Organization oversize risk			*X*	0	0	0	0	0	0	0	*V*
4	Energy market price volatility risk				*X*	*X*	0	0	0	0	*V*	0
5	Risk of regional price difference widening					*X*	0	0	0	0	*V*	0
6	Risk of a grid failure or production stop						*X*	*A*	*A*	*X*	*V*	*A*
7	Technical failure risk							*X*	*V*	*V*	*V*	*A*
8	Explosion or fire risk								*X*	*X*	*V*	*A*
9	Exposure to live wires									*X*	0	*A*
10	Risk of commercial loss										*X*	0
11	Risk of use of improper equipment											*X*

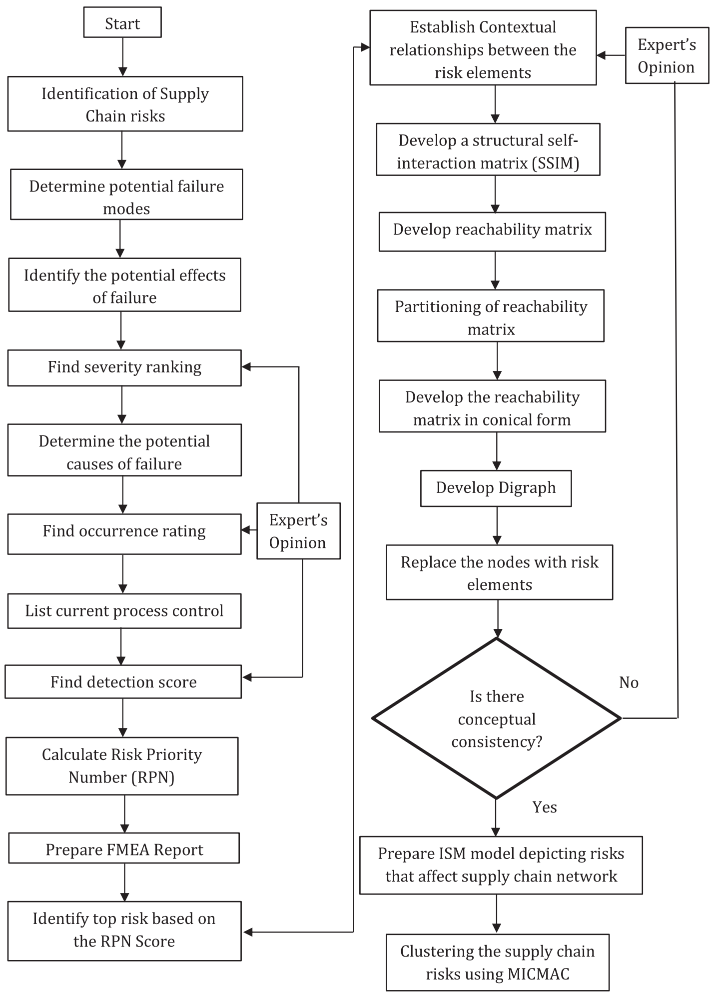

Figure 2.
Flow diagram for the proposed model

These abovementioned risks are incorporated into the FMEA model for further quantification and prioritization.

Risk prioritization. The abovementioned risks may need immediate treatment since the effects may be devastating. And hence prioritizing these risks to identify those which must be addressed first needs to be done. This is done through the quantification of the risks based on its three determinants.

First, the risks associated with the given process or system is identified. Each risk is determined based on its severity level (*S*). This level is rated from 1 to 10, 1 being insignificant and 10 being catastrophic. Further, the occurrence (*O*) of the risk is identified, i.e. the frequency with which the risks occur. This is again rated on a scale of 1–10, 1 being unlikely and 10 being inevitable. The third determinant is the detection rating (*D*). This rating estimates how well the controls can detect either the cause or its failure mode after they have happened represented by a value from 1 to 10, 1 being the control is certain to detect the problem and 10 being the control is certain not to detect the problem.

Finally, a RPN is calculated, which is the product of severity, occurrence and detectability.

$$\mathrm{RPN} = S*O*D$$

In this research work, these three determinant values are identified through the expert's judgment for all the entities of the risks.

The FMEA table for the risks identified for the power distribution company under the study is given in Table 2. Potential causes of failure for certain risks and the current process controls were also identified through a thorough study of the secondary data.

In the case of the security breaches in the Information and Communication Technologies (ICT) system, the potential causes of failure can be phishing and application vulnerabilities and the process control would be technical training the employees to remain vigilant and identify suspicious links, all software and applications receive regular updates (Seqrite, 2018).

One of the process functions identified is power distribution loss. These losses arise due to technical and commercial losses. The reasons for the elevation in these losses is because of resistance to power flow by the power system, nonperforming and underperforming meters, wrong applications of multiplying factors, defects in Current Transformer (CT) and Potential Transformer (PT) circuitry, meters not read, pilferage by manipulating or bypassing of meters, theft by direct tapping. The current control mechanism to loss reduction is "Accurate Metering, Appropriate range of meter concerning connected load, Electronic meters with (TOD, tamper-proof data and remote reading facility) for HT and HV services, intensive inspections by pooling up staff, reducing meter exceptional, using energy Audit as a tool to pinpoint areas of high losses, eradication of theft and AMR systems". (Concepts and Principles of Distribution Loss, 2006).

The risk of a grid failure or production stop thereby causing total supply failure, is attributed to the demand generation gap and failure of the islanding system. The current control mechanism is preventive maintenance (power distribution reforms in Maharashtra, 2009).

Analysis of FMEA

Table 2 shows the calculation of RPN for all the possible failures.

For the process functions of the supply chain in the power distribution firm under study, the failures or the risks that are prioritized (based on RPN value) are:

(1) Internal operations: Highest RPN for "Poor housekeeping and maintenance" (280) followed by "Explosion or fire" (108), "Exposure to live wires" (90), use of improper equipment (84).

(2) Production: “Grid failure or production stops” (120).

(3) Information technology system: “Technical failures” (120).

(4) Regulatory and market condition on power supply chain: “Energy market price volatility” (140) followed by “Rising energy prices and regional price differences are widening” (120).

(5) Employees: “Oversize of the organization” (160).

(6) Customer: “Customer Outrage” (180).

(7) Supply of power: “Commercial loss” (75).

Thus these abovementioned failure modes become the high-level risks in the system.

Why consolidate of the ISM approach to FMEA methodology?

FMEA is an effective method for ensuring better reliability of a system through the identification of the failure modes in the performance of a system and affects the failure produces on the performance. This would gradually prevent the unacceptable failures to reach the customers thereby aiding the management in proper resource allocation. At times FMEA analysis may be confusing. The same RPN number for two or more risks may lead to confusion in prioritizing the risks. A high RPN number may not necessarily mean high risk or two failure modes with the same RPN number may not have the same risk level. Hence risk can also be prioritized through the team discussion. But a large number of risks may lead to a lengthier and unending discussion. A matrix for combining the RPN and the severity, occurrence and detectability can be used. In cases where the company finds it difficult to find the detection rank, detection rank can be misused and the critical number can be used. Critical number (CN) = severity (S) × occurrence (O) (Hartwell). The study (Narayanagounder and Gurusami, 2009) presented a new approach to improve the evaluation of RPN. The traditional limitation of FMEA of two or more risks having the same RPN number is removed by risk priority code. The proposed method of evaluation of RPN in design FMEA has benefits when two or more failure modes have the same RPN and when the team has a disagreement in the ranking scale for severity, occurrence and detection.

A more logical approach to confront the limitations of FMEA can be to identify the driving power of the risks which may lead to the risk origin and further to identify the dependency among these risks. An interrelationship approach for the risks would be an answer to the disruptions in the power distribution supply chain. This process is facilitated through the use of the ISM approach.

Interpretive structural modeling. ISM is a general-purpose technique for analysis and decision supporting system for identifying and structuring relationships among the important issues or problems. It provides a structured method for dealing with complex situations. The output of the ISM model is the visual map of the problems generated through the dependencies of the risks within. (Pandey and Sharma, 2017) used the ISM model approach to finding out the structural relationship among the risks in the automotive supply chain. ISM is a well-established methodology for identifying and arranging the relationships between important problems. These relationships between the factors or the risks develop a better understanding of the overall problem of the given system than understanding the factors individually. For identifying the enablers for the competitiveness of the Indian manufacturing sector, ISM was used to understand the relationships among the different enablers (Dewangana *et al.*, 2015). This helped the authors get the primary idea for developing a map of the complex associations between the numerous elements in the manufacturing sector concerned with multifaceted conditions. (Aeeni *et al.*, 2019) used ISM to map the hierarchical relationships of the main factors/challenges of the Urban Management System in Iranian New Towns. Thus after examining the relationship between the variables, the approach was further used to determine the driving power and dependence of the factors. According to (Srivastava and Pandey, 2018), ISM is optimally suited to deal with the multifaceted situation and further deriving solutions. In their study, they identified different factors that were responsible for a change in responsiveness of customers toward advertisement, and later ISM modeling was done to forecast the association between various variables. (Kuo *et al.*, 2010) used ISM to partition the barriers for the product service system into a multilevel structural hierarchy established on their associations. This hierarchical relationship presented a clear understanding of the significance of each barrier that further supported strategic analysis.

Development of structural self-interaction matrix (SSIM). To identify the contextual relationship among the risks, the experts from academia and industry are consulted. SSIM matrix is built using four symbols that denote the relationship among the factors as shown in Table 3.

For any two factors "*i*" and "*j*", the terminologies used are:

V: if factor *i* influence the factor *j*;

A: if factor *j* influence the factor *i*;

X: if both the factors influence each other;

O: if the factors are unrelated.

The reachability matrix is prepared from the SSIM table. The symbols *V*, *A*, *X*, *O* are converted into Zero "0" and one "1" based on the rules as follows.

If (*i*, *j*) position in the SSIM table is *V*, the position in the reachability matrix will become 1, and the (*j*, *i*) positions will become 0. If the (*i*, *j*) position is A, then the position in the reachability matrix will become 0 and the (*j*, *i*) position will become 1. If the (*i*, *j*) position in the SSIM is *X*, then positions (*i*, *j*) and (*j*, *i*) both will become 1. If the position of the SSIM is *O*, then in the reachability matrix, both the positions, (*i*, *j*) and (*j*, *i*) will become 0. Based on this rule, the reachability matrix is formed as shown in Table 4. Further, the total driving and the dependence power are calculated as shown in Table 5.

Partitioning of reachability matrix into different levels or level partitioning:
The final reachability matrix is fragmented by grouping the variables into different levels through an algorithm-based process of level partitioning. This is used to develop the structural model depending upon the interrelationships between the risk variables. Thus an

S. no.	Reachability matrix	1	2	3	4	5	6	7	8	9	10	11
1	Poor housekeeping and maintenance risk	1	0	0	0	0	1	1	1	1	0	1
2	Customer outrage risk	0	1	0	0	1	0	0	0	0	1	0
3	Organization oversize risk	0	0	1	0	0	0	0	0	0	0	1
4	Energy market price volatility risk	0	0	0	1	1	0	0	0	0	1	0
5	Risk of regional price difference widening	0	1	0	1	1	0	0	0	0	1	0
6	Risk of a grid failure or production stop	0	1	0	0	0	1	0	0	1	1	0
7	Technical failure risk	0	0	0	0	0	1	1	1	1	1	0
8	Explosion or fire risk	0	0	0	0	0	1	0	1	1	1	0
9	Exposure to live wires	0	0	0	0	0	1	0	1	1	0	0
10	Risk of commercial loss	0	0	0	0	0	0	0	0	0	1	0
11	Risk of use of improper equipment	1	0	0	0	0	1	1	1	1	0	1

Table 4.
Reachability matrix

S. no.	Risks	1	2	3	4	5	6	7	8	9	10	11	Driving power
1	Poor housekeeping and maintenance risk	1	0	0	0	0	1	1	1	1	0	1	6
2	Customer outrage risk	0	1	0	0	1	0	0	0	0	1	0	3
3	Organization oversize risk	0	0	1	0	0	0	0	0	0	0	1	2
4	Energy market price volatility risk	0	0	0	1	1	0	0	0	0	1	0	3
5	Risk of regional price difference widening	0	1	0	1	1	0	0	0	0	1	0	4
6	Risk of a grid failure or production stop	0	1	0	0	0	1	0	0	1	1	0	4
7	Technical failure risk	0	0	0	0	0	1	1	1	1	1	0	5
8	Explosion or fire risk	0	0	0	0	0	1	0	1	1	1	0	4
9	Exposure to live wires	0	0	0	0	0	1	0	1	1	0	0	3
10	Risk of commercial loss	0	0	0	0	0	0	0	0	0	1	0	1
11	Risk of use of improper equipment	1	0	0	0	0	1	1	1	1	0	1	6
	Dependence power	2	3	1	2	3	6	3	5	6	7	3	41/41

Table 5.
Reachability matrix with driving and dependence power

ISM is built having multilevel of the risk variables (Developing the Structural Relationship Model for RSSC, 2014).

Level partitioning is done with the help of the reachability set, antecedent set and intersection sets that are generated for each risk factor. The reachability set is a combination of the risk variable *i* and the other risk variables which are affected by it. Similarly, the antecedent set is the combination of the risk variable *j* and the other variables which are affected by it. The intersection set consists of those variables which are common to both, reachability set and antecedent set. A risk factor's level is identified by checking those risks having the same set of reachability and intersection (Singhal *et al.*, 2018). Table 6 shows the first iteration of level partitioning.

The risk variables 9 and 10 are the first level risks that have the highest priority in the ISM hierarchy. Hence they are removed from all the sets and the second iteration is done as shown in Table 7.

S. no.	Risks	Reachability set	Antecedent set	Intersection set	Level
1	Poor housekeeping and maintenance risk	1, 6, 7, 8, 9, 11	1, 11	1, 11	
2	Customer outrage risk	2, 5, 10	2, 5, 6	2, 5	
3	Organization oversize risk	3, 11	3	3	
4	Energy market price volatility risk	4, 5, 10	4, 5	4, 5	
5	Risk of regional price difference widening	2, 4, 5, 10	2, 4, 5	2, 4, 5	
6	Risk of a grid failure or production stop	2, 6, 9, 10	1, 6, 7, 8, 9, 11	6, 9	
7	Technical failure risk	6, 7, 8, 9, 10	1, 7, 11	7	
8	Explosion or fire risk	6, 8, 9, 10	1, 7, 8, 9, 11	8	
9	Exposure to live wires	6, 8, 9	1, 6, 7, 8, 9, 11	6, 8, 9	I
10	Risk of commercial loss	10	2, 4, 5, 6, 7, 8, 10	10	I
11	Risk of use of improper equipment	1, 6, 7, 8, 9, 11	1, 3, 11	1, 11	

Table 6.
Iteration 1

The risk variables 2, 4 and 5 are the second level risks that have the next highest priority in the ISM hierarchy. Hence they are removed from all the sets and third iteration is done as shown in Table 8.

The risk variable 6 is the second level risk that has the next highest priority in the ISM hierarchy. Hence it is removed from all the sets and the fourth iteration is done as show in Table 9.

The risk variable 8 is the second level risk that has the next highest priority in the ISM hierarchy. Hence it is removed from all the sets and fifth iteration is done as shown in Table 10.

S. no.	Risks	Reachability set	Antecedent set	Intersection set	Level
1	Poor housekeeping and maintenance risk	1, 6, 7, 8, 11	1, 11	1, 11	
2	Customer outrage risk	2, 5	2, 5, 6	2, 5	II
3	Organization oversize risk	3, 11	3	3	
4	Energy market price volatility risk	4, 5	4, 5	4, 5	II
5	Risk of regional price difference widening	2, 4, 5	2, 4, 5	2, 4, 5	II
6	Risk of a grid failure or production stop	2, 6	1, 6, 7, 8, 11	6	
7	Technical failure risk	6, 7, 8	1, 7, 11	7	
8	Explosion or fire risk	6, 8	1, 7, 8, 11	8	
11	Risk of use of improper equipment	1, 6, 7, 8, 11	1, 3, 11	1, 11	

Table 7. Iteration 2

S. no.	Risks	Reachability set	Antecedent set	Intersection set	Level
1	Poor housekeeping and maintenance risk	1, 6, 7, 8, 11	1, 11	1, 11	
3	Organization oversize risk	3, 11	3	3	
6	Risk of a grid failure or production stop	6	1, 6, 7, 8, 11	6	III
7	Technical failure risk	6, 7, 8	1, 7, 11	7	
8	Explosion or fire risk	6, 8	1, 7, 8, 11	8	
11	Risk of use of improper equipment	1, 6, 7, 8, 11	1, 3, 11	1, 11	

Table 8. Iteration 3

S. no.	Risks	Reachability set	Antecedent set	Intersection set	Level
1	Poor housekeeping and maintenance risk	1, 7, 8, 11	1, 11	1, 11	
3	Organization oversize risk	3, 11	3	3	
7	Technical failure risk	7, 8	1, 7, 11	7	
8	Explosion or fire risk	8	1, 7, 8, 11	8	IV
11	Risk of use of improper equipment	1, 7, 8, 11	1, 3, 11	1, 11	

Table 9. Iteration 4

The risk variable 7 is the second level risk that has the next highest priority in the ISM hierarchy. Hence it is removed from all the sets and sixth iteration is done as shown in Table 11.

The risk variables 1 and 11 are the second level risks that have the next highest priority in the ISM hierarchy. Hence they are removed from all the sets and seventh iteration is done as shown in Table 12.

The complete level partitioning of the risk variables from first to final is shown is Table 13.

Table 10. Iteration 5

S. no.	Risks	Reachability set	Antecedent set	Intersection set	Level
1	Poor housekeeping and maintenance risk	1, 7, 11	1, 11	1, 11	
3	Organization oversize risk	3, 11	3	3	
7	Technical failure risk	7	1, 7, 11	7	V
11	Risk of use of improper equipment	1, 7, 11	1, 3, 11	1, 11	

Table 11. Iteration 6

S. no.	Risks	Reachability set	Antecedent set	Intersection set	Level
1	Poor housekeeping and maintenance risk	1, 11	1, 11	1, 11	VI
3	Organization oversize risk	3, 11	3	3	
11	Risk of use of improper equipment	1, 11	1, 3, 11	1, 11	VI

Table 12. Iteration 7

S. no	Risks	Reachability set	Antecedent set	Intersection set	Level
3	Organization oversize risk	3	3	3	V

Table 13. Level partitioning – first to final iteration

S. no	Risks	Reachability set	Antecedent set	Intersection set	Level
1	Poor housekeeping and maintenance risk	1, 6, 7, 8, 9, 10, 11	1, 11	1	VI
2	Customer outrage risk	2, 5, 10	2, 5, 6	2	II
3	Organization oversize risk	3, 11	3	3	VII
4	Energy market price volatility risk	4, 5, 10	4, 5	4	II
5	Risk of regional price difference widening	2, 4, 5, 10	2, 4, 5	5	II
6	Risk of a grid failure or production stop	2, 6, 9, 10	1, 6, 7, 8, 9, 11	6	III
7	Technical failure risk	6, 7, 8, 9, 10	1, 7, 11	7	V
8	Explosion or fire risk	6, 8, 9, 10	1, 7, 8, 11	8	IV
9	Exposure to live wires	6, 9, 11	1, 6, 7, 8, 9, 11	9	I
10	Risk of commercial loss	10	1, 2, 4, 5, 6, 7, 8, 10	10	I
11	Risk of use of improper equipment	1, 6, 7, 8, 9, 11	1, 3, 9, 11	11	VI

Table 14. Conical matrix

S. no.	Risks	9	10	2	4	5	6	8	7	1	11	3	Driving power
9	Exposure to live wires	1	0	0	0	0	1	1	0	0	0	0	3
10	Risk of commercial loss	0	1	0	0	0	0	0	0	0	0	0	1
2	Customer outrage risk	0	1	1	0	1	0	0	0	0	0	0	3
4	Energy market price volatility risk	0	1	0	1	1	0	0	0	0	0	0	3
5	Risk of regional price difference widening	0	1	1	1	1	0	0	0	0	0	0	4
6	Risk of a grid failure or production stop	1	1	1	0	0	1	0	0	0	0	0	4
8	Explosion or fire risk	1	1	0	0	0	1	1	0	0	0	0	4
7	Technical failure risk	1	1	0	0	0	1	1	1	0	0	0	5
1	Poor housekeeping and maintenance risk	1	0	0	0	0	1	1	1	1	1	0	6
11	Risk of use of improper equipment	1	0	0	0	0	1	1	1	1	1	0	6
3	Organization oversize risk	0	0	0	0	0	0	0	0	0	1	1	2
	Dependence power	6	7	3	2	3	6	5	3	2	3	1	41/41

The conical form of the reachability matrix

A conical matrix is developed by bringing together the risk variables of the rows and columns in the order of the rank from high to low. Driving power and dependence power are calculated by summing up the 1s in the rows and columns, respectively, as shown in Table 14.

Node digraph: Based on the relationship between the risks identified in the Power Distribution Supply Chain, a node digraph is constructed. Nodes are the risks that are prioritized through the FMEA analysis and further level partitioning of the reachability matrix (see Figure 3).

ISM digraph: The nodal digraph is converted into the ISM model by replacing the nodes with the risk variable associated with the node number (see Figure 4).

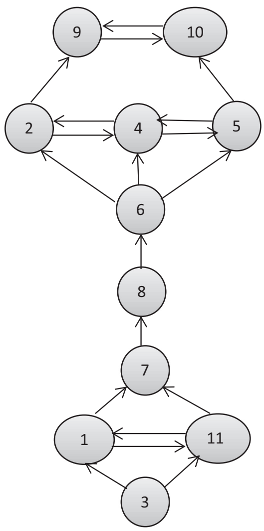

Figure 3. Digraph displaying the level of power distribution supply chain risks

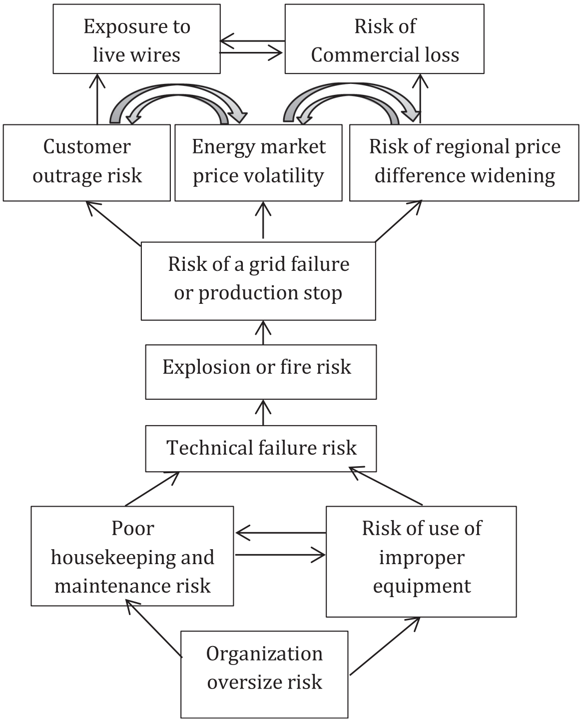

Figure 4.
ISM model

Findings and conclusion

To analyze and model the risks in the power distribution supply chain, seven supply chain process functions were identified with 17 failure modes.

Firstly, FMEA analysis has been done to identify the potential failure modes, their severity, and occurrence and detection scores. This helped the author to identify 11 enablers or risk variables that needed to be attended. The results of FMEA showed that in the internal operations process function, the highest RPN was obtained for "Poor housekeeping and maintenance" of 280, followed by "Explosion or fire" (108), "Exposure to live wires" (90), use of improper equipment (84). In production function, the "Grid failure or production stops" risk showed the RPN of (120), technical failures under Information Technology System as (120), under Regulatory and Market Condition on Power Supply Chain: "Energy market price volatility" (140) followed by "Rising energy prices and regional price differences are widening" (120), Employees: "Oversize of the organization" (160), Customer: "Customer Outrage" (180), Supply of Power: "Commercial loss" (75).

Secondly, an ISM model (Figure 4) has been developed to identify and understand the interrelationships among these enablers. Seven iterations were done in level partitioning to sequence/prioritize the risk variables.

Further, the Matriced' Impacts Croise's Multiplication Appliquée a UN Classement (MICMAC) analysis is done to compartmentalize the risk variables in four quadrants based on their combination of driving and dependency powers. In MICMAC analysis, the variables are grouped based upon the driving power and the dependency power derived from the ISM's reachability matrix (Pandey and Sharma, 2017). This analysis is used to identify the driving and the dependence power of various elements through the outputs of ISM. The outcomes of ISM are fed to MICMAC analysis as inputs to identify which element is performing as the most leading one. (Dewangana *et al.*, 2015) identified the driving power and dependence power of enablers of the competitiveness of the manufacturing sector using MICMAC analysis. This analysis was used to establish the interdependence of supply chain intricacy drivers of a typical mining and construction equipment located in India. This helped the authors to identify the driving and the dependency powers of the supply chain intricacy drivers (Prabu *et al.*, 2015). Thus, a lot of studies show the significant application of MICMAC analysis for understanding the variables through their driving and dependency power.

Figure 5 shows the risk variables clustered in four types as driving variables, linkage variables, autonomous variables and dependent variables based on their driving power and dependency powers.

MICMAC analysis divides the risk variables into four clusters as below.

Cluster 1: Autonomous variables: These variables are least connected to the system since their driving power and dependency power are weak. In this study, the autonomous variables are customer outrage risk, organization oversize risk and energy market price volatility risk. Therefore, among the 11 selected risk variables in the supply chain, these three variables do not have much influence on the supply chain practices.

Cluster 2: Linked variables: These are the variables that have strong driving power and strong dependency power. Change in any of these variables will affect themselves and others in the system. Hence they are said to be unstable and may affect the supply chain. In this study, the linked variables are the risk of a grid failure or production stop and the risk of explosion or fire.

Cluster 3: Dependent variables: These are the variables that have weak driving power but strong dependent power. In this study, exposure to live wires and risk of commercial loss are seen as strong dependent risks. Since these are dependent on the other risks, they have top priority in the ISM model and hence needs to be addressed on high priority.

Cluster 4: Driving variables: These are the variables that have strong driving power and low dependent power. This means that these variables are capable of driving the other risks variable in the supply chain and hence they are also called as the independent variables. Poor housekeeping and maintenance risk, risk of regional price difference widening, technical failure risk and risk of use of improper equipment are derived as the independent variables in the supply chain of the power distribution company.

Thus this study concludes that there are various risks associated with the supply chain function of the distribution of power. Internal operations, customer and supplier's linkage,

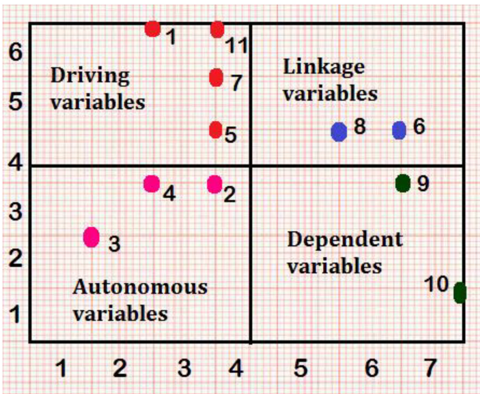

Figure 5.
Cluster of supply chain risks

regulatory and market conditions, and other drivers of the supply chain in distribution may encounter various problems in the form of risks. These risks need proper identification and treatment before they reach the end-user. Hence the organization needs to be cautious about identifying and prioritizing the risks. Since the power distribution sector requires a large number of human resources at different levels, gradually the organization starts oversizing. This causes less controlling and improper maintenance of the oversized workplace. This factor has given rise to the other risks like poor housekeeping, poor maintenance and improper usage of the equipment used in the distribution-related activities.

In power distribution-related activities, the risk of hazards is high and maintenance of the facilities, equipment, training to the employees is crucial. Improper usage of the equipment may lead to other risks like a technical failure. Technical failure can cause explosion or fire at the workplace this may further result in grid failure or production stoppages. ISM model represents the sources of risk and other risks arising from it in the power distribution sector. Hence the supply chain practitioners need to identify ways to reduce the risks occurring at the bottom level. Supply chain practitioners in this sector would get a better insight into those critical areas, which if addressed, would reduce the risks in the sector and a proper risk assessment would be done. This assessment would help them tackle the supply chain risks by now identifying ways to remove or mitigate them through various measures, processes and control mechanisms.

Through FMEA and ISM analysis, the risk assessment for power distribution is done. Future research studies can be initiated to identify various measures, ways or control mechanisms to reduce the intensity and impact of the risks on the sector. The proposed model developed through the ISM technique is based on the expert's judgment. SEM analysis may be used in the future to confirm this model. This study was limited to a power distribution supply chain. This study can further be extended to the power generation supply chain.

References

Aeeni, M., Zabihi, H. and Zarabadi, Z.S. (2019), "An assessment model for challenges of urban management system in Iranian new towns, based on interpretive structural modeling (ISM) approach", *The Scientific Journal of NAZAR Research Center (NRC) for Art, Architecture and Urbanism*, Vol. 16 No. 75, pp. 35-50.

Ahsen, A.V. (2008), "Cost-oriented failure mode and effects analysis", *International Journal of Quality and Reliability Management (RESEARCHGATE)*, Vol. 25 No. 5, pp. 466-476.

Beyene, T.D., Gebeyehu, S.G. and Mengistu, A.T. (2018), "Application of failure mode effect analysis (FMEA) to reduce downtime in a textile share company", *Journal of Engineering, Project, and Production Management*, Vol. 8 No. 1, pp. 40-46.

Concepts and Principles of Distribution Loss (2006), available at: https://mahadiscom.com, http://mahadiscom.com/emagazine/may06/concept.shtm.

Developing the Structural Relationship Model for RSSC (2014), available at: http://shodhganga.inflibnet.ac.in/bitstream/10603/88964/16/16_chapter%206.pdf.

Dewangana, D.K., Agrawal, R. and Sharma, V. (2015), "Enablers for competitiveness of Indian manufacturing sector: an ISM-fuzzy MICMAC analysis", *Procedia - Social and Behavioral Sciences*, Vol. 189, pp. 416-432.

Dube, A. and Gawande, R. (2016), "ISM-fuzzy MICMAC approach for analysis of GSCM", *International Journal of Logistics Systems and Management*, Vol. 24 No. 4, pp. 426-451.

Holmukhe, R.M. (2016), "Electricity distribution sector in India: key challenges for service to customer & way out", *International Journal of Application or Innovation in Engineering and Management*, Vol. 5 No. 7, pp. 116-119.

Kuo, T.C., Ma, H.Y. and Huang, S.H. (2010), "Barrier analysis for product service system using interpretive structural model", *International Journal of Advanced Manufacturing Technology*, Vol. 49 No. 1, pp. 407-417.

Liu, H.C., Liu, L. and Liu, N. (2013), "Risk evaluation approaches in failure mode and effects analysis: a literature review", *Expert Systems with Applications*, Vol. 40 No. 2, pp. 828-838.

Liu, M., Wu, F.F. and Ni, Y. (2010), "Risk management in electricity markets", *Managerial Finance*, Vol. 36, pp. 1-6.

Lv, L., Li, H., Wang, L., Xia, Q. and Ji, L. (2019), "Failure mode and effect analysis (FMEA) with extended MULTIMOORA method based on interval-valued intuitionistic fuzzy set: application in operational risk evaluation for infrastructure", *Information*, Vol. 10 No. 313, pp. 1-22.

Maheshwari, S. and Jain, P. (2014), "Supply chain management – review on risk management from supplier's perspective", *DAAAM International Scientific Book 2014*, pp. 557-566.

Moja, S.J., Van Zuydam, C.S. and Mphephu, F. (2016), "Hazard and risk assessment in the electricity sector: a case of Swaziland Electricity Company", *Journal of Geography and Natural Disasters*, Vol. S6: 006, pp. 1-6, doi: 10.4172/2167-0587.S6-006.

Narayanagounder, S. and Gurusam, K. (2009), "New approach for prioritization of failure modes in design FMEA using ANOVA", *International Journal of Industrial and Manufacturing Engineering*, World Academy of Science, Engineering and Technology, Vol. 3 No. 1, pp. 73-80.

Pandey, A. and Sharma, R. (2017), "FMEA-based interpretive structural modeling approach to model automotive supply chain risks", *International Journal of Logistics Systems and Management*, Vol. 27 No. 4, pp. 395-419.

Prabu, N., Nallusamy, S. and Rekha, R. (2015), "A MICMAC and ISM for correlation analysis of supply chain intricacy drivers", *International Journal of Research in Mechanical, Mechatronics and Automobile Engineering*, Vol. 1 No. 6, pp. 100-107.

Rogers, H., Srivastava, M., Pawar, K.S. and Shah, J. (2015), "Supply chain risk management in India – practical insights", *International Journal of Logistics*, Vol. 9 No. 4, pp. 1-22.

Seqrite (2018), "7 major causes of data breaches", available at: https://www.seqrite.comhttps://blogs.seqrite.com/7-major-causes-of-data-breaches/.

Sharma, S.K. and Bhat, A. (2014), "Modeling supply chain agility enablers using ISM", *Journal of Modelling in Management*, Vol. 9 No. 2, pp. 200-214.

Singhal, D., Tripathy, S., Jena, S., Nayaka, K. and Dash, A. (2018), "Interpretive structural modelling (ISM) of obstacles hindering the remanufacturing practices in India", *Science Direct Procedia Manufacturing*, Vol. 20, pp. 452-457.

Srivastava, U. and Pandey, A. (2018), "Developing interpretive structural model of consumer responsiveness towards advertisement", *International Journal of Business Analytics and Intelligence*, Vol. 6 No. 2, pp. 24-35.

Further reading

Concepts and Principles of Distribution Loss (2009), *Power Distribution Reforms in Maharashtra*. IDFC.

Hartwell, J. (2020), *FMEA RPN - Risk Priority Number, Calculation And Evaluation*, available at: www.iqasystem.com: https://www.iqasystem.com/news/risk-priority-number/.

Nordgard, D., Sand, K. and Wangensteen, I. (n.d.), "Risk assessment methods applied to electricity distribution system asset management".

Corresponding author
Pallawi Baldeo Sangode can be contacted at: pallavi_sangode@yahoo.com