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PRIORITIZING POWER OUTAGES CAUSES IN DIFFERENT SCENARIOS OF THE GLOBAL BUSINESS NETWORK MATRIX BY USING BWM AND TOPSIS

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Abstract. *Power outage is one of the significant problems for electricity distribution companies. Power outages cause customer dissatisfaction and reduce distribution companies' profits and revenues. Therefore, the electricity distribution companies are trying to moderate the leading causes of the outage. However, the dynamics of environmental conditions create uncertainties that require prioritizing the solutions to outages causes in different situations. Therefore, this study presents a scenario-based approach to prioritizing power outage causes. Four case studies have been conducted in four cities of Kerman province in Iran. First, the prioritization criteria and causes of the outage were identified using literature and interviews with experts in this field. Then, the Global Business Network matrix was used to create four possible scenarios. Then, the Best-Worst method and TOPSIS method were applied to weight the prioritizing criteria and prioritize the causes of the outages in different scenarios. The results showed that working in the power network limit zone, as one of the causes of outage in Sirjan and Jiroft cities, has the most priority. Also, the collision of external objects, birds, and annoying trees should be considered by managers as the leading causes of outages in Bam and Kahnuj cities.*

Keywords: *Power distribution networks, Power outage, Scenario planning, TOPSIS, BWM*

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1. Introduction

Power outage is referred to a failure in the components and elements of distribution networks that cause the power to be disconnected (Lakrevi & Holmes, 2014). The outages are generally divided into two categories, including planned and unplanned ones. The planned outage means the outage of subscribers' power with a previous intention. An unplanned outage is any unforeseen outage of facilities and equipment that leads to subscribers' power outages.

Today, households' need for electricity is increasing, indicating the increasing loss due to outages (Carlsson et al., 2021). Although households are highly flexible in adapting to outages, this does not mean that they do not valorize reliable electricity sources (Wethal, 2020). Instead, societies are highly dependent on power systems to supply their energy needs (Castillo, 2014). Thanks to improved batteries and backup systems, the frequency and length of outages have decreased in many countries (Carlsson et al., 2021). On the other hand, the interest in strengthening the power system aiming to withstand outages has increased compared to the past; however, the outage risk can not be reduced entirely (Castillo, 2014). Power grids are resistant to outages to maintain the safety and security of society and citizens (Landegren et al., 2016). These outages occur for various reasons, including weather events, the primary source of power grid outages (Shield et al., 2021). Therefore, reducing the events, outages, and undistributed energies is essential for electricity distribution companies (Ghasemian Fard & Mousavirad, 2017).

Focusing on increasing the strength of power systems while reducing the carbon effect, Sepúlveda Mora and Hegedus developed a way to design a flexible, environmentally friendly microgrid. They chose the microgrid configuration based on economic, environmental, and resilience criteria. The proposed microgrid consisted of photovoltaics (PV), battery, natural gas generator, and electric charge of an office building with an average consumption of two megawatt-hours per day. The results of this study showed that the installation of a microgrid with a 600 kW PV array and a 2.8 MWh lithium-ion battery in an office building prevents the release of a maximum of 287 tons of CO_2 per year; in addition, to endure two days of outage during peak demand (Sepúlveda Mora & Hegedus, 2021).

In a study using data from three typhoons, including Rammasun, Kalmaegi, and Mujigae, Yuan et al. developed two models, one for the frequency of customers' power outages and another for the poles damaged in Xuwen, Guangdong, China. Their validation showed that the developed models accurately estimate the frequency of customers' power outages and poles damaged by the typhoon. The mean relative errors in the definite customer and pole damage models were 5.1% and 9.6%, respectively. Their models, which were used to support better decision-making, had two critical improvements compared to previous works. First, these models used various static and dynamic variables to provide more accurate predictions describing typhoon risk and local environmental conditions. Second, they showed that it is possible to predict outages at a resolution of one kilometer skillfully. This spatial resolution was much higher than in previous models (Yuan et al., 2020).

In a paper, Zhai et al. presented an algorithm that generated an artificial power grid scheme solely based on public data for each US city and then simulated outages at the surface of each building under loading hazard using fragility functions. Their method provided estimates of the probability of outages due to natural hazards that were more local and at the building level. Zhai et al. validated their model by comparing the grid features and outage events based on their method and actual data from the Ohio Power System. They found that if accurate fragility curves are available, their model will rely less on input data than statistical learning methods, making accurate predictions (Zhai et al., 2021).

Because current analysis and state estimation require accurate information about the electrical system, He and Cheng, in an article, developed a practical analysis that did not fit perfectly to these items. They focused on the identification of power lines. They used a machine learning framework to locate the outages and predict single-line and multi-line outages. They examined a wide range of machine learning algorithms and feature extraction methods. Their proposed methods used only the phasor angles obtained from the continuous monitoring of the basses. The algorithms were designed to get the necessary dynamic properties of the power system during sudden topological changes. He and Cheng tested the prediction efficiency of their proposed plans under different levels of noise and absence. They showed that their proposed plans were more tolerant of missing and noisy data than previous works involving solving power flow or state estimation equations (He & Cheng, 2021).

In a study using multiple datasets, Shield et al. examined the occurrence and variety of major weather-related power outages. They showed that the weather is the cause of 50% of all events, and 83% of customers are affected. Lightning is the cause of 47% of weather events, while winter storms and tropical tornadoes result in 31.5% and 19.5% of events, respectively. The average repair cost for installations during major storms was 12 million pounds, with an average repair time of 117.5 hours (about five days). Tropical tornados had the highest average number of affected customers, followed by lightning and winter storms. Joint rescue teams were used for lightning less than tropical or winter storms. Case studies of Hurricane Harvey, Texas, in 2017, Hurricane Atlantic in 2011, and severe thunderstorms in Alabama in 2011 were highlighted as the unique challenges faced by electrical installation. By showing the difference in the number of outage events (r¼ 0.79) and the affected customers (r ¼ 0.65), they concluded that the number of storms primarily influences these values. Despite investing in storm-related outage prediction models and system retrofitting, weather-related outages are still a fundamental cause of power outages (Shield et al., 2021).

In a paper comparing the results of two studies on the willingness to pay (WTP) of Swedish households to prevent outages in 2004 and 2017, Carlsson et al. examined whether the WTP had changed or not. They found three main differences: (1) from 2004 to 2017, the proportion of households that were reluctant to pay to avoid outage decreased highly, (2) in 2017, the WTP was significantly higher than in 2004; however, (3) WTP has been reduced for the duration of an outage. The results of their study have consequences for encouraging and regulating electricity suppliers because a reliable source of electricity is more important than what has been shown by previous studies (Carlsson et al., 2021).

In an article, Cerrai et al. described the development of two outage prediction models (OPM) for snow and ice storm-related outages in power distribution networks and their performance evaluation in the northeastern United States. The first model was based on machine learning (ML) to predict outages in a typical four-kilometer network. The second model was a generalized linear model (GLM) to predict complete outages throughout the city. Their inputs to both models included (1) Numerical Weather Prediction Outputs (NWP), (2) Leaf Limit zone Index (LAI) obtained from satellite, (3) Land Cover Data, (4) Useful Infrastructure Data, and (5) The historical data of outage. The most critical variables for both models were the number of assets on the ground, LAI, snow density, and the amount of frozen rain for the ice model. The results of cross-validation experiments based on 54 outage events in three order sizes showed a median absolute error percentage of about 70% for both models. According to the results, GLM is better than ML models for predicting severe and destructive events. In contrast, ML models have better performance for low-impact events and better describe the spatial distribution of power outages (Cerrai et al., 2020).

Wethal, who aimed to use household perspectives to understand the consequences of the outage and to show the impact of the outage on relationships between infrastructure, methods, customers, and suppliers, used qualitative interviews with Norwegian rural households in an article examining how simple life changes during an outage, and how households experience the consequences of such outages. Using the three elements of materials, experts, and meanings, Wethal showed how outages temporarily cut off the relationship between elements in electricity-dependent methods. He also showed how households made connections between other elements and technologies to continue their daily lives. The practical reassembly of the elements illustrated the complexity of the outage consequences and explained how Norwegian rural households could get on well with long-term outages. Wethtal's analysis highlighted the difficulties of reducing the effects of the outage to financial issues and acknowledged that families focus on maintaining their daily lives rather than worrying about the economic costs of an outage. Adapting during outages indicates high flexibility of households, but it does not mean that they do not valorize reliable electricity sources (Wethal, 2020).

In a study, Ghasemian Fard and Mousavirad used the theory of system dynamics to identify and prioritize the factors affecting the reduction of outages in the electricity distribution network of the north of Kerman province. Their research showed a reduction in redistributed energy in the case of implementing the improvement policies. Network standardization, staff training, and justification of instructions were some of the policies they proposed to reduce unscheduled outages. In this paper, some factors such as power outages during low-precipitated hours and seasons, in the shortest range, and non-frequent power outages in a specific limit zone were proposed for scheduled outages (Ghasemian Fard & Mousavirad, 2017).

Al-Shaalan examined the practical measures that reduce severe outages and cut off access to energy. He did this in two steps: first, to explore the effects of power outages from consumers' perspectives in Riyadh, and second, to propose, analyze, and implement cost-effective strategies that reduce energy consumption and costs. His study showed that in case of an outage at certain times and seasons and for a long time, some customers suffer tangible and intangible losses. Finally, practical measures and desirable solutions were proposed in this study to reduce the outage and, consequently, its undesired effects and consequences while not overshadowing the needs, consumer satisfaction, and comfort (Al-Shaalan, 2017).

Acknowledging that the margin and sensitivity of power grids are fundamental aspects of the lesser-considered concept of resilience, Landegren et al. proposed a simulation-based method. This method considered repair teams and materials required to repair the network components, specifically the power grid. This method was demonstrated in a municipal electricity distribution system in Sweden with outages with a severity of 12 independent damage. The overall result of his research was a quantitative assessment of the margin and power grids' sensitivity concerning the repair system resources. The information in this study could play a key role in deciding on the appropriate amount of resources (Landegren et al., 2016).

In a study using the Analytic Hierarchy Process (AHP) and Geographical Information System (GIS) decision-making methods, Yari et al. identified the essential criteria and their weight to identify critical points for installing remote control terminals. They finally ranked all possible options and implemented their proposed method on a medium air pressure feeder in the Tehran power distribution network (Yari et al., 2017).

In an article, Hosein Abadi et al. located the power switches optimally to smarten the power system using AHP. They conducted a case study on the medium pressure feeders of Kowsar alley in Arak city and presented the results while considering the economic parameters. The main result of his research was that installing the optimal number of power switches with remote control units in optimal locations has many advantages, including technical and economic benefits (Hosein Abadi et al., 2016).

Focusing on self-healing as one of the critical features of smart power distribution networks, Hafezi and Eslami, in a study, examined the reduction of outages in self-healing smart grids and presented three different scenarios. The first scenario looked at the traditional network. The second and third ones increased reliability and reduced outage by smartening and adding distributed resources. They used the genetic algorithm to optimize and select distributed generation sources' size, location, and number. The research results showed the smart grids' efficiency and distributed products as part of self-healing (Hafezi & Eslami, 2016).

Numerous algorithms and models are available to predict the risks of customers losing access to energy services. Many quantitative and qualitative approaches have been used to determine restoration strategies in the event of an outage, and few studies have evaluated restoration strategies regarding anticipated events risk. Following the storms that damaged critical infrastructure in the United States, this became a growing limit zone for research. Castillo presented various previously completed studies in the literature review and discussed potential limit zones for future research (Castillo, 2014).

When the power grid shuts down in the case of uncertain data, there is no single way to assess risk, which Iešmantas and Alzbutas discussed in an article. They used the Bayesian method for the statistical analysis of outage data. The bayesian method enabled a more coherent plan to express data uncertainty and obtain network reliability-related metrics. Their method showed how to properly manage the statistical inference process with actual North American power grid outage data. Various cases of power lines' unreliability and sudden damage at different levels of complexity, ranging from a simple Bayesian evaluation to building a more general Bayesian hierarchical model, were investigated in that study. Iešmantas and Alzbutas concluded that diversity has a significant effect on a geographical and environmental level and suggested analyzing the network line uncertainties by considering the characteristics of each line. They showed that this diversity significantly impacts the reliability of the whole network or any network. Taking into account cascade outages, they obtained a hierarchical model based on the Borel-Tanner distribution. They demonstrated the ability to simulate significant outages, the occurrence of which is unlikely according to records in recent decades (Iešmantas & Alzbutas, 2014).

In a case study, Jha et al. analyzed the importance of assessing the services' reliability for electricity customers. The study assessed power outages for residential and commercial customers in ten regions of the northern Indian state of Rajasthan. To obtain feedback from customers, they prepared a questionnaire containing information about the quality of the power supply, outage losses, the customer's desire for an uninterruptible power supply, compensation for increased outages, and alternative measures to neutralize the effects of the outage. This study also calculated the outage cost with two approaches: (1) Preparatory Action Approach and (2) the Contingent Value Approach. The results of this research were significant from the companies' perspective to ensure the continuity of adequate services and customer satisfaction (Jha et al., 2012).

Believing that the former technical methods were ineffective in reducing the outage following the advancement of technology and power grids, Rahimkhani and Jafartabar identified the factors affecting outages and analyzed them scientifically to reduce outages. Using the hierarchical analysis decision-making method and the opinion of experts, they identified and prioritized the factors affecting the reduction of power outages in Khuzestan. Their studied factors included training, motivational factors, time management, privatization, staff training, maintenance of preventive systems, and management of unauthorized electricity (Rahimkhani & Jafartabar, 2012).

The concept of a specialized microgrid called the Independent Distribution Power System (IDAPS) was presented in an article by Rahman et al. This microgrid managed the power distribution resources of the customers so that these assets could be distributed in an independent network under normal and outage conditions. They predicted that their proposed concept would be helpful in emergencies and in creating a new market for electricity transactions between customers (Rahman et al., 2007).

So far, numerous and different studies have been done in the field of power outages. For instance, an article screened and ranked fault risks of distribution network (Dongli et al., 2018). Another study used outage data to rank grid components (Nalini Ramakrishna et al., 2021). A study, which aimed to identify and asses power systems vulnerabilities, ranked the most vital branches in the transmission grid (Gjorgiev & Sansavini, 2022). These studies show the importance of research in the area of outages.

Although prioritization was done in some fields like human error roots (Tavakoli & Nafar, 2021) and smart cities (Hajduk & Jelonek, 2021), prioritization of outage causes and uncertainty of upcoming scenarios has been rarely considered in precious studies.

Previous studies often utilized classic methods such as AHP, which has apparent drawbacks. Therefore, the novelty of this study is prioritizing outage causes and addressing challenges that should be considered and the way to get over them. Uncertainty is a vital challenge in this area; the main contribution of this paper is to get over uncertainty by considering upcoming scenarios and providing a scenario-based approach to prioritize power outage causes. Besides scenario planning, novel beneficial methods, with fewer comparison data and more consistent comparisons, have addressed some drawbacks of the AHP method, which was popular in previous studies.

Since factors such as tropical or cold regions and environmental pollution are effective in the outage, limit zones with the same characteristics were studied. Sirjan, Jiroft, Kahnuj, and Bam were selected respectively as cities of cold, tropical, and high environmental polluted regions. The power outages in these cities in 2019 were 248, 333, 324, and 420 minutes respectively.

Kerman Electricity Distribution Company needs to review its developed plans to reduce the outages arising from the constantly changing environmental conditions for achieving its planned goals. Therefore, this study aims to provide a scenario-based approach to prioritize the power outages causes. The current article is presented in five sections to achieve this goal. The first section shows the necessity of outages prioritization in the introduction. The second section explains the research background in the field of outages. The step-by-step method of the research is described in the second section. The third section presents the research results in the developed scenarios. The fourth section presents the sensitivity analysis. Finally, this article's fifth section provides conclusions and suggestions for managers and researchers.

2. Research Methods

This study aims to provide a scenario-based approach to prioritize the power outages causes. For this purpose, a case study has been conducted in Sirjan city in Kerman province, covered by the power distribution company in the south of Kerman province. In this research, the literature review and interviews with Kerman Electricity Distribution Company experts are used to identify the causes of outages and decision-making criteria regarding the prioritization of outages. The Global Business Network (GBN) matrix approach is also used for scripting the scenario.

2.1. GBN Matrix

The GBN matrix, introduced in 1991 (Schwartz, 1991), is known as the default scenario planning technique. This matrix consists of two dimensions of uncertainty. Therefore, this technique is also called the bivariate method or 2×2 matrix. These two dimensions, which form the two axes of a coordinate system, define four regions that produce four scenarios based on the logic of possible futures.

This method is used to find two factors causing most of the uncertainties in the studied system. Then, four scenarios are formed based on these two factors. An example of this matrix is shown in Figure 1.

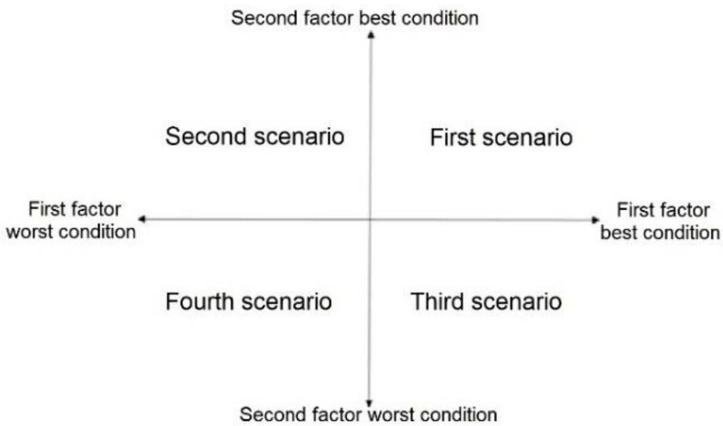

Figure 1. GBN matrix

Next, the Best-Worst Method (BWM) method introduced in 2015 is used to weight the criteria for prioritizing the outage causes. BWM has some similarities with the AHP method, which has been used in this field. For instance, both questionnaires are based on pairwise comparisons, and both of them are set with a nine degrees spectrum. Of course, Rezaei has mentioned that the 10-degree scale can be used in BWM.

However, according to total deviation, minimum violation, conformity, and consistency ratio, BWM significantly outperforms the AHP technique. In a BWM questionnaire, only the best and worst elements are compared instead of all criteria. The AHP technique calculates the number of comparisons with the n (n-1)/2 connection, but the BWM technique uses the (n-2)×2 connection. Thus, BWM, with fewer comparison data, has more consistent comparisons, which leads to reliable results. In addition, in BWM, the respondent does not get bored. (Rezaei, 2015):

The steps of the BWM are described below (Rezaei, 2015):

Step 1 – Determining a set of decision-making criteria (C).

$$C=\{c_1,c_2,\ldots,c_n\} \tag{1}$$

Step 2 - Determining the best, most desirable, or most crucial criterion (B) and the worst, most undesirable, or least important criterion (W).

Step 3 - Determining the superiority of the best criterion among all criteria using numbers between 1 and 9 and forming the vector A_B.

$$A_B = (a_{B1}.a_{B2}.\ldots.a_{Bn}) \tag{2}$$

Where a_{Bj} indicates the superiority of the best criterion over the criterion j. Also, $a_{BB} = 1$.

Step 4 - Determining the priority of all criteria over the worst criterion using numbers between 1 and 9 and forming the A_W vector.

$$A_W = (a_{1W}.a_{2W}.\ldots.a_{nW})^T \tag{3}$$

Where a_{jW} indicates the superiority of criterion j over the worst criterion. Also, $a_{WW} = 1$.

Step 5 - Finding the optimal weights (W).

$$W = \{w_1^*, w_2^*, \ldots, w_n^*\} \tag{4}$$

The optimal weight for the criteria is where $w_B/w_j = a_{Bj}$, $w_j/w_W = a_{jW}$ for eachw_B/w_j and w_j/w_W pair. To establish this condition for all js, the answer which minimizes the maximum$\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ for all js need to be obtained. Given that the conditions for the weights is not harmful and the sum of the weights is equal to one, the result is the following problem:

$$\min \max_j \left\{\left|\frac{w_B}{w_j} - a_{Bj}\right| . \left|\frac{w_j}{w_W} - a_{jW}\right|\right\} \tag{5}$$

s, t,

$$\sum_j w_j = 1$$

$$w_j \geq 0. \text{for all j}$$

The previous problem can be changed to the following one.

$$\min \xi \tag{6}$$

s, t,

$$\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi\,. \text{for all j}$$

$$\left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi\,. \text{for all j}$$

$$\sum_j w_j = 1$$

$$w_j \geq 0.\ \text{for all j}$$

Compatibility Rate (CR) - The Compatibility Rate is obtained using the optimal value of ξ in the above problem and the Compatibility Index (CI) in Table 1.

$$CR = \xi^*/CI \tag{7}$$

Table 1. Compatibility Index

CI	a_{BW}
0	1
0.44	2
1	3
1.63	4
2.3	5
3	6
3.73	7
4.47	8
5.23	9

In this research, the technique for preference by similarity to the ideal solution (TOPSIS) method is used to prioritize outage causes in different scenarios. This method has been utilized in similar studies. For instance, an article used a TOPSIS-based decision making technique to evaluate smart cities and rank them based on energy performance (Hajduk & Jelonek, 2021). Another study utilized a combination of TOPSIS, Shanon entropy, and mathematical expectation to rank human error roots in the maintenance of power grid (Tavakoli & Nafar, 2021).

TOPSIS method is a favorable option for prioritization due to the following advantages (Zavadskas et al., 2016):

- Effortless decision making by utilizing both positive and negative criteria
- The number of alternatives has little effect on the performance.
- Increasing the number of alternatives and criteria will amplify rank differences lesser.
- It can be used for both quantitative and qualitative data.
- It is comparatively fast, comprehensible, and easy to implement.
- It provides a systematic analytical procedure that is well-structured.
- It is possible to apply the number of criteria simultaneous with the decision operation.
- In determining the choice set, it is flexible to a great extent.
- Scalar values that provide a superior understanding of similarities and differences among alternatives lead to a preferential prioritization of the possible options.
- In the rank reversal problem, which means change in the alternatives rank when introducing a non-optimal alternative, TOPSIS is known as one of the best techniques.

In the TOPSIS method, the distance of an option from the positive ideal point to the negative ideal one is considered. The selected option has the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. The steps of this method are as follows (Azimifard et al., 2018):

Step 1 - Unscaling the decision matrix (D) and creating a normal decision matrix (ND):

$$D = \left(r_{ij}\right)\ ;\ i = 1. \ldots . m. j = 1. \ldots . n \tag{8}$$

$$N_D = \left(n_{ij}\right)\ ;\ i = 1. \ldots . m. j = 1. \ldots . n \tag{9}$$

$$n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}} \tag{10}$$

Step 2 - Creating a normal weighted matrix (V) using the weight vector (w):

$$w = \left(w_j\right)\ ;\ j = 1. \ldots . n \tag{11}$$

$$M_w = \begin{bmatrix} w_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & w_n \end{bmatrix} \tag{12}$$

$$V = \left(v_{ij}\right) = N_D \times M_w\ ;\ i = 1. \ldots . m. j = 1. \ldots . n \tag{13}$$

Step 3 - Determining the ideal solution (A +) and the negative ideal solution (A-):

$$A^+ = \left(v_j^+\right) = \left\{\left(\max_i v_{ij} \mid j \in J\right) . \left(\min_i v_{ij} \mid j \in J''\right)\right\}\ ; \tag{14}$$

$i = 1. \ldots . m$

$$A^- = \left(v_j^-\right) = \left\{\left(\min_i v_{ij} \mid j \in J\right) . \left(\max_i v_{ij} \mid j \in J''\right)\right\}\ ; \tag{15}$$

$i = 1. \ldots . m$

Set J contains positive criteria, and j ′ contains negative criteria.

Step 4 - Calculating the distance of each option from the ideal solution (+di) and the negative solution (-di) by the Euclidean method:

$$d_{i+} = \left\{\sum_{j=1}^{n}\left(v_{ij} - v_j^+\right)^2\right\}^{0.5}\ ;\ i = 1. \ldots . m \tag{16}$$

$$d_{i-} = \left\{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2\right\}^{0.5}\ ;\ i = 1. \ldots . m \tag{17}$$

Step 5 - Calculating the proximity of each option with the ideal solution (cli +):

$$cl_{i+} = \frac{d_{i-}}{d_{i+} + d_{i-}}\ ;\ 0 \le cl_{i+} \le 1\ ;\ i = 1. \ldots . m \tag{18}$$

Step 6 - Ranking the options based on the descending order of cli +; the better option has more cli +.

3. Results

In this study, the following criteria were identified to prioritize the causes of outages through interviewing the experts of the Electricity Distribution Company and reviewing the literature:

- Frequency of failure
- SAIDI (the System Average Interruption Duration Index) in minutes (average outage duration for each customer per year)
- Undistributed energy
- The cost of troubleshooting solutions
- The severity of the failure affects reducing losses

Then, to identify the main factors influencing the outage, the results of investigating 755 cases of outages that occurred in the electricity distribution network of southern Kerman province and the interviews with the experts of the Southern Electricity Distribution Company of Kerman province (dispatching, monitoring, and operation departments and engineering office) were used. Consequently, eight factors influencing outages were identified as follows. 1- Fault in cut-out fuse 2- Work in network limit zone 3- Modification and optimization of the network 4- Unfavorable weather conditions 5- Fault in the transformer 6- Collision of external objects, birds, and annoying trees 7- Fault in the jumper 8- Other causes. A comparison of the best outage criterion with other criteria in the first scenario is presented in Table 2.

Table 2. Comparison of the best outage criterion with other criteria in the first scenario

Other options	SAIDI in minutes
frequency of failure	2
SAIDI in minutes	1
Undistributed energy	3
The cost of troubleshooting solutions	9
The severity of failure affects the reduction of losses	5

In this study, among the criteria related to outages and macro-level operational plans, two key factors affect their prioritization with high uncertainty: 1) The economic conditions of the company and society, 2) weather and environmental conditions. Therefore, the GBN matrix was plotted with the following figure in four scenarios.

The results of prioritization of outage causes in each scenario are given below:

Scenario 1: Favorable economic, weather, and environmental conditions

According to the scenario, it is assumed that the economic condition will improve, and more financial resources will be available. Thus, the importance of the criterion of cost of troubleshooting solutions will be reduced. Therefore, according to the BWM method, the criterion of "cost of troubleshooting solutions" is given low priority, and consequently, the worst criterion is considered in this method. Then, during a meeting with experts in the company, comparisons were performed related to the BWM method, which can be seen in the following tables.

Now by giving the scores mentioned, the new weights of the criteria are obtained. The inconsistency rate obtained in this weighting equals 0.073, which indicates the validity of the results because it is close to zero.

According to Scenario 1, the cost of troubleshooting solutions was low. According to this scenario, the weather condition is considered appropriate to prioritize the causes of outages. Therefore, the importance of the cause of unfavorable weather conditions is considered to be less than the other seven causes of outages. Based on the weighting of the BWM method, according to the above scenario, the prioritization of outage causes using the TOPSIS method is expressed in Table 5.

Scenario 2: Unfavorable economic conditions and favorable weather and environmental conditions

According to this scenario, we assume that the economic condition will worsen. Therefore, the criterion of cost of troubleshooting solutions would be crucial. According to the approach we had in scenario 1, we also used the same approach to weigh the criteria and score the causes. Based on the weighting by the BWM method, according to the above scenario, the TOPSIS method is used for prioritization, which is presented in Table 6.

Scenario 3: Favorable economic conditions and Unfavorable weather and environmental conditions

According to Scenario 3, we assume that the economic condition will be improved, and more financial resources will be available. Thus, the importance of the cost of troubleshooting solutions criterion will be reduced. Therefore, the cost of this criterion takes low priority, and consequently, it is considered the worst criterion in this method. According to the approach we had in Scenario 1, we also used the same approach to weigh the criteria and score the causes in this scenario. Based on weighting by the BWM method, according to the above scenario in unfavorable weather and environmental conditions, the TOPSIS method was used for prioritization. The results are expressed in Table 7.

Scenario 4: Unfavorable economic conditions and unfavorable weather and environmental conditions

According to Scenario 4, we assume that the economic condition will worsen, and the cost of troubleshooting solutions will be crucial. Therefore, the criterion of the cost of troubleshooting solutions is given high priority, and as a result, it is considered the best criterion in this method. According to the approach we had in scenario 1, we also used the same approach to weigh the criteria and score the causes.

The unfavorable weather condition is also considered for prioritizing the factors according to the scenario. Based on the weighting by the BWM method, according to the above scenario, the TOPSIS method was used for prioritization. The results are presented in Table 8.

The first result obtained with the Table IX is to determine the priority of plans to reduce outages. Also, by managing low-cost factors such as working in the network limit zone, the network outages can be reduced.

Table 3. Comparison of the worst outage criteria with the worst criterion in the first scenario

Other options	The cost of troubleshooting solutions
frequency of failure	8
SAIDI in minutes	9
Undistributed energy	6
The cost of troubleshooting solutions	1
The severity of failure affects the reduction of losses	3

Table 4. Weight of outage criteria in BWM method in the first scenario

Criterion	Weight
frequency of failure	0.254
SAIDI in minutes	0.435
Undistributed energy	0.169
The cost of troubleshooting solutions	0.040
The severity of failure affects the reduction of losses	0.102

Table 5. Prioritization of outage causes in the first scenario in cities by BWM and TOPSIS methods

Causes	Kahnuj	Jiroft	Bam	Sirjan
Fault in cut-out fuse	6	5	2	1
Work in network limit zone	5	3	3	2
Modification and optimization of the network	4	4	4	4
Unfavorable weather conditions	7	7	7	7
Fault in transformer	3	6	6	6
Collision of external objects, birds, and annoying trees	1	1	1	3
Fault in the jumper	2	2	5	5

Table 6. Prioritization of outage causes in the second scenario in cities by BWM and TOPSIS methods

Causes	Kahnuj	Jiroft	Bam	Sirjan
Fault in cut-out fuse	6	1	1	1
Work in network limit zone	4	3	3	2
Modification and optimization of the network	5	6	6	6
Unfavorable weather conditions	7	4	4	4
Fault in transformer	3	7	7	7
Collision of external objects, birds, and annoying trees	1	5	2	3
Fault in the jumper	2	2	5	5

Table 7. Prioritization of outage causes in the third scenario in cities by BWM and TOPSIS methods

Causes	Kahnuj	Jiroft	Bam	Sirjan
Fault in cut-out fuse	7	6	2	1
Work in network limit zone	6	4	4	2
Modification and optimization of the network	5	5	5	5
Unfavourable weather conditions	2	1	3	4
Fault in transformer	4	7	7	7
Collision of external objects, birds, and annoying trees	1	2	1	3
Fault in the jumper	3	3	6	6

Table 8. Prioritization of outage causes in the fourth scenario in cities by BWM and TOPSIS methods

Causes	Kahnuj	Jiroft	Bam	Sirjan
Fault in cut-out fuse	6	1	2	1
Work in network limit zone	5	3	3	2
Modification and optimization of the network	7	6	6	6
Unfavourable weather conditions	2	5	5	5
Fault in transformer	4	7	7	7
Collision of external objects, birds, and annoying trees	1	4	1	3
Fault in the jumper	3	2	4	4

Table 9. Comparison of the priority of outage causes in target cities in current conditions

Causes	Kahnuj	Jiroft	Bam	Sirjan
Fault in cut-out fuse	7	1	5	3
Work in network limit zone	6	2	3	4
Modification and optimization of the network	5	5	6	6
Unfavourable weather conditions	3	4	1	2
Fault in transformer	1	7	7	7
Collision of external objects, birds, and annoying trees	2	3	2	1
Fault in the jumper	6	6	4	5

Figure 2 depicts how ranks of criteria change in different scenarios. It can also be seen that those cost items such as transformer faults, and to some extent, fault in jumpers have low priority in the current condition. According to the previous season statistics, we will see that the network improvement and optimization in Sirjan city have received more attention than the others, and these results confirm the accuracy of the results by prioritizing this case in Sirjan city lower than in other cities. Another vital analysis obtained from the results is that the issues of unplanned outages such as transformer faults, cut-out fuse faults, and jumper faults were not among the highest priorities. Instead, the causes of the planned outages, such as working in the network limit zone and network modification and optimization, were among the highest priorities for allocating facilities. This shows that reducing the planned outages should be the priority of distribution companies.

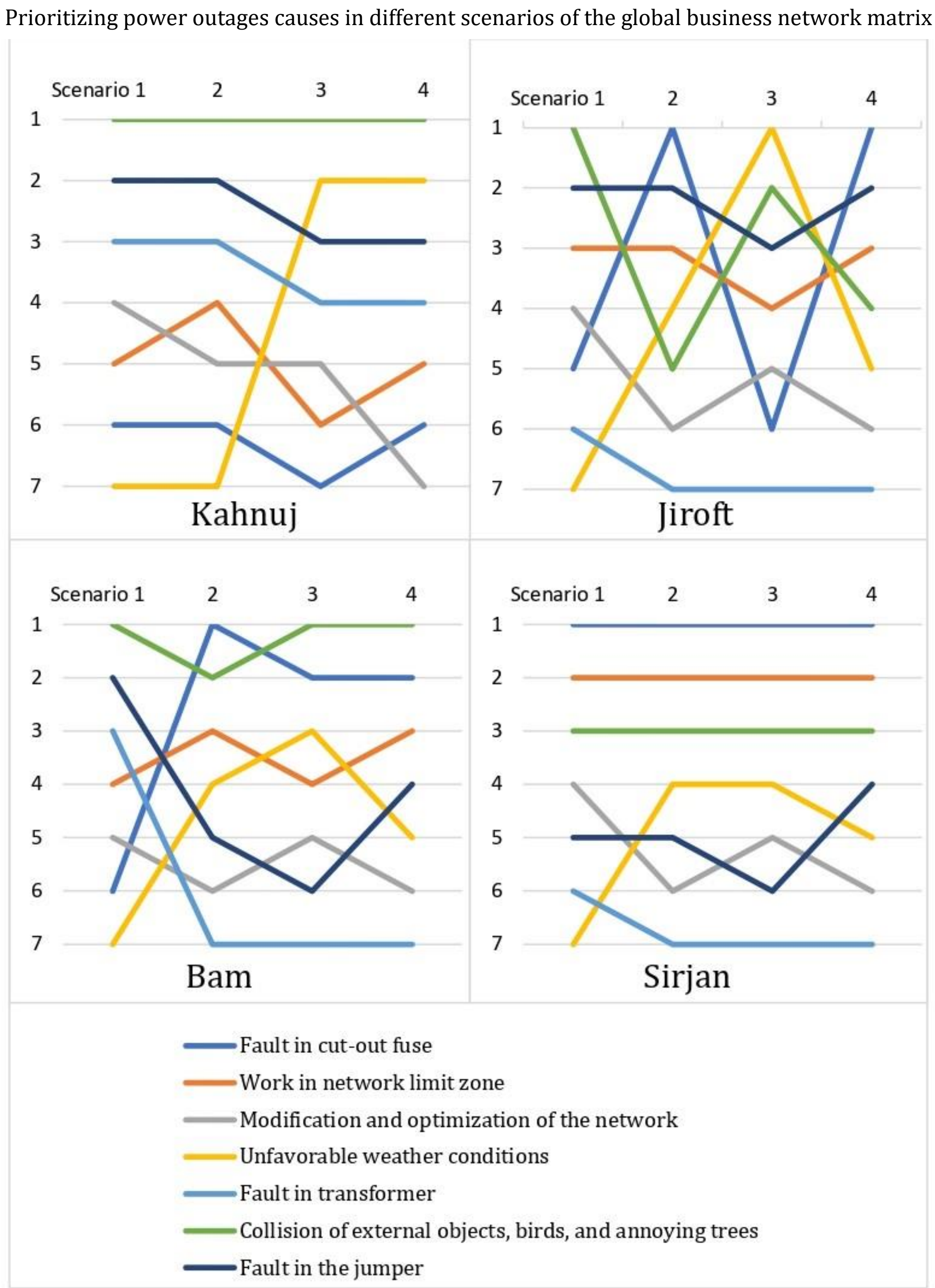

Figure 2. Ranks of criteria in different scenarios

4. Sensitivity Analysis

A sensitivity analysis has been applied for the first scenario to evaluate the sensitivity of the priority of outage causes in target cities due to the changes in criteria's importance. In this sensitivity analysis, the undistributed energy criterion is assumed to be more important than SAIDI in minutes and frequency of failure criteria, respectively (please see TABLE 10 and TABLE 11). The results of these changes have been demonstrated in Table 12 and Table 13.

Table 10. Comparison of the best outage criterion with other criteria in the first scenario for sensitivity analysis

Other options	Undistributed energy
frequency of failure	3
SAIDI in minutes	2
Undistributed energy	1
The cost of troubleshooting solutions	9
The severity of failure affects the reduction of losses	5

Table 11. Comparison of the worst outage criteria with the worst criterion in the first scenario for sensitivity analysis

Other options	The cost of troubleshooting solutions
frequency of failure	7
SAIDI in minutes	8
Undistributed energy	9
The cost of troubleshooting solutions	1
The severity of failure affects the reduction of losses	3

Table 12. Comparison of outage criteria weights in the first scenario for sensitivity analysis

Criterion	Weight Before changes	Weight After changes
frequency of failure	0.254	0.173
SAIDI in minutes	0.435	0.259
Undistributed energy	0.169	0.428
The cost of troubleshooting solutions	0.040	0.038
The severity of failure affects the reduction of losses	0.102	0.104

Table 13. Prioritization of outage causes in the first scenario for sensitivity analysis

Causes	Kahnuj		Jiroft		Bam		Sirjan	
	Before changes	After changes	Before changes	After changes	Before changes	After changes	Before changes	After changes
Fault in cut-out fuse	6	6	5	6	2	3	1	3
Work in network limit zone	5	5	3	1	3	4	2	1
Modification and optimization of the network	4	4	4	3	4	2	4	4
Unfavorable weather conditions	7	7	7	7	7	7	7	7
Fault in transformer	3	3	6	5	6	6	6	6
Collision of external objects, birds, and annoying trees	1	1	1	4	1	1	3	2
Fault in the jumper	2	2	2	2	5	5	5	5

5. Discussion and Conclusion

The following criteria were identified, prioritizing the causes of outages in this study by interviewing the experts of the Electricity Distribution Company and reviewing the literature.

- Frequency of defects
- SAIDI in minutes
- Undistributed energy
- The cost of troubleshooting solutions
- The severity of the effects of the defect on reducing losses

Then, to identify the leading causes of the outage using the results of 755 cases of outages in the power distribution network in the south of Kerman province, the following eight causes were identified and verified by the experts of the distribution company (dispatching, supervision, and interest departments and the engineering office of the Southern Distribution Company of Kerman Province) would be selected as influential causes.

- Fault in cut-out fuse
- Work in network limit zone
- Network modification and optimization
- Unfavorable weather condition
- Fault in transformer
- Collisions of external objects and birds and annoying trees
- Fault in Jumper
- Other causes

Then, four scenarios were developed based on the GBN scenario method. In general, the results showed that working in the network limit zone is one of the causes of outage in Sirjan and Jiroft cities has the priority of investigation. Also, managers' collision of external objects, birds, and annoying trees should be considered the leading causes of outages in Bam and Kahnooj cities.

Therefore, electricity distribution companies can allocate and plan the necessary resources, including budget and time, to reduce outages according to their priorities. Other results that can be stated include reducing outages by managing low-cost causes such as working in network limit zone. Another vital analysis obtained from the results is that unplanned outages such as transformer faults, cut-out fuse faults, and jumper faults were not prioritized. Instead, the planned outages such as work in the network limit zone and modification optimization prioritized allocating facilities. This indicates that reducing the planned outages should be a priority for distribution companies. In future research, other sustainability criteria such as environmental, social, and economic ones can prioritize the causes of outages. Also, other outage causes can be added to the list of causes identified in this research. Furthermore, other multi-criteria decision-making methods such as Vikor or Electra can prioritize outage causes and compare the results with the findings of this study. Using the approach mentioned in this research to prioritize outage causes in other cities can also play an essential role in the optimal use of resources of electricity distribution companies.

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