Received: 10 May 2020 | Revised: 30 April 2021 | Accepted: 31 May 2021

DOI: 10.1002/qre.2941

RESEARCH ARTICLE

WILEY

Estimating and ranking the impact of human error roots on power grid maintenance group based on a combination of mathematical expectation, Shannon entropy, and TOPSIS

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Abstract

Due to the importance of electrical grid reliability, analysis and evaluation of human error in the maintenance of electrical networks should be also considered seriously. The root causes of these errors must be identified and prioritized to plan for human error reduction. One of the objectives of the present study is to identify and predict these roots for power transmission maintenance groups from organizational, job position, communication, individual, and supervision aspects along with the relationships between these factors. In particular, this paper demonstrates that supervisor behavior as an external factor has a significant effect on maintenance personnel error. For this reason, special attention has been paid to identifying and controlling human factors from a supervisory point of view in this study. This paper also provides a method for detecting the extent of the expected influence of these roots on each personnel, since human error has a random nature. This is done based on the law of mathematical expectation. Finally, a method is suggested to rank roots based on greater effectiveness and evaluate personnel with higher error expectations. The proposed method is a combination of intermediate methods, Shannon entropy, and technique for order of preference by similarity to ideal solution (TOPSIS). The origins of the four human errors between 2014 and 2018 related to the two experts of Fars Electricity Maintenance Contractor Company are compared by the proposed method.

KEYWORDS

human error, maintenance groups, mathematical expectation, Shannon entropy, TOPSIS

1 | INTRODUCTION

Human error is one of the factors affecting the reliability of electricity networks.[1] Therefore, the need for sustainability and quality of the energy supply has increased due to the expansion of electricity utilization in recent years. Because any power swing or interruption in the supply of electricity can inflict financial or life damages on the industrial, commercial, hospital, etc. For this reason, various analyses and investigations have been carried out to identify the cause of these interruptions and a strategy to reduce them.[2–4] Most of these analyses are about finding the technical roots of equipment failure and ways to fix them, and researches on the roots of the interruptions due to human errors are not well established.[5,6] Human error analysis has been widely performed in nuclear energy, national aviation, shipbuilding, and industrial production,[7] but this fact is not followed consistently in the power system.

The probability of activities carried out correctly by a person over a given period under certain working conditions is called human reliability.[6] Ref. 8 introduces various factors such as environmental, organizational, job factors, and personal characteristics that affect human reliability in maintenance and shows that with a positive change in a factor, to a large extent human reliability is affected. Ref. 9 presents a case study of human reliability assessment using an absolute probability judgment method on a 10/0.4 kV steel mesh tower, "Nogaje," in the Serbia Electric Power Company.

Although some studies have examined human error and its effects, however, some issues have not yet been fully investigated. The main purpose of this paper is to clarify and to complete the following issues:

1. Investigate the causes that affect the performance of personnel and their error.
   Previous research has focused on finding human factors influencing events, analyzing human errors in operational processes, and calculating the probability of error behavior.[7] Therefore, the cause of actual human errors has been identified for power transmission companies limitedly and generally and the potential causes have been less predicted.
2. Study the factors affecting power industry maintenance groups.
   In most researches, the error of the power grid operators has been studied. Whereas surveys show that the human error of power grids maintenance groups is greater than power grids operators.[10,11] According to Ref. 11 the cause of two of 14 major accidents in the world from 2003 to 2015 is due to the human error of maintenance groups.
3. Improve the quality of maintenance operations.
   Supervisors are always asked to control and check the maintenance operations. Therefore, the performance of the supervisor can affect the performance of executive maintenance personnel.
4. Investigate the effect of cooperation between members of maintenance executive teams.
   The results of the current study show that communication between them and their relationship with other members of the organization affects team performance. This issue is explained in Section 5.

In this paper, according to the above discussed, the real and potential factors that affect the performance of power transmission maintenance personnel are predicted and identified from various aspects such as organization, communication, work position, individual, and especially supervision. Of course, some of these factors cause personnel to perform positively, and the same factor may negatively affect another person. A negative impact leads to human error.

The next purpose of this paper is to determine the influence of the extent of the human error roots on personnel. The effect of roots on personnel in different papers is estimated such as in Ref. 12 with the help of cost-saving analysis, in Ref. 8 by calculating human reliability through fuzzy cognitive map methodology, and in Refs. 13 using human reliability measurement based on Bayesian network and cognitive reliability and error analysis method (CREAM) methods. A new approach is followed in this article to estimate the impact of roots on personnel based on mathematical expectation. Probability indicates the chance extent of human error, but the mathematical expectation shows the average number of human errors occurring over a time interval, which is more understandable. This index can have a positive or negative or zero value. If its value is positive, it indicates that the person has many errors that should be controlled.

This research is done using a case study on Fars Electricity Maintenance Contractor Company (FEMCC) events and utilizing the knowledge of specialists. The case study shows that ways to prevent errors can be identified and implemented by identifying and prioritizing the roots of the error. In other words, due to the limited financial resources and time, the ways that have the greatest impact on reducing human error are identified with the help of the method proposed in this paper.

2 | BACKGROUND AND THE RELATED WORKS

Power systems security analysis requires consideration of vulnerabilities to natural and human-related threats that have a major impact on the power system.[14] Due to the range of human intervention in the sociotechnical environment, managers blame human factors (e.g., operator training, communication) in most events.[15] Power grid threats due to humans are classified into intentional (e.g., sabotage) or unintentional (human error).[14]

Human error is the subject of research in almost all industries. Since the 1960s, many attempts have been made to provide a technical definition of the concept of human error. Although the term error has a relatively simple meaning in everyday life, it is technically very difficult to accurately distinguish the term.[16] In the few years that the concept of "human error" has been the subject of scientific debate (Woods et al. 1994; Reason 1997; Rochlin 1999; Hollnagel and Amalberti 2001; Woods and Cook 2002, Hollnagel 2005; Stojiljkovic 2011), it seems that a comprehensive definition of the term has not yet been obtained.[17] Of course, the development of research on "human error" has grown and raised the concept of human error to a prominent level,[18] after major accidents such as the "Three Mile Island" in 1979, the release of Bhopal poisonous gas in 1984, Chernobyl in 1986, and Houston in 2005.[19]

As cited in Refs. 16, researchers have used the term "error" for many years to denote the outcome or consequence, the actual action, the causal factor, and intentional violations. For example, The British philosopher John Locke wrote in 1979: "All men are liable to error; and most men are, in many points, by passion or interest, under temptation to it." Petersen in 1996 had argued that "human errors are caused by the situations in which people find themselves-a particular situation at a particular moment that makes it normal and logical to commit an error that may result in an accident and an injury." Strauch in 2002 has defined human error as "an action or decision that results in one or more unintended negative outcomes." Dhillon (2003) in the field of reliability engineering, has described the human error as "the failure to perform a task (or the performance of a forbidden action) that could lead to the disruption of scheduled operations or damage to property and equipment." Hollnagel in 2004 had determined an accident as "a short, sudden, and unexpected event or occurrence that results in an unwanted and undesirable outcome. The short, sudden, and unexpected event must directly or indirectly be the result of human activity … ."

Violation of constraints is usually considered a human error or violation of duty. To be a successful performance, humans must move between boundaries. One boundary is determined by the control requirements imposed by the system. The other limiting boundary is provided by human characteristics that depend on individual characteristics such as competence, mental ability, and physical strength.[20] However, in Refs. 21, the violation is considered different from the concept of human error. In this article, the violation is an action that has been predicted to deviate from a rule, while human error is an action that has not been done according to plan. Refs. 22 has categorized human error into three groups: (1) Group "A": actions during maintenance that can cause equipment malfunction; (2) Group "B": errors that affect the start of events; (3) Group "C": errors related to the operator's response to an accident.

1. Group A: Colombia's blackout in 2007 left about 41,000,000 people without power for 4.5 h. The cause of the event was a human error while correcting maintenance of a protective device in a 230 kV substation.[11]
2. Group B: On August 14, 2003, numerous individual errors led to widespread blackouts in the U.S.–Canadian grid that affected out the electricity of 50 million households. The incident started with a mistake by a power plant operator and subsequent individual errors led to the spread of the accident. The power plant operator pushed one generator near Cleveland too hard, resulting in an automatic exit at 1:31 p.m.
3. Group "C": The Arizona–Southern California accident in 2011 led to a sudden power outage that left nearly 7 million people without electricity. A 500 kV transmission line started the event. During this time, some lines and transformers became overloaded and voltage changes occurred, which led to a lack of timely decisions due to the lack of specific instructions for this time and the low experience of the operators. As a result, a cascade of accidents occurred.[23]

Refs. 24 examines 66 major power outages in some parts of the world from 2011 to 2019. This is not a comprehensive survey of all power outages in the world, but it is a good tool to show the reasons for power outages. The main cause of the outage is about 21 events due to human error or equipment failure. Therefore, historical blackout data, as well as interviews with power system operators, show that human behavior can severely affect cascade failures in power grids.[23] As a result, human error as an important factor that affects the reliability of power systems, and Refs. 1 has illustrated this effect on the two reliability indices of the power systems LOLP (loss of load probability) and EPNS (expected power not supply). However, most research focuses only on system-related malfunctions and neglects the impact of human factors on the performance of power systems.[5,24]

Various factors can influence the decisions of human operators and lead to performance with destructive effects. Examples of these factors include the mental state of operators at the time of the event, stress, fatigue, level of experience, duration of responding to a situation, knowledge and awareness of the situation.[23] In Refs. 16, the use of the procedure, fatigue, knowledge and experience, and time pressure are recognized as the most important human factors. In Refs. 25, the inappropriate workload of dispatchers is cited as one of the main causes of human error. A study on job stress in human resource management was conducted in Refs. 26, because psychological factors have a great influence on the performance of operators and have been neglected in traditional HRA studies. Refs. 27 presents a review of the methodologies of human factors and ergonomics in the fields of physical ergonomics, cognitive ergonomics, and organizational ergonomics. Refs. 28 argued that the occurrence of error was not only related to the individual attitude of the worker, but

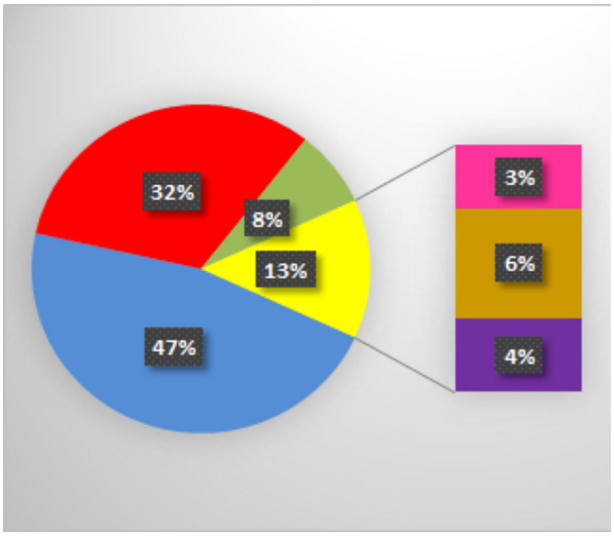

FIGURE 1 Percentage of the causes of automatic equipment outages of FREC from 2012 to 2017: environmental factors (blue); equipment failures (red); Network restrictions (green); human factors (yellow); operator and dispatcher errors (pink); errors of different maintenance groups (brown); contractor errors (purple)

the working conditions provided by the employer, such as equipment and materials, infrastructure, work process, salary, working hours, number of employees, job satisfaction, job stability, also affect job performance. Refs. 29 has shown that increasing employee satisfaction could lead to a reduction in occupational accidents. Job satisfaction depended on various factors, including salaries, benefits, promotion, communications, reward, and the conditions of married and single workers.

In Refs. 30, a study has been conducted on the gradual decrease of age-related human abilities and the increase of human errors. Studies show that in 47% of articles there is a relationship between aging and human system error. The results of research[9] illustrated that older operators had a lot of confidence in their experience when performing their tasks. In this case, they were less motivated to use tools and equipment for personal safety. Therefore, the error of this operator gradually increased. Refs. 20 examined the responses of highly trained operators in nuclear power plant (NPP) simulation. The findings of the article show that experienced people, instead of becoming more similar to each other over time, actually maintain some very distinct and individualistic response patterns.

In the health and safety executive (HSE) series of books,[31] the definition of human error is: "An action or decision which was not intended, which involved a deviation from an accepted standard, and which led to an undesirable outcome." Also, human error in Refs. 32 referred to any situation in which the operator does not follow a specific operating procedure. However, in Refs. 33, the definition of human error was based on performing an unsafe operation that led to a negative impact on the safety of the power plant, although it might be within the standard framework. Therefore, in most definitions, human error means any action that does not have the desired result and causes failure or accident.

3 | METHODS

Possible and potential errors must always be detected and controlled to reduce accidents in transmission networks. The first step to predict these errors is the statistical analysis of the causes of events. The causes of events in power transmission networks are displayed into four main groups for statistical analysis in FEMCC studies. The statistical analysis of the causes of the 5-year FEMCC events in Figure 1 shows that the percentage of automatic outages of equipment due to human factors is approximately 13.6%. Human error caused by maintenance groups in FEMCC over 5 years equals 6% of all events. Also, an analysis of 14 major incidents worldwide from 2003 to 2015 showed that the onset of 14% of blackouts was directly due to human error during network maintenance.[11] Therefore, it is necessary to take measures to manage human resources during maintenance due to the effect of personnel behavior and mind on network maintenance.[34] For this reason, this paper proposes a framework for qualitative and quantitative analysis of human error during maintenance

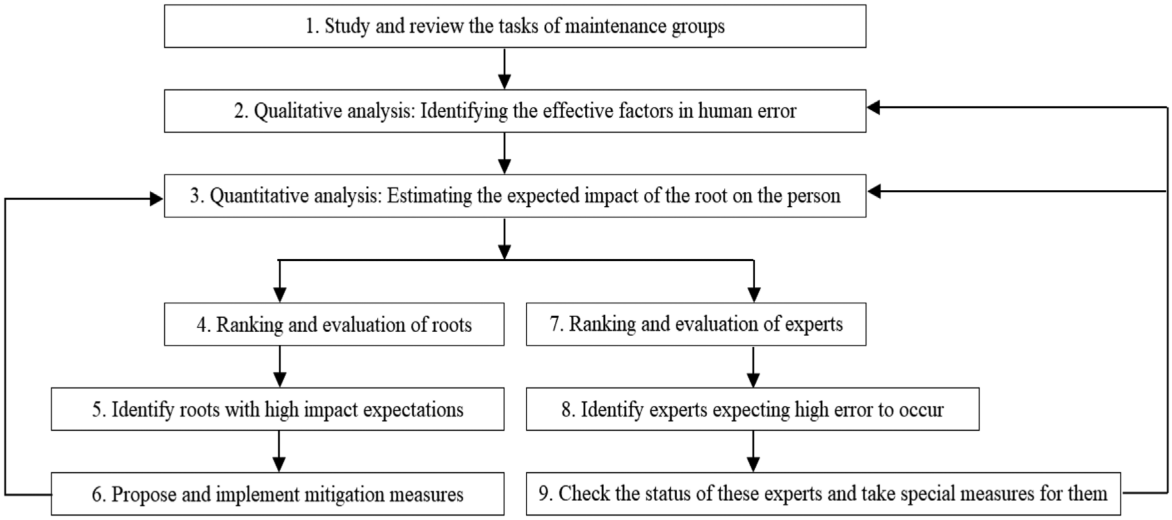

FIGURE 2 Proposed framework for qualitative and quantitative analysis of human error during a maintenance operation of the power transmission grids

of the power transmission industry as shown in Figure 2. The proposed framework contains nine steps that are described as follows.

1. Studying the tasks of maintenance groups
   The prerequisite for human error analysis in the electricity industry is accurate and comprehensive knowledge of the tasks of maintenance groups. In this way, groups with a high risk of error are identified. The study of the tasks of maintenance groups is described in Section 4.
2. Qualitative analysis
   Human error can be triggered by a variety of factors, including inaccuracy, lack of consideration, lack of understanding and following rules, lack of concentration, and so on. As a result, all errors are natural consequences of human behavior under certain conditions.[17] As explained in the previous section, human error is an action that a person takes and causes an undesirable result. Therefore, the action that each person takes is affected by one or more reasons that have a negative impact on the person and have caused him to error. In Section 5, actual and potential factors affecting maintenance personnel from various behavioral, workplace, economic, etc. aspects are identified and classified.
3. Quantitative analysis
   The impact of the identified factors on each person is different, because each person may adapt and adjust to factors. This paper shows the extent to which a person adapts/adjusts to any factor with the intensity of the root effect. In Section 6, a method for estimating the expected impact of each root on individuals for a long time is proposed. The method proposed in this paper is based on the concept of mathematical expectation.
4. Ranking and evaluation of roots
   Managers need to identify the roots that have a higher priority in order to plan to reduce the effect of factors or eliminate them. Therefore, in Section 7, a method for evaluating and ranking the roots is proposed, which is a combination of the average mathematical expectation of experts' opinions and Shannon entropy.
5. Identification of the roots with a high impact expectations
   With the help of the proposed method in Section 7, more effective roots are identified on all personnel who were less able to adapt/adjust to it.
6. Suggestions and implementation of measures to reduce the effect of roots
   In Section 8, examples of measures taken to reduce the effect of some roots are presented. Then, according to the framework in Figure 2, the expected impact of the roots on the personnel is re-estimated.
7. Ranking and evaluation of experts
   In Section 7, experts are evaluated and ranked using the technique for order of preference by similarity to ideal solution (TOPSIS) technique and combining the two methods of the average mathematical expectation and Shannon entropy.

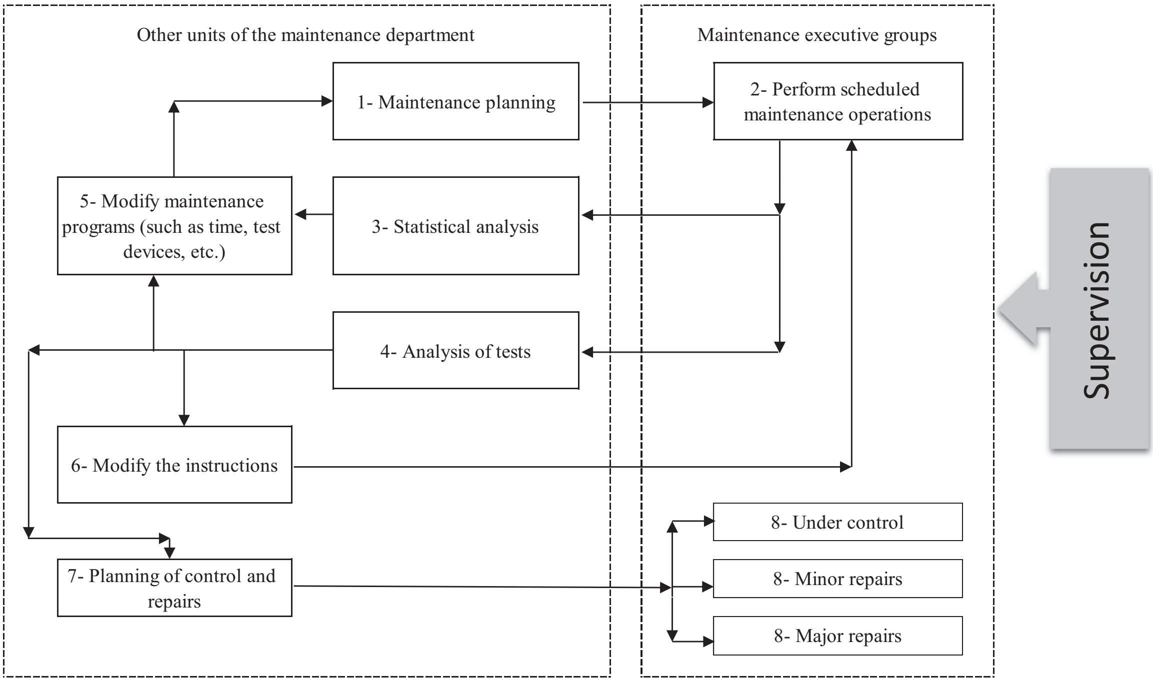

FIGURE 3 Maintenance flowchart at Fars Regional Electricity Company

8. Identification of the experts expecting high error to occur
   Experts who expect high errors can be identified by the method proposed in Section 7. The goal is to reduce maintenance costs and make companies more profitable, as high-risk experts cause equipment failure or successive and sometimes large-scale events that cost companies dearly.
9. Examine the status of high-risk experts and take special measures for them
   By special examination of the status of high-risk experts, it is sometimes possible to become aware of factors that have not been previously identified and to modify the root database. It is also possible to improve the effect of high-risk roots by taking special measures to eventually improve the situation of these experts in a way that reduces the expectation of error in them.

4 | STUDY AND ANALYSIS OF MAINTENANCE AT FEMCC

Due to the size of the FEMCC's network—about 15,000 km of transmission line and 243 HV substations—a detailed maintenance schedule needs to be planned to increase the availability of the power grid. Figure 3 shows a maintenance flowchart at FEMCC. This operation is planned and executed in eight steps by the maintenance department. The first step to a successful maintenance operation is to set its schedule. Then, according to the anticipated plan, maintenance operations will be carried out by approximately 70 executive teams in the presence of a supervisor every day. Maintenance operations include visits, service, and periodic tests under instructions and checklists. The performed operations are analyzed from two perspectives. One is the statistical analysis that gives feedback on the program modification. The second is the analysis of the test results, which can determine the four situations i.e. healthy, controlled, partial, or overhaul. Required control and repair operations are planned by the maintenance planning unit and executed by executive teams. Also, another result of these analyses may lead to the modification of the guidelines, the results of which will be reflected in the executive group for implementation. In order to increase the efficiency and effectiveness of maintenance operations, there is a need for continuous monitoring of maintenance operations. The supervisor conducts an overall assessment of the quantity and quality of the executive teams and test equipment prior to commencing maintenance. During maintenance, it monitors the correct operation based on test sheets, catalogs, instructions, and so on. At the end of the operation, the supervisor gives a score for the work that the executive team does, which includes criteria such as duration of the operation, cleaning the workplace, the quality of the operation, and so on. Figure 3 shows that supervisors oversee all operations of the executive groups.

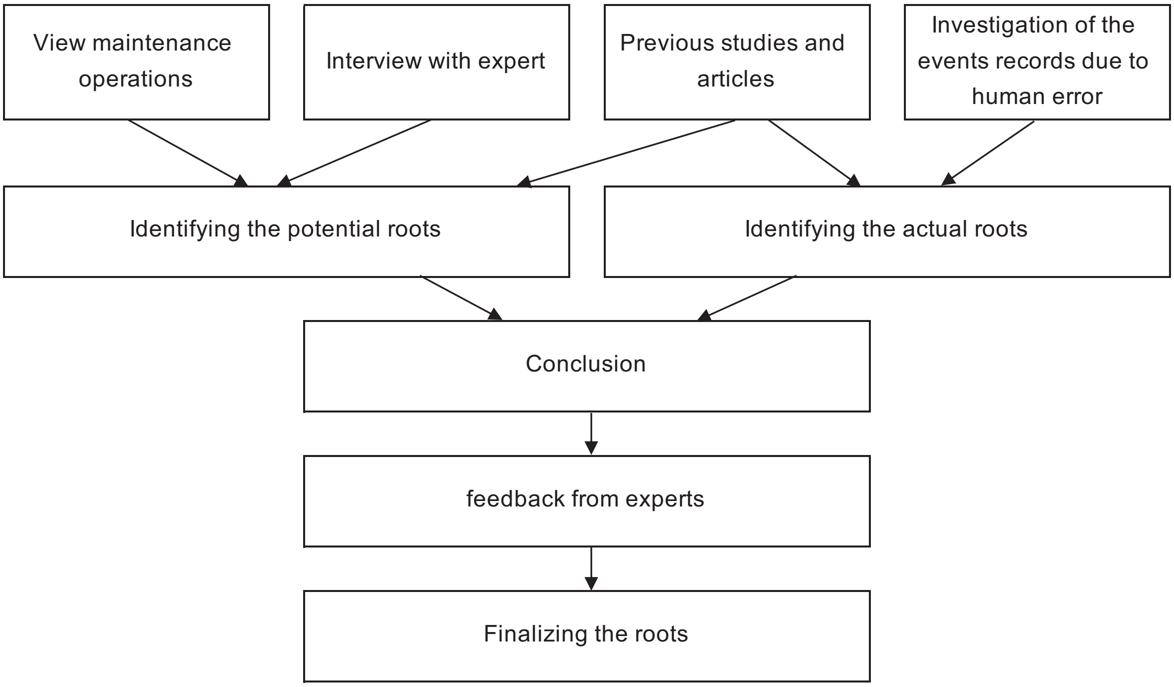

FIGURE 4 Algorithm for identifying and predicting the roots of the executive groups errors

5 | IDENTIFICATION OF THE HUMAN ERROR ROOTS IN THE MAINTENANCE GROUPS

In this section, a case study has been conducted to identify and predict the possible causes of human error accidents in maintenance operations with respect to the subgroups of FEMCC in Section 2.

Figure 4 is used to identify and predict the actual and potential causes that led to a mistake in the FEMCC executive groups. According to this algorithm, using the past records of events, investigations, observation of maintenance operations, and results of interviews with FEMCC experts (about 108 people hours), the actual and potential roots of executive group errors are identified and concluded. Then experts are again consulted on the identified roots. Finally, the roots of executive group errors are finalized.

Some investigations into the causes of maintenance personnel error include the following: In the identification of human error roots, Refs. 35 investigates the fact in the human, machine, and environmental aspects. Also, the relationships of these factors in maintenance activities are presented. Refs. 12 provides a way to find the most important human factors from a maintenance perspective. In this reference, fatigue, knowledge, experience, and time pressure are recognized as the most important human factors. Refs. 36 examines the impact of motivation and competence factors as the most important factor in human performance in power transmission maintenance. Refs. 37 examined the 10 main causes associated with maintenance work in a power plant. These factors are documentation, time pressure, housekeeping and tool control, coordination and communication, tools and equipment, fatigued, knowledge and experience, bad procedures, procedures usage, and personal beliefs. Since the written procedures are sometimes long and experts prefer to rely on their experience and skills, "procedures usage" is recognized as the leading factor in this study. A review of the literature in the maintenance of mechanical systems showed that the causes of human error were poor management and supervision, organizational culture, incompetence, poor procedures, poor communication, time pressure, plant and environmental conditions, and poor work design.[38] Risk factors at different levels of technical, human, organizational, and environmental factors are presented in Refs. 39.

According to the surveys, the roots are categorized into five main factors: organizational factors, job position, personal, communication, and supervision, as shown in Figure 5. Two types of factors affect the operator's behavior: the external environment and the mental stimulus.[40] In the present study, organizational factors, job position, communication, and supervision as external stimuli on the behavior of maintenance personnel and individual factors as internal stimuli have been considered. According to Figure 5, supervision factors affect both personal and organizational factors, and

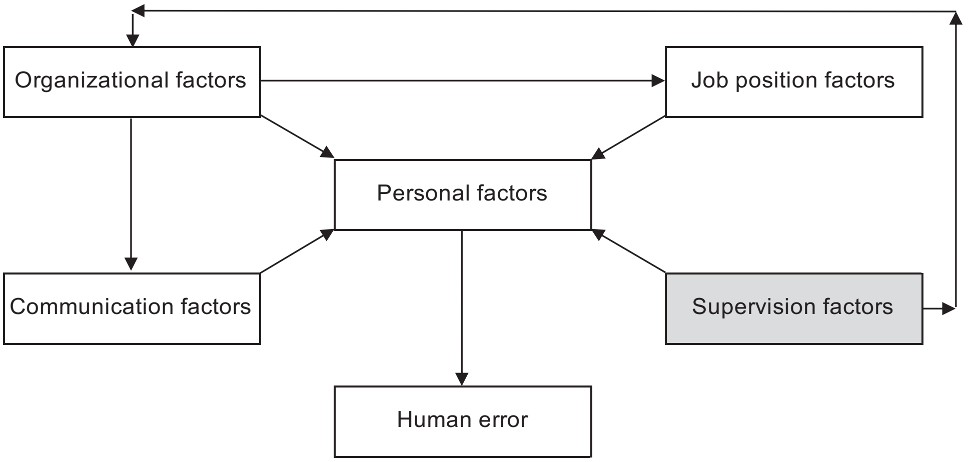

FIGURE 5 Factors affecting human error in power transmission maintenance groups

organizational factors influence the three factors of communication, personal, and job position. Personal factors are the only factors that four other factors can affect. The definition of each of these factors and the identified roots in each group is as follows:

Supervision factors: The maintenance of power transmission networks in FEMCC is carried out by the nongovernmental contractor. Therefore, the employer's supervisory teams and the contractor's headquarters indirectly affect the performance of the executive teams. For example, the incomplete knowledge and experience of the supervisors have caused the discomfort of experienced teams. Also, supervisory violations occasionally occur.

Violations are divided into four levels[21]: Routine violations indicate actions that have become commonplace and are considered routine by those who engage in the activity. Optimizing violations are conceptualized as "violating for the thrill." Necessary violations are thought of as situations in which one is forced to break the law, or in other words, work under pressure, lack of important elements (e.g., resources and equipment), coping with complexities, forcing the individual to make local adjustments/adaptations to the situation.[41] Exceptional violations are labeled "novel conditions," where the executor assumes that following the rules will not lead to the desired result. According to Refs. 42, adjustments/adaptations lead to positive as well as negative results. How events are handled due to these adjustments/adaptations depends on the dominant mindset of the organization or employer. If something bad happens, people are blamed for not following the rules.[19]

In the current study, routine and optimizing violations are considered violations of supervision. But errors that have occurred due to necessary or exceptional violations have been seen in the form of factors such as lack of knowledge and lack of equipment. For example, in order to stabilize the differential relay of the transformer, it needs to be done according to the manufacturer's instructions and the maintenance companies themselves. If the relay falsely operates after the test operation, it could be due to one of two reasons. There are no test instructions and the executive teams have tested based on their experience with the coordination of the supervisor, so this error is due to the lack of instructions. However, if there are instructions and the executive teams do not follow them as usual due to the prolongation of the test or other cases, this error is considered as a result of a supervisor violation. Three subfactors and 10 roots are identified for this factor in Table 1.

Organizational factors: Human resources are the most important assets of maintenance organizations. The behaviors and decisions of the managerial level directly affect the mental conditions and activities of the operating groups so that the smallest incorrect decision can cause disturbance and distrust in the whole organization. Therefore, strong motivational strategies can keep specialized and experienced personnel in the organization and attract new expert staff, because reducing the number of skilled personnel can make it difficult to maintain electrical equipment, which is becoming more specialized every day with the advancement of technology. Also, when financial resources are sufficient, personnel receive appropriate salaries and the testing equipment can also be updated along with the development of electrical equipment. For this factor, five subfactors and 23 roots are identified as described in Table 2.

Job position factors: Since transmission substations and lines are usually built in the suburb and to cover the proper maintenance of the network, the executive groups have been centralized in regions near the suburb. On average, each group covers 6,000 square kilometers and this causes the maintenance groups to be on missions outside their workplace continuously. On the other hand, heavy workload causes the tiredness of personnel due to insufficient relaxation time and

TABLE 1 Subfactors and roots related to supervision factors

Sub-factor	Roots code	Roots of the error
Violation	S1	Not paying attention to the mistakes expressed in previous operations and corrections by the relevant subgroups
Violation	S2	Supervisor decision for the operation of the maintenance outside the rules or guidelines as needed.
Violation	S3	The synchronization of corrective or defective projects with maintenance operation
Violation	S4	Doing something out of the maintenance program
Violation	S5	lack of exact analysis of the human errors event
Knowledge and experience	S6	The supervisor's limited knowledge and experience
Knowledge and experience	S7	The supervisor emphasizes the full implementation of the maintenance operation without prioritizing tasks.
Knowledge and experience	S8	The appearance and cleanliness of the work are less important than the correct performance of the equipment from the viewpoint of the supervisor.
Knowledge and experience	S9	Inappropriate honoring of the personnel
Documentation	S10	Lack of follow-up for the fixing of defects by the supervisor

also mental tiredness. In addition, a variety of weather conditions in various geographic regions such as heat and sultry weather in the warm season in the south and near the sea, or in cold weather and frost during the cold season in the north and mountainous regions of Fars province affect the behavior of the person. In this factor, five subfactors and seven roots are recognized according to Table 3.

Communication factors: Continuous communication between the personnel of the executive groups and between management levels and the personnel will increase job satisfaction. Because, if this relationship is established, the personnel's perspective problems with the management will be resolved and the working space inside the organization will be better and more enjoyable. For this factor, the three roots are predicted according to Table 4.

Personal factors: Self-personnel conditions such as mental, physical, and so on can affect personnel performance. Of course, external factors also affect the personnel's own condition and can make their situation worse. Five subfactors and 12 roots are specified in Table 5 for this factor.

6 | CALCULATION OF EXPECTED VALUE OF ACTUAL AND POTENTIAL HUMAN ERROR INFLUENCE ON PERSONNEL

Evaluating and ranking the roots and identifying experts with high human error expectations is finally done using multicriteria decision-making techniques (MCDM). MCDM techniques are powerful tools that are widely used in evaluating and ranking issues with several criteria that are usually complex.[43] Among the various MCDM techniques, the analytic hierarchy process (AHP) [44] and TOPSIS [45] are more effective than other techniques in the current problem. The reason for the widespread use of these techniques is the ease of analysis, high accuracy, and applicability in many subjects. The AHP method in a decision-making problem can both weigh and rank the criteria and can also evaluate and rank the alternatives. In performing the AHP method, it is necessary to first compare the criteria and alternatives in pairs, which are surveyed by questionnaires from experts. If the number of criteria and alternatives is high, it will increase the number of pair comparisons, which will prolong the questionnaire, and respondents may make mistakes in the comparisons or not fill the comparisons carefully due to boredom. Therefore, in order to resolve this MCDM in the current study, the TOPSIS method has been used for evaluation and ranking. However, it is only possible to rank experts using the TOPSIS, but the roots cannot be ranked and weighed. The Shannon entropy method, which is one of the most important topics in information theory and a powerful tool from MCDM,[46] is used in combination with the average mathematical expectation to calculate the weight and rank of roots.

Each electrical grid maintenance man at FEMCC performs on average about 180 days of maintenance per year. Therefore, each of these operations may be performed at a low quality under the influence of one or more roots by the

TABLE 2 Subfactors and roots related to organizational factors

Subfactor	Roots code	Roots of the error
Planning	O1	Tasks are more than a person's ability
Planning	O2	Choosing the wrong method for maintenance
Planning	O3	Maintenance personnel do not have the proper time to rest and upgrade their knowledge.
Planning	O4	Doing the maintenance operation at an inappropriate time (such as : from 0 AM to 6 AM or holidays)
Planning	O5	Some maintenance operations items are accompanied by repetitive actions
Planning	O6	Unsuitable Choosing of personnel for sensitive tasks
Planning	O7	Inappropriate planning to use all staff and facilities
Organizational climate	O8	Information, instructions, results of meetings, etc. from the directors or heads of departments to the personnel are not properly transmitted.
Organizational climate	O9	Transmission of stresses and work collisions from upstream to downstream
Organizational climate	O10	Insufficient financial and mental attention of the organization to personnel with responsibilities
Instructions and methods	O11	The personnel promotion manual is not transparent and appropriate
Instructions and methods	O12	There is not specific policy for empowering for personnel with a low work experience.
Instructions and methods	O13	Failure to update test and maintenance instructions
Instructions and methods	O14	Job description and organizational structure are not complete
Instructions and methods	O15	Lack of clear instructions for punishment and encouragement
Human resources	O16	Shortage of backup technician
Human resources	O17	There is no proper motive
Human resources	O18	Shortage of proper specialized training
Human resources	O19	Delays in employing expert personnel
Human resources	O20	The recruitment guidelines are not complete.
Funds	O21	Low salary
Funds	O22	In terms of salary, there is not much difference between people with and without responsibility.
Funds	O23	Shortage of budget to provide new or updates for the test equipment

maintenance man. This low quality, in addition to reducing the effectiveness of maintenance operations, may lead to the automatic outage of electrical equipment during operation. Since human error is a random concept, the expected value of each root's influence on personnel over a long period of time is calculated and evaluated in this section. This method can identify the most effective roots to plan for removal or reduction of their effects by the organization's managers. In the proposed method, the expected value of root influence is predicted in the long run on a person according to Equation (1).

$$E_r = \sum_{I} I_r f_r(I), \tag{1}$$

where E_r is expected value of r root influence, I_r is the influence intensity of the root occurrence on the person, $f_{\mathrm{r}}(I)$ is the r root probability distribution function.

The intensity of each root's influence on each person varies, because each person may adapt and adjust to factors. For example, the complex and varied electrical network equipment has little effect on some people as they constantly increase their knowledge to adapt to this root of the error. Or some people adjust to the maintenance schedule from 00:00 AM to 6:00 AM or holidays. Therefore, their performance in these hours depends on the extent to which they are adjusted to the conditions. Influence intensity is predicted in five categories: very high, high, medium, low, and very low for everyone according to his own opinion in the survey. If the root is not ineffective then the frequency of this influence or in other words the probability of it occurring should be estimated.

TABLE 3 Subfactors and roots related to job position factors

Subfactor	Roots code	Roots of the error
Workload and working time	J1	Hurry up in work
Workload and working time	J2	Longer maintenance time of more than the working hours
Equipment conditions	J3	Complex and varying electrical network equipment
Testing devices condition	J4	Shortage of sufficient and up-to-date equipment
Environmental conditions	J5	Continuous out-of-place missions due to dispersal of transmission substations and lines
Environmental conditions	J6	Not suitable environmental conditions (heat, cold, weather, etc.) that can affect the performance of the person
Physical design of equipment	J7	Instabilities in power grids in case of automatic outage of one equipment while maintaining other equipment in some places

TABLE 4 Subfactors and roots related to communication factors

Subfactor	Roots code	Roots of the error
	C1	Inappropriate knowledge of equipment instruction due to lack of proper transfer of prior experience
	C2	Tracking to fix mistakes related to the existing data, settings, spare parts etc. by executive teams at runtime
	C3	Lack of proper communication between the subgroups and feedback from each other

The probability of roots occurring (P_r) is predicted by surveying them in the five categories of frequent, probable, occasional, low, and very low, as the results of the expert opinion are qualitatively and linguistically received. To calculate Equation (1), qualitative comments are converted to numerical scores of 5 to 1 and the root probability function is defined in terms of numerical scores according to Table 6.

TABLE 5 Subfactors and roots related to personal factors

Subfactor	Roots code	Roots of the error
Individual error	I1	Failure to study the protection diagrams before the maintenance
Individual error	I2	Failure to follow the instructions
Individual error	I3	Mobile answering during work
Individual error	I4	The instructions and setting have not been revised and the mistakes have been repeated several times.
Knowledge and experience	I5	The existence of viewpoints that some checklist items are important and should be checked and the rest is not needed.
Knowledge and experience	I6	Insufficient knowledge of the cause and performance of each items in the checklist or settings
Knowledge and experience	I7	Pride for various reasons, including experience, age, specialty
Mental conditions	I8	The misconception is that increasing the workload grows the probability of a human error.
Physical and spiritual conditions	I9	Personnel are sometimes not ready for maintenance for any reason
Physical and spiritual conditions	I10	Psychasthenia
Physical and spiritual conditions	I11	Lack of paying attention to the family and time spent on them, which can be a source of discomfort and fatigue for the staff
Physical and spiritual conditions	I12	Physical tiredness

TABLE 6 Probability distribution function of the root influence intensity r

I_r	5	4	3	2	1	−5
$f_r(I)$	◆ orP_r	◆ orP_r	◆ orP_r	◆ orP_r	◆ orP_r	$1 - P_r$

The following issues should be considered in the probability function table:

1. For each root, only one intensity of the influence is considered. For each category I_r, the probability of the root occurring is specified 1 or P_r. Therefore, the probability of the root occurring for this influence intensity is predicted and the probability of the rest of the categories is assumed to be zero.
2. If the probability of root occurring is predicted to be P_r, then the probability of the root not occurring is $1 - P_r$. Improbability root occurrence can also have a high psychological impact on any person, on the contrary, the influence intensity is very high. Therefore, the influence intensity of nonoccurred root is considered with (−5) in this study.
3. The numerical value of P_r is 1, 0.8, 0.6, 0.4, and 0.2, respectively, according to frequent, probable, occasional, low, and very low surveys.

The expected value of the root influence on the person (E_r) is obtained after a large number of maintenance operations. If E_r is negative, it means that the root has no effect on the person in the long run, and the greater its value, the greater this ineffectiveness. On the other hand, roots with more positive expected values are in higher priority to evaluate and reduce their impact on experts.

7 | THE COMBINED METHOD OF TOPSIS AND SHANNON ENTROPY FOR EVALUATING AND RANKING INDICATORS AND EXPERTS

Since the organization's resources for reducing or eliminating roots are limited, managers need to identify the roots with the highest priority, first. The proposed method to evaluate and rank the roots is to combine the average mathematical expectation of personnel opinions and Shannon entropy. Using this method can prioritize the roots. Furthermore, the weights of each root can be used to solve the issue of multicriteria decision making, which is the evaluation of personnel.

The Shannon entropy method was introduced in 1948 by Claude Shannon.[47] Entropy represents the amount of uncertainty in a continuous probability distribution. In this method, we weigh the roots in five steps [48] according to the followings:

Step 1: Make a decision matrix. The decision matrix column is the roots and the rows are the experts.
Step 2: The decision matrix is normalized according to relation 2.

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}, \tag{2}$$

where n is the number of experts, x_{ij} is the expected value of j root influence on the expert i.

Step 3: The entropy of each index is determined by Equation (3).

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} r_{ij} \ln\left(r_{ij}\right). \tag{3}$$

Step 4: The degree of deviation is calculated using the relation (4).

$$d_j = \prime - e_j \tag{4}$$

Step 5: Calculate weight through relationship (5).

$$W_j = \frac{d_j}{\sum_{j=1}^{m} d_j}, \tag{5}$$

where m is the number of roots.

To rank the roots, first, the average expected value of the experts at each root influence is calculated according to Equation (6). If the value obtained is positive, it indicates that the sum of the experts' opinions concluded that this root is effective. So, the more positive this value, the more effective this root is. However, the expected value of the roots' influence on the experts can be between −5 and 5. The importance of roots to reduce their impact on personnel depends on both the mean and the dispersion of experts' expectations. The weight calculated according to the Shannon entropy method in Equation (5) somehow indicates the degree of dispersion. The proposed relationship in this paper is to determine the importance of roots in terms of effectiveness according to Equation (7).

$$AOE_j = \frac{\sum_{i=1}^{n} x_{ij}}{n}, \tag{6}$$

$$IR_j = AOE_j * W_j. \tag{7}$$

The TOPSIS technique[49] is used to rank and compare experts and select experts with high error expectations. This technique includes seven steps:

Step 1: Make a decision matrix. The decision matrix column is the roots and rows of the experts.
Step 2) Normalization of the decision matrix according to Equation (8).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}}. \tag{8}$$

Step 3) Determine the normal weighted matrix: In this step, we have to multiply the weight of the roots obtained by the Shannon entropy method in the normal matrix to get the weighted matrix.
Step 4) Determine the worst and the best alternatives. The highest and lowest values are determined in the root column.
Step 5) The distance between each alternative and the worst and the best alternative is obtained with the help of Equation (9).

$$d_i^+ = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^+\right)^2},$$

$$d_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^-\right)^2}, \tag{9}$$

where v_{ij} is the expected value of normalizing and weighted root influence i is on the j expert, d^+ and d^- are the worst and the best alternatives set out in step 4.

Step 6) Determine the proximity coefficient for each of the alternatives. This coefficient represents the score of each alternative and is calculated based on Equation (10). The proximity coefficient range is from 0 (pure expectation of not influence) to 1 (pure influence expectation).

$$CL_i = \frac{d_i^-}{d_i^+ + d_i^-}. \tag{10}$$

Step 7) Rank experts based on proximity coefficient. The closer the index is to the number one, the higher the 100% expectation of error by the expert. Studies have shown that the coefficient of more than 0.5 means that there is a positive expectation of error in the experts, or in other words, the intensity expectation of the roots' influence on the expert is high.

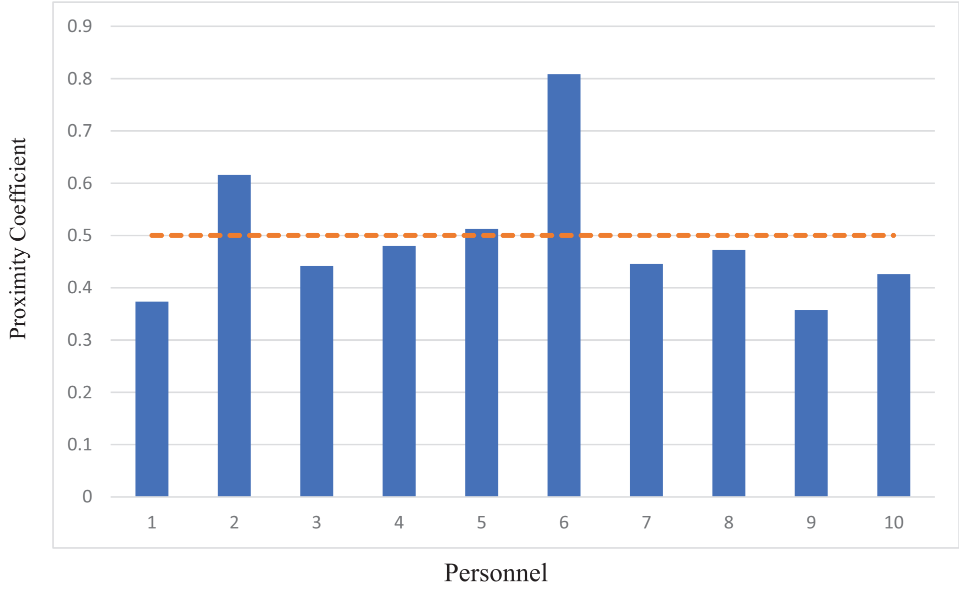

FIGURE 6 Ranking of 10 FREMCC experts according to their opinion

8 | CASE STUDY

In this part of the article, a case study is conducted on 10 FEMCC experts to identify experts with a high probability of error and roots with the expectation of more impact. First, influence intensity and the probability of each root on these experts should be determined according to the information of previous incidents. However, since there was no accurate database, experts expressed their qualitative opinion about the intensity of the impact and the probability of each root occurring with the help of a questionnaire. Then, the expected value of each root influence for each person was calculated with the help of Equation (1). Table 7 presents the opinions of three experts.

With the help of the proposed method, experts are evaluated and ranked according to their own opinion in terms of the degree of the expected error. Figure 6 shows the results of this ranking. As can be seen, almost 70% of experts expect that they will not make mistakes during many operations, because their proximity coefficient is less than 0.5. However, about 30% of personnel are frustrated, so one of the first steps in FEMCC is to increase morale and confidence in personnel. According to Figure 6, experts 2, 5, and 6 expected more errors. Table 7 also shows that more roots affect experts 2 and 5 than expert 7.

Investigations revealed that experts 2 and 5 caused the automatic outage of three transformers and one transmission line due to human error over the years 2014 to 2018. The influential roots on experts 2 and 5 that caused their human error are shown in Table 7 with "*." According to Table 7, 75% of human error roots by expert 2 are consistent with the predicted expected value of these roots' influence pursuant to the proposed method. Also, the roots that are expected to be more influential are more effective in these expert errors. For expert 5, about 80% of the error roots correspond to the expected value of the roots' influence.

Figure 7 shows the prioritization of roots based on the effectiveness of the roots, which are evaluated according to Equation (7). The results that can be drawn from Figure 7 are:

- The O22 and O3 roots are the worst roots that should have high priorities for proposing and implementing prevention strategies, because it affects the performance of 80% of the staff.
- Approximately 43% of the roots are expected to have a greater influence on experts as their average expectations are positive. Therefore, organization managers need to pay more attention to reducing or eliminating the effects of these 24 roots (C2, I4, I8, J3, J5, O3, O4, O9, O10, O11, O12, O14, O15, O16, O17, O18, O19, O21, O22, O23, S3, S5, S8, S10) by determining priority solutions.
- According to Table 6, approximately 75% of the error roots of Experts 2 and 5 between 2014 and 2018 have a positive IR coefficient based on Figure 7, or in other words, according to the proposed method, they have priority for the attention of managers.

TABLE 7 the opinions of three experts

Roots code	Expert 2 Probability	Expert 2 Intensity	Expert 2 Expected value	Expert 2 influential roots	Expert 5 Probability	Expert 5 Intensity	Expert 5 Expected value	Expert 5 influential roots	Expert 7 Probability	Expert 7 Intensity	Expert 7 Expected value	Expert 7 influential roots
C1	Occasional	Medium	−0.2		Low	Low	−2.2		Unlikely	Very low	−5	
C2	Probable	Medium	1.4		Low	Medium	−1.8		Occasional	Medium	−0.2	
C3	Frequent	High	4		Occasional	Very high	1		Low	Medium	−1.8	
I1	Unlikely	Very high	−5		Probable	High	2.2		Low	Low	−2.2	
I2	Low	High	−1.4		Probable	Very high	3		Low	Low	−2.2	
I3	Low	High	−1.4		Low	Medium	-1.8		Low	Medium	−1.8	
I4	Occasional	Medium	−0.2		Probable	High	2.2		Frequent	Medium	3	
I5	Low	High	−1.4		Occasional	High	0.4		Unlikely	very low	−5	
I6	Low	High	−1.4		Low	Low	−2.2		Low	Low	−2.2	
I7	Low	High	−1.4		Occasional	High	0.4		Unlikely	very low	−5	
I8	Occasional	Medium	−0.2		Low	Medium	−1.8		Low	Low	−2.2	
I9	Low	High	−1.4		Low	Low	−2.2		Unlikely	Medium	−5	
I10	Low	High	−1.4		Probable	Medium	1.4		Low	Low	−2.2	
I11	Occasional	Medium	−0.2		Low	Low	−2.2		Occasional	High	0.4	
I12	Low	High	−1.4	*	Occasional	Low	−0.8	*	Low	Low	−2.2	
J1	Probable	High	2.2		Frequent	Very high	5	*	Low	Medium	−1.8	
J2	Occasional	Medium	−0.2		Occasional	High	0.4	*	Occasional	Medium	−0.2	
J3	Occasional	High	0.4		Occasional	Very high	1		Low	Low	−2.2	
J4	Frequent	Very high	5		Occasional	High	0.4	*	Occasional	Medium	−0.2	
J5	Occasional	High	0.4		Probable	Very high	3		Low	Medium	−1.8	
J6	Low	Medium	−1.8		Low	Very low	−2.6		Low	Medium	−1.8	
J7	Occasional	High	0.4		Probable	High	2.2		Low	Low	−2.2	
O1	Low	High	−1.4		Occasional	High	0.4		Unlikely	Low	−5	
O2	Low	High	−1.4		Occasional	Medium	−0.2		Unlikely	Low	−5	
O3	Frequent	High	4		Occasional	Medium	−0.2		Low	Low	−2.2	
O4	Occasional	High	0.4		Occasional	High	0.4		Occasional	Medium	−0.2	
O5	Low	Medium	−1.8		Occasional	High	0.4		Low	Low	−2.2	
O6	Occasional	High	0.4		Probable	High	2.2		Occasional	High	0.4	
O7	Probable	Medium	1.4		Occasional	Medium	-0.2		Low	Medium	−1.8	
O8	Occasional	High	0.4		Occasional	Low	-0.8		Low	Medium	−1.8	

(Continues)

TABLE 7 (Continued)

Roots code	Expert 2				Expert 5				Expert 7			
	Probability	Intensity	Expected value	influential roots	Probability	Intensity	Expected value	influential roots	Probability	Intensity	Expected value	influential roots
O9	Occasional	Very high	1	*	Probable	Medium	1.4		Low	Medium	-1.8	
O10	Probable	High	2.2		Unlikely	Low	−5		Frequent	Very high	5	
O11	Occasional	Medium	−0.2		Occasional	High	0.4		Frequent	Very high	5	
O12	Probable	High	2.2		Occasional	Medium	−0.2		Probable	Medium	1.4	
O13	Occasional	High	0.4		Low	Medium	−1.8		Unlikely	Low	−5	
O14	Probable	Medium	1.4		Probable	Low	0.6		Low	Low	−2.2	
O15	Frequent	Very high	5		Low	Low	−2.2		Probable	High	2.2	
O16	Occasional	High	0.4		Probable	Very high	3		Low	Medium	−1.8	
O17	Occasional	High	0.4		Low	Medium	−1.8		Probable	Very high	3	
O18	Probable	Medium	1.4		Occasional	High	0.4	*	Low	Low	−2.2	
O19	Probable	Medium	1.4		Probable	High	2.2		Probable	very low	−0.2	
O20	Occasional	Very high	1		Occasional	High	0.4		Unlikely	Low	−5	
O21	Occasional	Medium	−0.2		Low	High	−1.4		Probable	Very high	3	
O22	Frequent	Very high	5		Occasional	Very high	1		Frequent	Very high	5	
O23	Frequent	Very high	5		Occasional	Medium	−0.2		Low	Low	−2.2	
S1	Occasional	Medium	-0.2		Occasional	High	0.4		Unlikely	Low	−5	
S2	Low	Medium	−1.8		Frequent	High	4		Occasional	Medium	−0.2	
S3	Frequent	Very high	5	*	Probable	High	2.2		Occasional	Medium	−0.2	
S4	Occasional	High	0.4		Low	Medium	−1.8		Occasional	High	0.4	
S5	Frequent	Very high	5		Probable	High	2.2		Occasional	Medium	−0.2	
S6	Occasional	High	0.4		Occasional	High	0.4		Occasional	High	0.4	
S7	Occasional	High	0.4		Low	Medium	−1.8		Occasional	High	0.4	
S8	Frequent	Very high	5	*	Occasional	High	0.4		Probable	Very high	3	
S9	Occasional	High	0.4		Low	Low	−2.2		Occasional	Medium	−0.2	
S1◆	Occasional	Medium	−0.2		Low	Low	−2.2		Low	Low	−2.2	
Ep			37.6				5.4				−61.2	

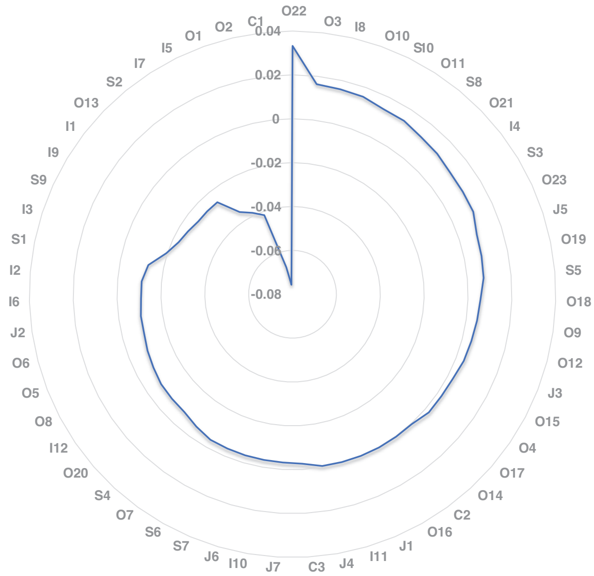

FIGURE 7 Prioritization of roots in terms of influence

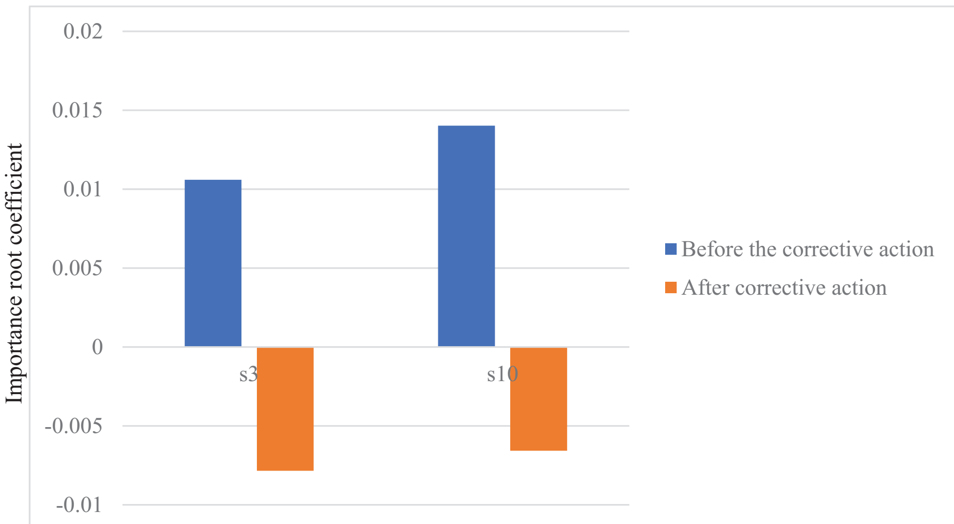

FIGURE 8 Changes in root importance according to experts before and after corrective actives of S3 and S10 roots

- The roots of the supervision factor have the greatest influence on experts after the organizational factor. Therefore, planning to supervise properly and within the framework of instructions can reduce the expectation of errors in maintenance personnel. In FEMCC, the following procedures have been taken to improve the S3 and S10 roots.
  - Completion and updating of substation protection maps
  - To prepare instructions for updating maps and implementing them
  - To prepare instructions for checking maps during maintenance and reporting breaches for corrections
  - Implement risk-free optimization programs the next day

These actions have led experts to believe that the influence severity of S3 root can be slightly improved in experts. However, the influence intensity of this root has greatly reduced according to experts due to more and better activities for S10 root. Figure 8 shows the IR coefficient of these roots before and after the corrective actions.

9 CONCLUSION

The maintenance of power grids is difficult, complex, and important due to the growing dependence of society on electricity. Therefore, maintenance personnel often work under pressure to complete work as quickly as possible to eliminate customer downtime in the shortest possible time or not to shut down as much as possible. Transmission maintenance personnel are constantly adapting/adjusting to financial, time, and technical conditions to achieve success. Of course, these adaptations often lead to positive personnel performance, but in some cases may have a negative impact on personnel. A negative impact leads to human error. In this paper, it is tried to increase the success rate of maintenance operations by finding the factors that personnel could not adjust/adapt to, and also by finding people who could not adjust/adapt to the shortcomings.

In the first step, roots are identified and classified into the five main factors of organizational factors, job position, individual, communication, and especially supervision. Studies conducted in this paper show that the roots of the supervision factor after the organizational factor have the greatest expected influence on experts, so the roots of this factor are important. In the next step, the expected effect of these roots on the individuals is calculated and analyzed in terms of mathematical expectation. Then, the roots were analyzed with the help of the proposed method, which is a combination of mean and Shannon entropy. The results of studies on 10 FEMCC experts show that approximately 43% of the roots have a positive impact on more than 50% of the experts and that managers should pay more attention to reducing or eliminating these 24 roots. Of course, the root that "Maintenance personnel does not have the proper time to rest and upgrade their knowledge" is the worst root that should be given high priority. Also, about 70% of experts hope that they will not make mistakes during many maintenance operations. The proposed method in this paper, which combines the methods of TOPSIS and Shannon entropy, can detect the expectation of error in maintenance personnel.

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How to cite this article: Tavakoli M, Nafar M Estimating and ranking the impact of human error roots on power grid maintenance group based on a combination of mathematical expectation, Shannon entropy, and TOPSIS. *Qual Reliab Eng Int*. 2021;37:3673–3692. https://doi.org/10.1002/qre.2941