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Fuzzy failure mode and effect analysis application to reduce risk level in a ready-mixed concrete plant: A fuzzy rule based system modelling approach

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Abstract

In this study, failure mode and effect analysis were applied to evaluate and eliminate potential failure modes in a Ready-Mixed Concrete Plant using a fuzzy-rule-base system. The questionnaires were specially prepared for each sub-department such as production plant, workshop and maintenance, dumping grounds, materials transportation and storage, utilities, administrative office, social facility, quality control laboratory and wastewater pool and recycling facilities. The questions were answered by the workers in each section. Risk Priority Numbers (RPNs) and Fuzzy Risk Priority Numbers (FRPN), which measure potential failure modes, were calculated using the risk parameters. High-risk areas were identified, and some suggestions were made to reduce accident risk at the Ready-Mixed Concrete Plant. Three questionnaires were prepared, based on these suggestions, and distributed to workers to determine whether the suggestions would reduce the risk or not. Based on conditions at the time the recommendations were implemented and improvement rates were calculated. The results showed that the fuzzy failure mode and effect analysis methodology were effective in identifying and eliminating potential failure modes at the Ready-Mixed Concrete Plant. The results can also be used by other ready-mixed concrete manufacturers who want to improve the safety of their operations.

Keywords: Failure mode and effect analysis; Fuzzy rule base system; Multi-Criteria Decision Making (MCDM); Ready-mixed concrete plant; Risk assessment

1. Introduction

Concrete has been the most important construction material in Turkey for many years [23]. According to the Turkish Ready-Mixed Concrete Association [3], over the last five years, the number of Ready-Mixed Concrete Manufacturers in Turkey rose from 500 to 600 and the number of facilities rose from 900 to 1080 [3]. Moreover, ready-mixed concrete production exceeded 100 million m^3 per year [3]. Ready-mixed concrete production is also located in the building industry. The rate of work-related accidents was 3.0%, and work-related illness and injury cost 1.7 million working days lost [12]. Many companies in the construction industry, where fatal accidents are as

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high as 22% struggle to reduce the number of accidents and increase workplace safety [15,21,36,57,64]. Failure mode and effects analysis (FMEA) are commonly used engineering techniques for designing, identifying and eliminating known and/or potential failures, problems, and errors before they reach the customer. This analysis can help to identify and eliminate potential failures in manufacturing sectors like concrete production [54]. FMEA has been shown to be a helpful and powerful tool for evaluating potential failures and avoiding them before they happen [30,46]. The results from such analysis can provide analysers to define and fix the failure modes that harm systems or processes and to enhance performance during the design and production stages [2,7,9,14,16,30,44,60]. Since its release as a useful tool for designers, FMEA has been used in a wide range of industries, including the aerospace, automotive, nuclear, electronics, chemical, mechanical, and medical technologies industries [2,7,9,14,16,22,30,44,60]. Traditionally; risk evaluation in FMEA is applied by building an index of risk priority numbers (RPNs) [30]. Nonetheless, the crisp RPN method has some crucial weaknesses when FMEA is carried out in real-world cases [30]. For this reason, many alternative approaches have been offered to overcome some of the defects of the crisp RPN method and to perform FMEA in real-world circumstances more efficiently [30].

FMEA frequently uses Multi-Criteria Decision Making (MCDM), 22.5% [30], with tools like the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for foaming machine and outpatient service, Decision Making Trial and Evaluation Laboratory (DEMATEL) for centrifugal pump operations, grey relational analysis (GRA) for paper machine and service quality, the Analytical Hierarchic Process (AHP) in the automotive, and hazardous substance fields, and Vlse Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) for risk assessment in two hospitals [4,5,19,27,31,48]. FMEA has also combined approaches like MCDM and Fuzzy logic, 11.25%. Integrated approaches have been used, for example, to [1] apply FMEA to risk management in the building industry using integrated fuzzy FMEA and fuzzy AHP [29]. It was offered a risk priority model for FMEA using fuzzy evidential reasoning (FER) and grey theory [28]. It was also considered a fuzzy approach, allowing analysts to use linguistic variables to determine occurrence, severity, and detectability, for FMEA by performing fuzzy TOPSIS combined with fuzzy AHP [6]. It was enhanced FMEA assessment by integrating GRA with DEMATEL.

In literature, the most widely used method with FMEA (40%) is artificial intelligence (AI). This method has used a fuzzy-rule-base-system for engineering applications such as chemical and volume control systems [16]; diesel engine gas turbocharger systems [58], marine industry [42], paper industry [49], electronic devices such as switched-mode power supplies [66]; nuclear engineering systems [17]; permanent magnet direct current (PMDC) micro-motors [8]; serial-connected systems [38], and floating, production, storage and offloading system [59], paper mills [50], test handler process in a semi-conductor manufacturing plant [56]; nuclear power plants [13], process plant [51]; purchasing process in a public hospital [26], bird nest processing [20], screw conveyor [33], communication security [52], sugar mill [34], construction of metro tunnels [43], food company [47], offshore engineering systems [61], sewage plant [63], semiconductor wafer process [62], construction industry [32].

Yeh and Chen [62] formed a questionnaire by using the data taken from the extant literature. Then, they created risk priority number sequences by comparing the literature-based data. On the other hand, Yeh and Hsieh [63] conducted a small-scale case study based on expert opinions. Proposed method in this paper differs from the Yeh and Chen [62] and Yeh and Hsieh's [63] studies with two important pillars: (i) Possible failures on a very large spectrum, their effects, and risk priority values were determined by the workers in conflict-zones from a security and risk-taking perspective. (ii) Preventive activities and the improvement rates in related zones were determined by the same workers. Thus, it has been proved that a more effective preventive action. Furthermore, Yeh and Hsieh [63] suggested a fuzzy logic based risk assessment study by using the conventional FMEA. On contrary, in our study, the fuzzy FMEA, fuzzy GRA and fuzzy TOPSIS are incorporated into a very wide and real data set with their single, binary or triple combinations.

This paper proposes an approach that integrates FMEA and a fuzzy inference system to assess, determine, and analyse potential failures and prevent them from occurring at a Ready-Mixed Concrete Plant (RMCP). The main contribution of this article is to demonstrate how this FMEA method with a fuzzy-rule-based system can identify and eliminate potential failure modes in the plant. The FMEA method with a fuzzy-rule-based system is first applied to improve the concrete manufacturing process, to collect information for reducing future failures, and to minimize the likelihood of failures in an RMCP. Another aim of this article is to use calculations that can help to determine whether anticipated improvement rates comply with the recommendations of experts. A third objective of this study is to reduce the possibility of the same kinds of failure at other firms with an RMCP.

The innovations of this work are as follows: (1) building a fuzzy rules matrix based on expert suggestions and applying a fuzzy FMEA method to identify the existing risks in the ready mixed concrete facility and to take the

Table 1
Severity guidelines for design FMEA (1–10 qualitative scale).

Effect	Rank	Criteria
No.	1	No effect.
Very slight	2	Customer not annoyed.
Slight	3	Customer slightly annoyed.
Minor	4	Customer experiences minor nuisance.
Moderate	5	Customer experiences some dissatisfaction.
Significant	6	Customer experiences discomfort.
Major	7	Customer dissatisfied.
Extreme	8	Customer very dissatisfied.
Serious	9	Potential hazardous effect.
Hazardous	10	Hazardous effects.

Table 2
Occurrence guidelines for design FMEA (1–10 qualitative scale).

Effect	Rank	Criteria
Almost never	1	Failure unlikely. History shows no failure.
Remote	2	Rare number of failures likely.
Very slight	3	Very few failures likely.
Slight	4	Few failures likely.
Low	5	Occasional number of failures likely.
Medium	6	Medium number of failures likely.
Moderately	7	Moderately high number of failures likely.
High	8	High number of failures likely.
Very high	9	Very high number of failures likely.
Almost certain	10	Failure almost certain.

necessary measures, (2) implementing a sustainable and effective method with a compressive case study in a sector, such as the construction industry, where accidents can frequently occur, from the service to production section (3), comparing the fuzzy-based, TOPSIS-based, and GRA-based FMEA methods with a case study from a ready-mixed concrete plant. These three approaches are the most used methods integrated with FMEA in the literature.

The remainder of this article is organized as follows. A brief introduction to FMEA and fuzzy logic is provided in Section 2. The solution method is discussed in Section 3. The results from the Fuzzy FMEA application, RPN, and Fuzzy RPN are in Section 4. Also in Section 4 is an evaluation and analysis of the risk assessment findings by these three methods, including calculations of anticipated improvement rates in failure modes. Finally, Section 5 contains a discussion and conclusions.

2. FMEA and the Fuzzy-rule-based system

2.1. FMEA

In the RPN methodology, failure analysis is carried out using the parameters such as the severity of the event, the probability of the event will occur and the detection of the event [37]. The qualitative scales widely used for severity (S), occurrence (O), and detectability (D) indexes are illustrated in Tables 1–3 [53]. Severity and occurrence are ranked according to how seriously a failure will affect the process or the user and according to the failure probability, that is the relative number of failures anticipated during the design life of the item [37]. The effects of a failure are normally defined by the impact on the utilizer of the product or as they would be sighted by the utilizer [37]. Detectability is an evaluation of how well a design validation programme can define a potential weakness before the part is released for production [37]. The RPN is obtained by multiplying the severity, the occurrence and the detection values (Eq. (1)) [37]. RPN values allow us to determine which types of failures are more critical and require corrective action [40].

$$Crisp\ RPN = S * O * D \tag{1}$$

Table 3
Detectability guidelines for design FMEA (1–10 qualitative scale).

Effect	Rank	Criteria
Almost certain	1	Proven detection methods available in concept stage.
Very high	2	Proven computer analysis available in early design stage.
High	3	Simulation and/or modelling in early stage.
Moderately high	4	Tests on early prototype system elements.
Medium	5	Tests on preproduction system components.
Low	6	Tests on similar system components.
Slight	7	Tests on product with prototypes and system components installed.
Very slight	8	Proving durability tests on products with system components installed.
Remote	9	Only unproven or unreliable technique(s) available.
Almost impossible	10	No known techniques available.

2.2. Fuzzy-rule-base system

Zadeh, who led the development of fuzzy logic in place of classical Aristotelian logic, presented the concept of "fuzzy set" [18,65]. Fuzzy logic (FL) tool provides the integration of linguistic knowledge and numerical data in a systematic method, thus making it possible to process inaccurate information and account for uncertainties [18,65]. The key aspects in human thinking are levels of fuzzy sets through linguistic words but not numbers [18,65]. Fuzzy propositions such as, IF–THEN statements are used to characterize the state of the system and the proposition's truth-value is a measure to show how well the definition matches the state of the system [18,65]. In the beginning, the fuzzy concept did not find a common application because it contained many complex techniques such as probability theory, mathematics, statistics and stochastic processes [18,65]. However, fuzzy logic has been developing because of innovations in the world of computers, and it is now being used in several industrial applications [18,65]. The key idea behind fuzzy is the allowance of partial belongings of any object by taking into consideration the subsets of a universal set [18,65]. The Fuzzy Associative Map (FAM), which is also called the fuzzy associate memory transforms a set of inputs to the corresponding set of outputs [18,25,65].

The fuzzy tool used in this paper is outlined as follows. The input variables – the severity of the failure (S), the probability/occurrence of the failure (O), and the probability of not detecting the failure (D) – are divided into several subsets with simple trapezoidal fuzzy membership functions. The output variables – the risk priorities numbers (RPNs) – are divided into several subsets with simple trapezoidal fuzzy membership functions [45]. An example could be to define the method used in the study. For example, consider three input variables where S is very low, O is low, and D is high, then some rules can be written [10,45], such as:

$R_{1:}$ IF S is very small, O is low, and D is high THEN RPN is low.

The first rule expressed here can be written as follows. If the severity of the failure is very small (the destructive effect of the event is very low) and the probability/occurrence of the failure is almost zero and the probability of not detecting the failure is almost zero (it was noticed immediately after a failure occurs) then RPN is low (there is a very low risk).

$R_{2:}$: IF S is small, O is normal, and D is very high THEN RPN is low.

$R_{3:}$ IF S is high, O is normal, and D is low THEN RPN is high.

For each stimulated rule the membership degrees for S, O and D are calculated and then are multiplied to give the weight W_k to be designated to the corresponding output Y_k [10,11,45]. Thus, the weighted average of the outputs from three rules is a single output, y, [10,11,45], as:

$$y = \frac{\sum_{k=1}^{n} W_k Y_k}{\sum_{k=1}^{n} W_k}, \tag{2}$$

where m and n are the number of subsets (in other words, the number of membership functions) and the number of rules, respectively. The rule base takes the shape of an output Y_k $(k = 1, 2, \ldots, m^2)$ with three inputs (S, O and D) and m subsets. Wk is the weight of each rule for data point m. It is computed multiplying the fuzzy subset values of S, O, and D that related to that rule and squaring the result. The rule list is set up, values of the output can be calculated from Eq. (2) for any combination of input variable fuzzy subsets [10,11,45].

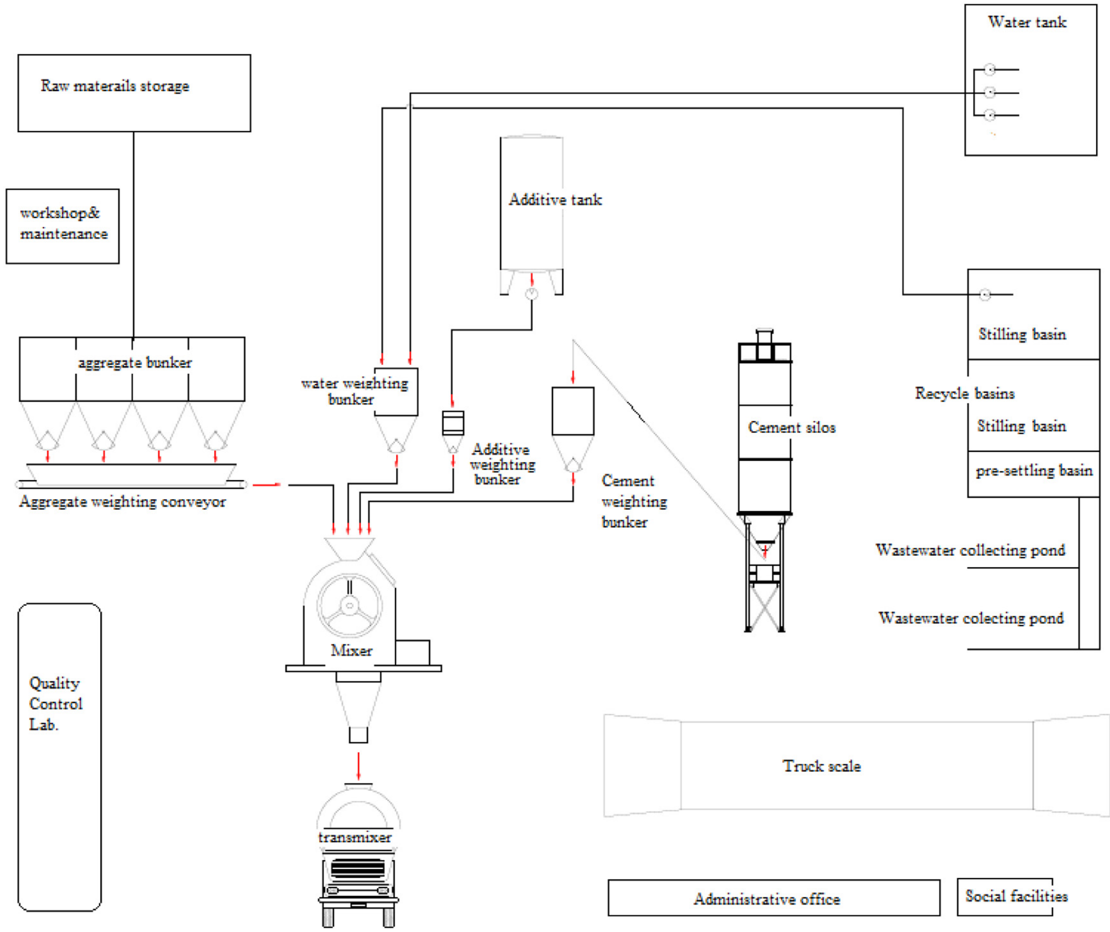

Fig. 1. Ready-mixed concrete plant.

In our study, the Mamdani fuzzy logic method is carried out and the fuzzy logic (FL) model was obtained by using the fuzzy logic toolbox in MATLAB® version 2014b. The Mamdani fuzzy inference system was selected because of its remarkable advantages such as being intuitive, well-suited to human input, and having a more interpretable rule base and widespread acceptance [35]. The method of Mamdani fuzzy inference system, which is more suitable for subjective data, is preferred because this study is based on questionnaires.

3. Proposed methodology

3.1. Questionnaire design and procedure

The company which is the focus of the study has been in business for over 30 years. It operates in four geographical regions: the Mediterranean, Marmara, the Black Sea, and the Ankara Central Offices. It is a member of the American Concrete Institute, and it manufactures cement at factories it owns. The company has events in ready-mixed concrete production (Fig. 1). These include special concrete such as underwater concrete, frost-durable concrete, sulphate-durable concrete, colourful concretes, fibrous concrete, and concrete roads. The company has an annual capacity of 5.0 million m^3 with 26 ready-mixed concrete facilities. 34 concrete plants, 322 mixers, 78 concrete pumps, and 3 aggregate ovens.

With the help of experts, the RMCP was separated into the nine sections: production plants, workshop and maintenance, dumping grounds, materials transportation and storage, utilities, administrative office, social facility, quality control laboratory, and wastewater pool and recycling facilities. The potential types of accidents on each

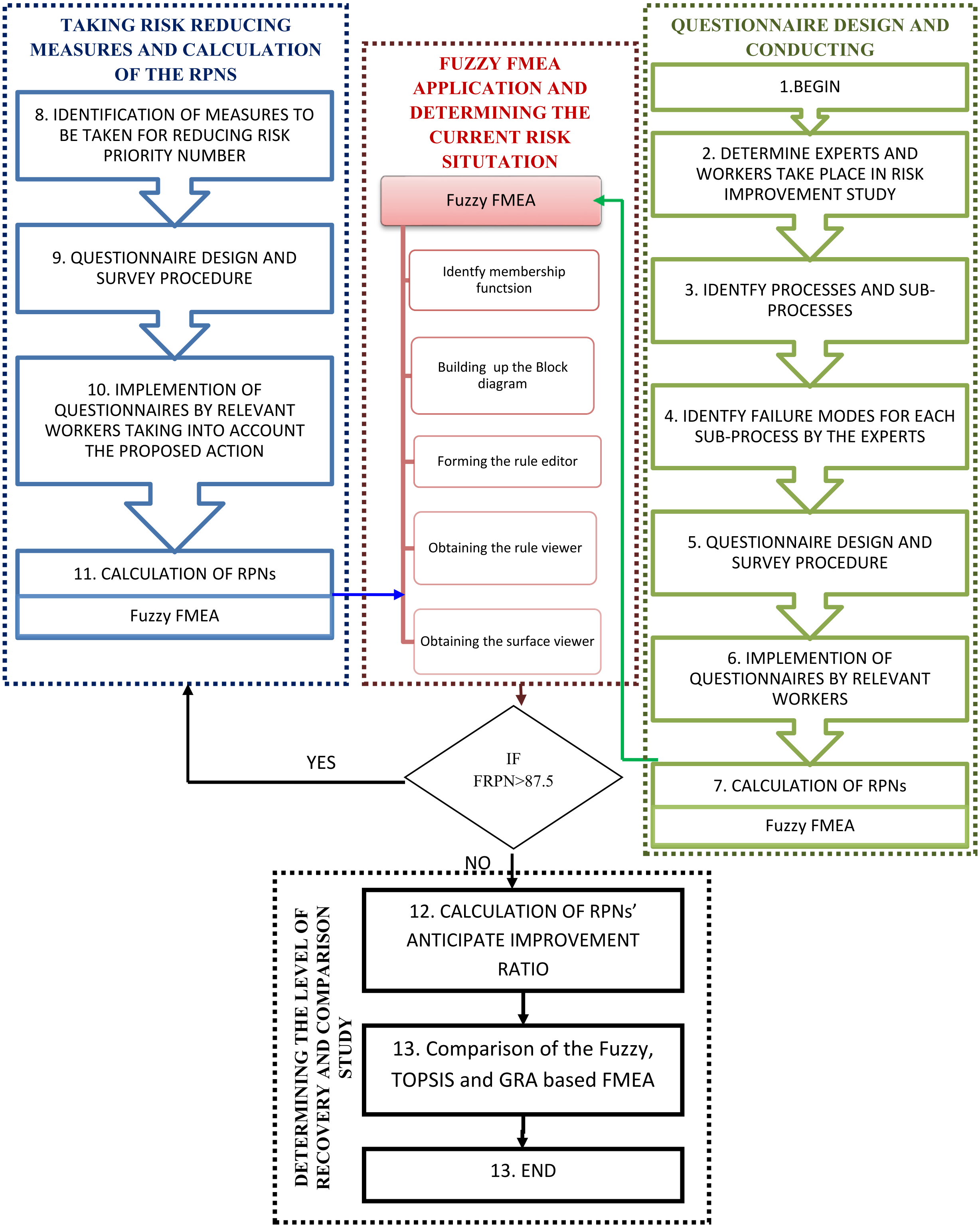

Fig. 2. Proposed risk assessment of RMCP framework.

Table 4
Potential failure modes, effect and causes in production plant.

No.	Activity	Failure cause and mode	Failure effect
1	Supplying material through the aggregate bunker edge, removing the large parts on the bunker grill	Falling from the bucket while lifting passengers with the loader bucket at the bunker exit.	Serious injury
2	Supplying material through the aggregate bunker edge, removing the large parts on the bunker grill	Falling into the bunker due to the absence of bunker grill	Serious injury
3	Supplying material through the aggregate bunker edge, removing the large parts on the bunker grill	Squeezing one's feet into the grill because of the wide-spared above bunker grills	Minor lacerations
4	Cleaning the material accumulated under the aggregate band	Catching up one's limbs in the drums or rollers during the cleaning of the lower band.	Serious injury
5	Walking between the aggregate band and the bunker	Fall of materials from the band.	Minor lacerations
6	Providing a good vision in the dark, when filling concrete into the transit mixer at night	Crashing into the passengers or equipment stepping out of the filling	Serious injury
7	Providing a good vision in the dark, when filling concrete into the transit mixer at night.	Crashing into the power plant construction while approaching to the filling.	Financial loss
8	Maintenance and cleaning works for the concrete mixer.	Slipping or falling because of the disorganized hose or of lubrication	Serious injury
9	Maintenance and cleaning works for the concrete mixer.	Falling from the gaps nearby the power plant	Serious injury
10	Manufacturing	Health issues arising from noise	Minor lacerations
11	Control, maintenance and repair works for silo helix and motors	Falling because of working at height	Serious injury
12	Control, maintenance and repair works for silo helix and motors	Exposure to dust because of the uncontrolled cement flow	Eye diseases
13	Cementing by cement trailer	Silo laceration due to the increase in the cementing pressure	Serious injury
14	Cementing by cement trailer	Explosion/fall of the filter because of the overfill arising from the failure of the silo filling warning siren	Serious injury
15	Cementing by cement trailer	Excessive dust formation due to the hose explosion	Skin/Eye diseases
17	Cementing by cement trailer	Because of the dust emission on the upper covers of the cement trailer; causing the cover to pop out when it is intervened	Serious injury
18	Controlling and cleaning the filters, overfill relief valves and level indicators on the cement silo	Falling down when stepping up on the silo	Serious injury
19	Storage of calibration weights	Falling/tumbling because of the irregular stacking	Smash/Minor lacerations
20	Calibration activity	Lifting and carrying the weights by hand	Waist regions
21	Loading the concrete into the transit mixer	Rapid concrete discharge due to the maladjustment of power plant covers	Minor lacerations
22	Cleaning of the under-bunker	Falling because of the slippery ground with crushed stone	Minor lacerations
23	Cleaning of the under-bunker	Crashing into the equipment because of the cramped and hard working space	Minor lacerations
24	Drawing the transit mixer into the power plant	Crashing into the equipment among the manoeuvres	Financial loss
25	Use of admixture motors	Contact with the rotating equipment due to the absence of coupling housing	Cut/Minor lacerations
26	Transfer of chemicals into the admixture tanks	Overheating due to the engine breakdown and chemical spill during maintenance	Skin/Eye diseases

(*continued on next page*)

Table 4 (*continued*).

No.	Activity	Failure cause and mode	Failure effect
27	Admixture storage for the vehicles to take along	Chemical spill during admixture intake	Skin/Eye diseases
28	Works nearby the bucket	Falling into the bucket pit	Serious injury
29	Works nearby the bucket	Dropping the bucket while working in the bucket pit	Serious injury
30	On-site Truck/Heavy Construction Equipment Circulation	Crushing when the walk way is not split	Serious injury
31	Interference with the hydraulic failures without taking the necessary precautions	Hydraulic fluid splash	Skin/Eye diseases
32	The greasy surface stepped when the operations on the machine, were being conducted	Slipping when stepped on the oil	Minor lacerations
33	Working with unshielded belts, wheels and chains	Catching up one's limbs in the unshielded equipment	Serious injury
34	Fixed Pump Mounting on-site	Falling from the construction during pipe installation	Serious injury
35	Fixed Pump Mounting on-site	Sticking one's hand when using the hand tools	Smash/Minor lacerations
36	Use of generator on-site	Exposure to the diesel supply for the generator	Skin/Eye diseases
37	Use of generator on-site	Exposure to the electric shock when interfering with the generator panel	Serious injury
38	Navigation of the trucks in traffic	Accidents occurring as the speed limit is exceeded	Serious injury
39	Navigation of the trucks in traffic	Accidents occurring when the vehicle is not used according to the road condition	Serious injury
40	On-site traffic	Accidents occurring due to the violation of on-site traffic rules	Serious injury
41	On-site mobile pump use	Catching up one's limbs in the boiler during mobile pump cleaning	Loss of limb
42	On-site mobile pump use	Crashing into the equipment during on-site boom-opening	Financial loss
43	On-site mobile pump use	Vehicles slipping because the parking brake is not engaged or the wheels are not chocked after mobile pump parking.	Financial loss
44	On-site transit-mixer use	Boiler rotating when there is a cleaning in the transit-mixer boiler	Serious injury
45	On-site transit-mixer use	Vehicle accidents occurring as the vehicle is left in working condition	Financial loss
46	On-site transit-mixer use	Vehicles slipping because the parking brake is not engaged or the wheels are not chocked after transit-mixer parking	Serious injury

questionnaire were prepared by specialists in occupational safety at ready-mixed plants; most were environmental engineers. One question was added to the surveys which were prepared for each department and the accidents' risks were enquired of the employees who met in the unit.

One question was added to the surveys. It asked where the employees were in the last 5 years or they thought them as possible. Each survey was answered by three employees from each relevant unit.

Average values were determined for the severity, occurrence, and detectability of each problem. The reliability of the surveys was demonstrated by the similarity of values given by the respondents at a given department. The riskiest items were from departments in the ready-mixed facilities. They were production plant, workshop and maintenance, dumping grounds, materials transportation, and storage, in that order. The failure modes, their reasons, and the effects on these departments are given in Tables 4–7. The less risky departments were laboratory, auxiliary facilities, administrative office, social facilities and recycling facilities in that order. The error types, their reasons, and the effects on them are given in Appendices A1–A5. Their values of crisp RPN and fuzzy RPN were calculated with average values obtained from three employees and transferred to the Appendices A6–A10.

Table 5
Potential failure modes, effect and causes in workshop and maintenance.

No.	Activity	Failure cause and mode	Failure effect
1	Intra-storage cleaning, vehicle under frame lubrication	Depending on cold, hot or greasy surfaces	Injury
2	Intra-storage cleaning, vehicle under frame lubrication, channel cleaning, grinding the pump booms, flange welding for pump conduit pipes, intra-boiler sheet measurement of the concrete transit-mixers	Pieces possible to leap/bolt	Injury, death
3	Grinding the pump booms, grinding by spiral stone, cutting pump conduit pipes	Depending on explosion(stone, rubber, etc.)	Injury, death
4	Use of pressure washing machine	Noise related issues (health, etc.)	Hearing loss
5	Cleaning of the nozzles by concrete solvent	Depending on leakage/spillage	Injury
6	Channel cleaning	Problems arising from the inconvenience of the system	Neckache, backache
7	Repair of pump, mixer, hydraulics	Section/material with cutting or sharp edge	Injury
8	Channel cleaning	Carrying by hand or hand tools	Neckache, backache
9	Pump, mixer mounting and disassembly, cutting the materials by oxygen welding, intra-boiler sheet measurement of concrete transit-mixers	Dusty/gaseous section (welding gas)	Respiratory disorder
10	The entire process	Depending on the lack/excess of lighting	Health problems
11	Piece cutting by oxygen welding	If there is a closed area, (gas entrapment, suffocation etc.)	Injury, death
12	The entire process	If there is a heavy vehicular, (health, exhaust gas etc.)	Serious injury, death
13	Grinding by spiral Stone, cutting pump conduit pipes	If there is de-energizing/energizing activity (electric shock etc.)	Serious injury, death
14	Cleaning of the nozzles by concrete solvent	If there is a work including chemical materials (acid, etc.)	Injury
15	Piece cutting by oxygen welding	If there is a recoil of the material, (gun trigger recoil etc.)	Injury
17	Painting the concrete pump booms	Chemical factors (paint smoke etc.)	Serious health problems
18	Assembly and disassembly of concrete transit-mixers' boiler pulleys, flange welding for pump conduit pipe	Working with machinery and rotating components (squeezing, crushing etc.)	Loss of limb
19	Channel cleaning, transport of incoming pieces	Working with repeated movements (standing/sitting all the time etc.)	Neckache, backache
20	The entire process	Failure possibility and changing frequency of the equipment/devices that we work with, and the significance level of the device in terms of (cost. etc.)	Halt of production
21	Maintenance,repair	Working at height	Serious injury, death
22	Use of pressure welding machine	Depending on working with pressure water	Serious injury, death
23	Piece cutting by oxygen welding	Accident risk depending on fire	Serious injury, death
24	The entire process	Accidents that might happen during maintenance and repair	Serious injury

3.2. *Proposed fuzzy FMEA framework*

The proposed risk assessment methodology including fuzzy FMEA for concrete manufacturing is given in Fig. 2. For this study, the fuzzy FMEA method was preferred because of the disadvantages of the classical method, as described in the Introduction. The potential failure modes were determined by the occupational safety specialists and the company's employees. Then, RPN and fuzzy RPN values were calculated from the survey responses. Suggestions were given for decreasing risk from the potential failure modes that received high fuzzy RPN and RPN values.

Fuzzy RPN values were determined after a survey was conducted with these suggestions. Lastly, improved rates which were expected for each potential failure mode were calculated. Thus, the risky regions were identified

Table 6
Potential failure modes, effect and causes in dumping grounds.

No.	Activity	Failure cause and mode	Failure effect
1	Site selection and installation of the pump	Pump legs tilting or overturning because they do not lie flat on the ground	Injury, death
2	Site selection and installation of the pump	Picking a wrong site for the pump to be installed	Injury, death
3	Adjustment of surface and wedge suitable for pump legs	The ground on which the pump will be installed, must be solid	Injury, death
4	Adjustment of surface and wedge suitable for pump legs	Pump legs tilting or overturning as they slide down from the wedge	Injury, death
5	Opening the boom	Passing the boom to the unseeable spots	Injury, death
6	Opening the boom	Paying no attention while opening or clearing the boom	Injury, death
7	Opening the boom	Stress on the pistons because the booms are not opened in turn	Injury, death
8	Opening the pump legs	Pump legs tilting or overturning as they are not opened completely	Injury, death
9	Paying no attention to high-tension lines while removing the boom	Exposure to electric shock	Injury, death
10	Transfer of concrete from the mixer to the pump	Being stuck between the vehicles as they move because of the slope	Injury, death
11	Pouring of concrete	Pump legs sinking, tilting or overturning due to ground-related problems	Injury, death
12	Not securing the pump and its perimeter when pouring the concrete	Traffic accident	Injury, death
13	The absence of safety pin on the pipe clamps, pipes being damaged	Clamp, opening and popping out	Injury, death
14	The absence of safety pin on the pipe clamps, pipes being damaged	Pipe burst	Injury, death
15	Pump operator moving away from the vehicle while the pump is installed	Unauthorized use	Injury, death
16	Clearing the boom	Crash, tripping or friction due to fatigue, insomnia and inadequate attention	Skin diseases
17	Clearing the boom	Oil spilling around in the event of a hydraulic hose burst or boom slipping	Injury, death
18	Clearing the boom	Boom fall due to boom piston stripping	Injury, death
19	Clearing the boom	Uncontrolled movement of the booms due to the failure in ratchet valve	Skin diseases
20	Clearing the boom	The fall of residual concrete from the edge hose of the pump	Injury, death
21	Opening the boom before the legs during pump cleaning	Tilting, overturning	Injury
22	Internal cleaning of pump concrete pipes	Ball jamming, concrete water splashing around	Injury
23	Using cell phone in the vehicle	Losing control of the vehicle, traffic accident due to the lack of attention	Injury, death
24	Walking around the building site	Material fall	Injury, death
25	Walking around the building site	Nail-pricked foot	Injury, death
26	Staying in the traffic for a long time	Overfatigue, traffic accident due to the lack of attention	Injury, death
27	Use of maintenance-free vehicle	Traffic accident due to vehicle breakdown	Injury, death
28	Maintenance and control when the pump and mixer are in motion and working condition	Mobile mechanical parts	Injury, death
29	Approaching to the edges of the mould when working at heights	Falling down from height	Injury, death

(*continued on next page*)

and eliminated from the process of concrete production, as FMEA and artificial intelligence techniques were used together.

Table 6 (*continued*).

No.	Activity	Failure cause and mode	Failure effect
30	Moving the machine while the pump legs or boom are open	Pump legs crashing or bending	Injury, death
31	The presence of safety warning and signs on site	Not complying with the warning and caution plates hung on different spots on site	Injury, death
32	The presence of safety warning and signs on site	The lack or wrongness of the caution plates on site	Injury, death
33	The misuse of machinery	Use of pump boom in the works apart from its duty	Injury, death
34	Failing to comply with the speed limits on site	Traffic accident	Injury, death
35	Vehicle cleaning	Vehicles moving away from the facility before they are cleaned	Injury, death
36	Vehicle cleaning	Traffic accidents that are possible to occur as the concrete residues are discharged into the construction site or outside the sites apart from those that the operator points out	Injury, death
37	Taking the necessary precautions and having the necessary tools present in the vehicles	Non-use of safety belt while travelling in the vehicle	Injury, death
38	Taking the necessary precautions and having the necessary tools present in the vehicles	Installing the vehicle cycle rails	Injury, death
39	Taking the necessary precautions and having the necessary tools present in the vehicles	Not having a fire extinguisher, first-aid kit etc. present inside the vehicle	Injury, death
40	Taking the necessary precautions and having the necessary tools present in the vehicles	Not having vehicle safety mirrors	Injury, death
41	Having the safety warning and signs present in the vehicles	The absence of reflector on the back side of the vehicle and on the pump legs	Injury, death

Table 7
Potential failure modes, effect and causes in materials transportation and storage.

No.	Activity	Failure cause and mode	Failure effect
1	Material handling by construction equipment (caterpillar)	Traffic accident arising from violating the on-site traffic rules	Injury, death
2	Material handling by construction equipment (caterpillar)	Use of unsafe vehicle	Injury, death
3	Material handling by construction equipment (caterpillar)	The absence of/failure to operate the caterpillar warning system	Injury, death
4	Material handling by construction equipment (caterpillar)	Employing unauthorized personnel	Injury, death
5	Material handling by construction equipment (caterpillar)	Loader operator being exposed to dust	Upper respiratory diseases
6	Material handling by construction equipment (caterpillar)	Loader operator being exposed to noise	Hearing loss
7	Material handling by construction equipment (caterpillar)	Vehicle rollover because the aggregate bunker ramp road is not secured	Injury, death
8	Material handling by aggregate band distributor	Material fall	Injury
9	Material handling by aggregate band distributor	Dust formation during transport	Upper respiratory diseases
10	Material handling by aggregate band distributor	The absence of emergency stop and protectors on the band relays	Injury
11	Material handling by aggregate band distributor	The absence/deficiency of rails on the walking platform, and slippery ground	Injury, death
12	Material handling by aggregate band distributor	The absence/deficiency of rails on the walking platform	Injury, death

(*continued on next page*)

Table 7 (*continued*).

No.	Activity	Failure cause and mode	Failure effect
13	Material handling by aggregate band distributor	Stumbling and falling, or slipping due to the presence of materials and tools on the band conveyor walking platforms	Injury, death
14	Material handling by aggregate band distributor	The absence of belt guards on the band conveyor motors	Injury, death
15	Aggregate bunker edge cleaning	Falling down due to the absence of bunker grill and to the excess of gap aperture	Injury, death
17	Aggregate under-band cleaning	Head crash in the places where there is low height	Injury
18	Transfer of chemical admixture into the tank	Spread of admixture around the site due to the burst of admixture discharging tanks' hose	Skin diseases
19	Transfer of chemical admixture into the tank	Popping out pump	Injury
20	Transfer of chemical admixture into the tank	Admixture tank overflow during filling	Skin diseases
21	Use of Bigbag chemical admixture tank	Improper stacking and insufficient space for stacking	Skin diseases
22	Transport of aggregate to the facility	On-site traffic accidents likely to happen during the trucks' manoeuvres	Injury, death
23	Transport of aggregate to the facility	Failure/fracture of damper piston	Injury, death
24	Transport of aggregate to the facility	Being trapped under the aggregate as the aggregate trucks start moving with open dampers	Injury, death
25	Transport of aggregate to the facility	Dust emission, material fall because of non-using of canvas in the vehicles when they are loaded with material	Upper respiratory diseases
26	Transport of aggregate to the facility	Traffic accident occurring due to the violation of on-site traffic rules	Injury, death
27	Cement trailers' entrance into the facility	Traffic accident occurring due to the violation of on-site traffic rules	Injury, death
28	Cement trailers' entrance into the facility	Traffic accident likely to happen during manoeuvre because of the inadequacy of the on-site working space	Injury, death
29	Cement trailers approaching to the silo and establishing connection for discharge	Cement trailers crashing into the drain pipe because of approaching to the silos incautiously, into which they will discharge.	Injury, death
30	Cement trailers approaching to the silo and establishing connection for discharge	Burst of flexible rubber pipes due to wearing, which are connected to the cement trailers for discharge	Injury, death
31	Cement discharge into the silo	Cement spreading around as the flange on the edge of the flexible rubber pipe is not bound to the drain pipe completely and tightly during discharge into the cement trailers	Upper respiratory diseases
32	Cement discharge into the silo	Exposure to electric shock because of receiving energy into the compressor on the cement trailer after the connections are made	Injury, death
33	Cement discharge into the silo	Covers popping out or breaking when they are opened to clear the blockage with high pressurization during discharge into the silo, and to discharge the compressed air remaining inside the cement trailer	Injury, death
34	Cement discharge into the silo	Exposure to electric shock because the electrical connection of the cement trailer is not proper	Injury, death
35	Cement discharge into the silo	Burst of cement trailer's discharge hose	Injury, death
36	Cement discharge into the silo	Burst of the filter during discharge	Injury, death

4. Fuzzy FMEA based risk assessment of RMCP

4.1. Fuzzy FMEA

The Mamdani fuzzy inference system was used in this study to determine the risk priority numbers. In the proposed method, severity, occurrence, and detectability were treated as fuzzy variables. They were divided into a

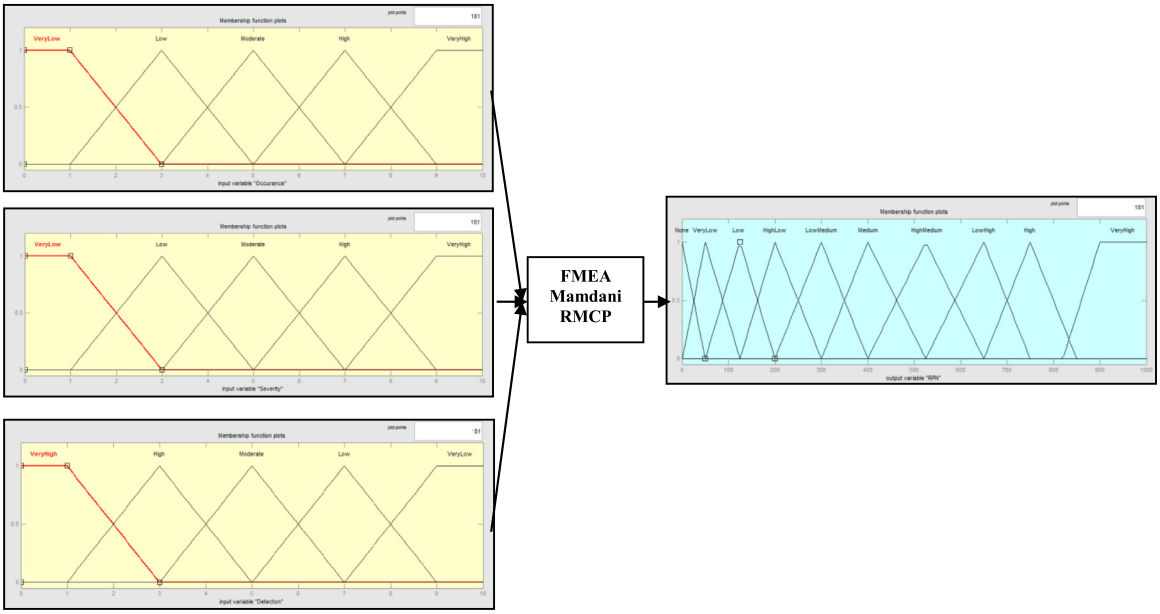

Fig. 3. Block diagram used for fuzzy modelling.

number of subsets with simple trapezoidal fuzzy membership functions taking into account the levels of the factors in [1,29]. Each membership function had five levels for severity (S) (very low, low, moderate, high and very high); occurrence (O) (very low, low, moderate, high and very high); and detectability (D) (very high, high, moderate, low and very low). They are shown in Fig. 3. Each membership function had 10 levels for RPNs (none, very low, low, high low, low medium, medium, high medium, low high, high, and very high)

In this stage of the study, the fuzzy-logic-based model was applied to calculate the priority of the risks in the questionnaires. The fuzzy rules were written for that purpose. Fig. 3 shows how we built the fuzzy logic-based algorithm model by using the FL toolbox in MATLAB®version 2014b. The FL model had three input parameters and one output parameter [24]. The rule editor the list of the rules that described the behaviour of the system [24,39]. 122 questionnaires have been performed in concrete companies. The numerical answers given to the surveys were made verbal by the authors and turned into rules. Thus, it was tried to create a more balanced list of rules. Workers in that area score the risk of accidents between the numbers 1 and 10 in terms of severity, occurrence and electability. Later, these values were converted into a rule by the authors by taking into account the membership functions. 122 × 4 matrices are added to Appendix B. Fig. 4 shows a part of formed rules in the rule editor and all of the written rules based on the worker suggestion were shown in Appendix B. The activity and weight of the rules or how individual membership function shapes affected the results could be seen on the viewer window (see in Fig. 5).

Furthermore, the stability of the RPN was analysed by the surface viewer or surface map [24,39]. The surface viewer or the surface map shows the behaviour of the criteria as detection and occurrence in Fig. 6. The surface viewer also gives information about how to design the fuzzy model.

The RPN and fuzzy RPN values with crisp FMEA (Eq. (1)) and fuzzy FMEA for the production plant, workshop and maintenance, dumping grounds and transportation and storage are given in Tables 8–11. A risk-decreasing activity was suggested for failure modes which received fuzzy RPN values above 87.50 (Tables 8–11). A second survey was given to three relevant employees in each department. The questions asked the employees to provide severity, occurrence, and detectability values for a problem if the risk-decreasing suggestions were applied by the company. The averages of the crisp RPN and fuzzy RPN values from the second survey are shown in Tables 8–11.

4.2. Prediction of anticipated improvement rates

For each failure mode, an expected improvement rate was calculated as fuzzy RPN values were received for the case that currency issue and suggested risk-decreasing events were applied. The expected improvement rates for

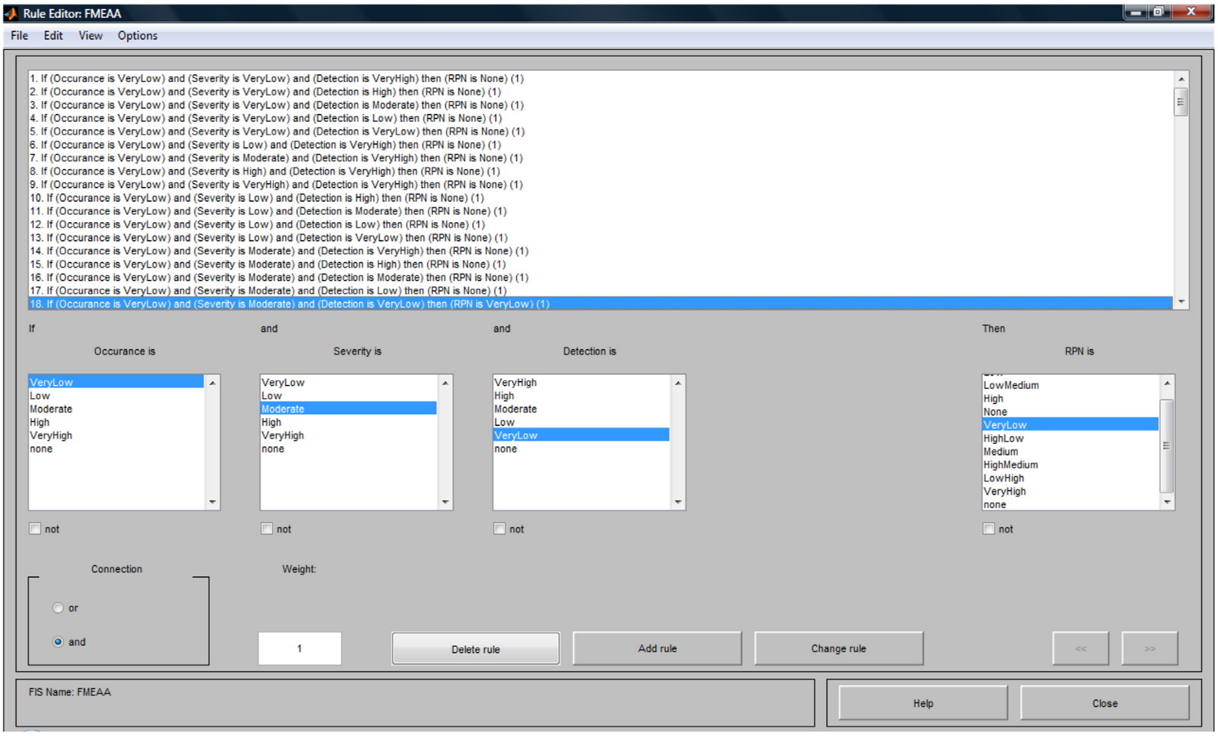

Fig. 4. A part of the formed rule editor.

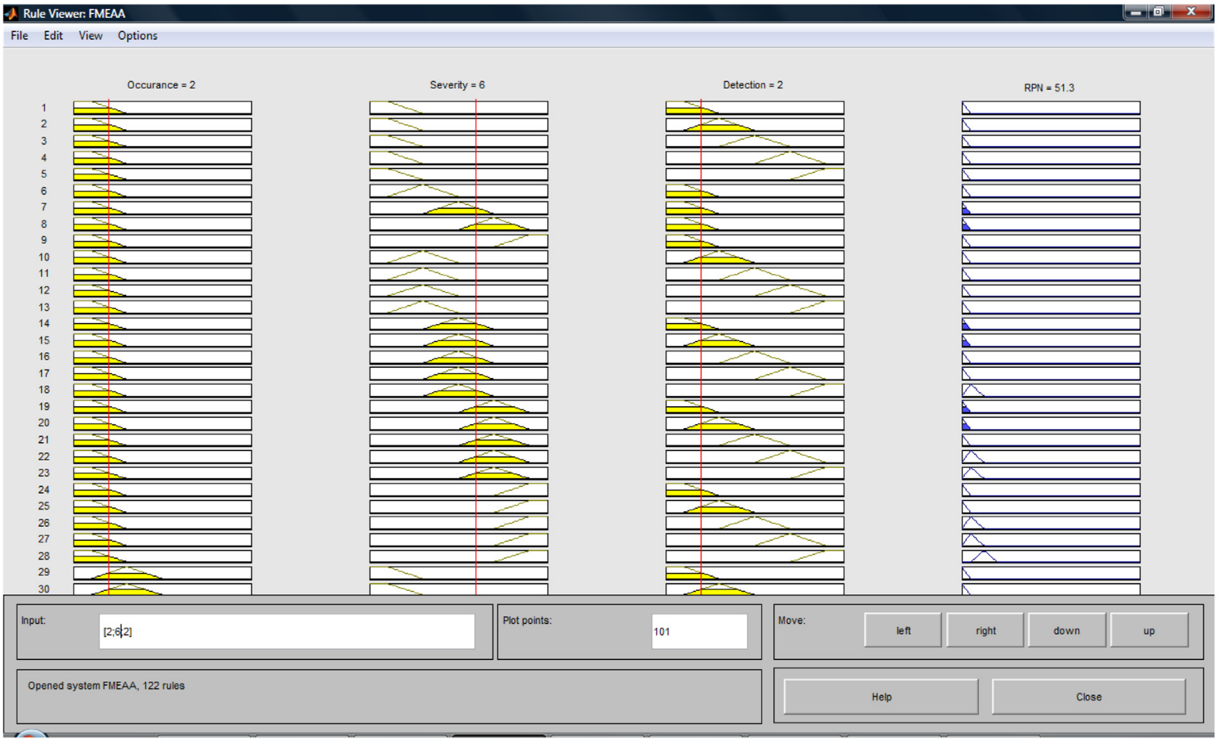

Fig. 5. A part of the rule viewer used for modelling the RPN.

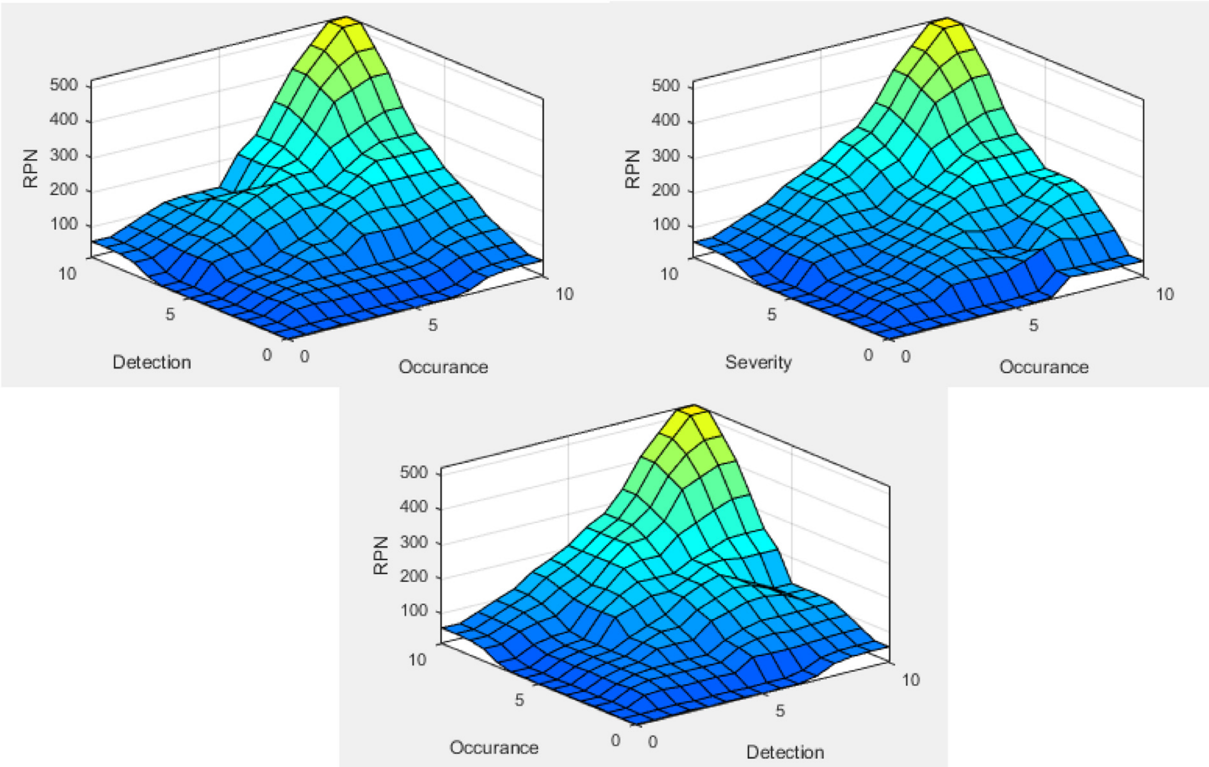

Fig. 6. The sample surface viewer or surface map for RPN (122 rules).

the failure modes that received high fuzzy RPN values are shown in Figs. 7–13. An anticipated improvement rate was calculated using Eq. (3) benefit from fuzzy RPN and improved fuzzy RPN (IRPN). Fuzzy RPN represents the company's current risk calculation, and fuzzy IRPN represents the risk calculation that will be achieved when the firm implements preventive actions.

$$Anticipated\ Improvement\ Rate = \left(\frac{FuzzyRPN - FuzzyIRPN}{FuzzyRPN}\right) * 100 \tag{3}$$

The expected improvement rates for the production plant, workshop and maintenance, dumping grounds and transportation and storage are given in Figs. 7–10.

The expected improvement rates for the utilities, administrative office, social facility, quality control laboratory, and wastewater pool and recycling facilities are shown in Figs. 11–13.

4.3. The evaluation of the risk assessment findings

The highest potential failure mode identified by an FMEA application at a concrete plant that constituted the most critical part of the ready-mixed concrete facility was 'Trapping limb to tambour or rolls during the cleaning upper-side of band' (with a fuzzy RPN value of 425). When the relevant employees were asked, they stated that having a plan for the cleaning procedure would decrease risk. The International Labour Organization defines an occupational accident as an event which is undesigned, unknown, and uncontrolled and would be harmful to the environment. If events that included risk were identified as being preplanned, the current accident risk would decrease at the company [24]. It was agreed for this failure modes that a checklist was to be made by specialists and an alternative plan would prevent this misfortune if workers adopt the checklist. If the recommended risk-reducing activity were implemented by the company, it was determined that the new fuzzy RPN value would decrease to 51.3 and the expected improvement rate would reach 87.93% (see Fig. 7 and Table 8).

Table 8
Fuzzy RPN and RPN values in production plant.

No.	Before planned actions							Planned actions	After planned actions				
	O	S	D	RPN	P[a]	FRPN	P		O	S	D	IRPN	IFRPN
1	3	9	4	108	14	97.5	14	The use of appropriate machine and equipment to work at high places	2	9	2	36	51.3
4	6	9	7	378	1	425	1	Cleaning under-side of band is made within a plan which is preplanned	3	9	2	54	51.3
5	5	6	5	150	5	125	10	It should be on an appropriate distance while working	2	6	3	36	51.3
6	6	7	3	126	9	125	11	Assignment of an indicator to arrange vehicles' traffic in facility	2	7	2	28	51.3
7	6	4	4	96	17	135	9	Assignment of an indicator to arrange vehicles' traffic in facility	2	4	3	24	51.3
9	5	8	3	120	11	97.5	15	Warning personnel and putting a warning sign in plant	2	8	2	32	51.3
11	5	6	3	90	20	97.5	16	The use of appropriate equipment and machine should be provided to work at high places , personnel should be informed	2	6	3	36	51.3
12	6	5	4	120	12	145	5	Employees who work at the region should use dust-mask	2	5	3	30	51.3
18	6	6	3	108	15	97.5	17	The use of seat-belt on works which are made at high places	2	6	2	24	51.3
19	5	6	4	120	13	97.5	18	Training of personnel, making setting in a plan	1	6	2	12	16.7
20	8	3	4	96	18	148	4	Putting informing signs related to lifting weights correctly	4	3	3	36	16.7
21	4	6	6	144	6	145	7	Making regular-controls for setting of plant coverings	2	6	3	36	51.3
25	7	8	3	168	3	172	3	Putting warning sign for regular control of coupling protection	3	8	2	48	51.3
26	5	5	5	125	10	125	12	The use of appropriate protective equipment on care works	2	4	3	24	51.3
28	4	6	4	96	19	97.5	19	Putting warning sign, informing personnel	2	6	3	36	51.3
30	5	8	4	160	4	145	8	Arranging pedestrian way and use of indicator	2	8	3	48	51.3
33	5	8	6	240	2	222	2	Hanging information sign around equipment	2	5	3	30	51.3
34	5	6	2	60	21	88.3	21	The use of seat-belt on works which are made at high places	1	6	2	12	16.7
40	5	7	4	140	7	125	13	Assignment of an indicator to arrange vehicles' traffic in facility	2	7	2	28	51.3
41	4	8	4	128	8	145	6	Training of personnel, making setting in a plan	2	8	3	48	51.3
42	5	5	4	100	16	97.5	20	Getting other equipments to necessary distance during opening boom	2	5	3	30	51.3

[a]O: Occurrence, S: Severity, D: Detectability, P: Prioritization, RPN: Risk priority number, FRPN: fuzzy risk priority number, IRPN: Improved risk priority number, IFRPN: Improved fuzzy risk priority number.

Another high-potential failure mode was determined as 'trapping limb to nonprotected equipment' while it was working with unprotected wheel and chains; it had a fuzzy RPN value of 222. To reduce that risk, it was suggested that protective equipment should be used and warning signs should be hung near these devices. If this regulator event would occur, the new fuzzy RPN value from the second survey was 51.3, and the expected improvement rate was 76.89. Another high-potential failure mode was 'contact with rotary parts as in the absence of coupling protection'. This would occur during the use of additive motors; it had a fuzzy RPN value of 172. It was suggested that appropriate material for protecting coupling would be a risk-decreasing event. Moreover, it was suggested that a warning sign be hung in working areas as a reminder to employees to see if there was coupling protection on additive motors (see Fig. 7 and Table 8).

Table 9
Fuzzy RPN and RPN values in workshop and maintenance.

No.	Before planned actions							Planned actions	After planned actions				
	O	S	D	RPN	P[a]	FRPN	P		O	S	D	IRPN	IFRPN
1	7	8	2	112	5	145	5	The use of protective glove	2	5	2	20	51.3
2	7	8	3	168	2	172	4	Making procedures of cleaning, oiling and grinding in a plan, sharing and controlling plan with employees	3	8	2	48	51.3
3	8	9	2	144	3	194	3	Making grinding procedures in a plan, sharing and controlling plan with employees	3	8	2	48	51.3
4	6	8	5	240	1	222	1	The use of ear-protective by employees in the region and hanging warning sign	2	5	3	30	51.3
7	4	6	4	96	8	97.5	8	Making grinding procedure with spiral stone by experienced employees	1	6	2	12	16.7
10	4	7	3	84	10	97.5	9	Inadequacy should be removed with artificial lighting	2	4	2	16	51.3
12	4	4	4	64	12	88.3	12	An indicator should be assigned to regulate intensive traffic	1	4	2	8	16.7
13	4	8	2	64	13	88.3	13	Equipment should be made as appropriate for contact of employees	1	5	2	10	16.7
15	4	6	3	72	11	97.5	10	The use of appropriate protective material	2	3	2	12	16.7
16	7	8	2	112	6	145	6	The use of appropriate protective mask	3	5	2	30	51.3
17	4	6	4	96	9	97.5	11	Making montage and demontage procedures by experienced employees as they are preplanned	2	6	2	24	51.3
19	7	8	2	112	7	145	7	Making cost analysis for changing often-changed devices with more qualified devices	2	7	2	28	51.3
20	5	7	4	140	4	222	2	It should be worked with a seat-belt	5	2	2	20	16.7

[a]O: Occurrence, S: Severity, D: Detectability, P: Prioritization, RPN: Risk priority number, FRPN: fuzzy risk priority number, IRPN: Improved risk priority number, IFRPN: Improved fuzzy risk priority number.

Some failure modes had fuzzy RPN values below 162.5, so they were given low priority. They included: carriage of weights by lifting in hand, exposure to powder or chemicals, quick discharge of concrete due to the disproportion of plant coverings, the smash due to the non-disjunction of pedestrian way and respective warning signs, protective equipment usage, making studies in plan, assigning an indicator and the appropriate equipment to work at high place for the appropriate carriage for falling due to the working at high places, personnel training. The expected improvement rate was 45% higher than the failure modes which involved all potential accident risks (see Fig. 7 and Table 8).

The highest-risk primary failure modes were, in order: health problems which arose from noise, working at a high place, rebounding and falling parts in the workshop, and maintenance which was one of intensive working regions in the ready-mixed concrete facility. Suggestions for these cases were: use ear protectors, use protective equipment and make grinding procedures in a plan, share the plan with employees, and prepare a control plan. With those suggestions, the expected improvement rates were 76.89, 92.48, 73.56, and 70.17%, respectively (see Fig. 8 and Table 9).

The most important failure modes at the dumping grounds were falling from a height (with a fuzzy RPN value of 625), traffic accident and rolling movable mechanical portions (with a fuzzy RPN value of 259), pump rollover, pipe explosion, unsound ground where pump would be established, and electric shock (with a fuzzy RPN value of 194), opening and flying off handcuffs and the unauthorized use of devices (with a fuzzy RPN value of 172). The following situations were suggested to address those failure modes: stretching the building net to floors where it was worked, regulation of vehicular traffic in facility by a controller, working with a safety harness, putting a wedge at the underside of pump stays, inspecting pumps every three months, electrical ground application, control of handcuffs' safety pin, and personnel training. With those suggestions, the expected retrofit rate which was over 70% was obtained (please see Fig. 9 and Table 10).

Table 10
Fuzzy RPN and RPN values in dumping grounds.

No.	Before planned actions							Planned actions	After planned actions				
	O	S	D	RPN	P[a]	FRPN	P[a]		O	S	D	IRPN	IFRPN
1	5	9	4	180	7	148	11	Making a check-list related to establish pump, making an installation procedure with this check-list while pump is installed	2	8	2	32	51.3
2	5	7	5	175	9	125	14	Making a check-list related to establish pump, making an installation procedure with this check-list while pump is installed	2	7	3	42	51.3
3	7	8	3	168	10	172	7	Ground is controlled by expert workers	3	7	2	42	51.3
4	6	8	4	192	4	194	4	Controlling wedge and settlement of wedge by expert workers	1	8	2	16	16.7
9	7	8	3	168	11	172	8	Application of earthing should be made	2	7	2	28	51.3
11	4	5	4	80	16	97.4	15	Making a check-list related to establish pump, making an installation procedure with this check-list while pump is installed	1	5	3	15	13.3
12	8	9	3	216	2	259	2	An indicator should be assigned to regulate vehicles' traffic in facility	2	8	2	32	51.3
13	4	5	7	140	13	172	9	Handcuffs' safety pin should be controlled by expert workers, application of handcuffs pin control, opening and gathering boom should be added on check-list	1	5	2	10	16.7
14	6	8	4	192	5	194	5	Pipes should be controlled with three-month periods	1	7	2	14	16.7
15	6	6	5	180	8	172	10	Personnel training	2	6	2	24	51.3
17	6	6	4	144	12	145	13	Protective material should be used	5	2	2	20	16.7
20	7	5	4	140	14	148	12	Protective material should be used	6	1	2	12	16.7
24	6	3	6	108	15	97.4	16	Warning sign should be put	2	3	4	24	51.3
25	4	3	4	48	18	88.3	18	Vaccine should be made regularly	1	1	3	3	13.3
27	5	7	2	70	17	95.4	17	An indicator should be assigned to regulate vehicles' traffic in facility	2	6	2	24	51.3
28	8	9	3	216	3	259	3	It should be worked with seat-belt	6	2	2	24	51.3
29	8	10	7	560	1	625	1	Building safety net should be put in floors where it is worked	2	1	2	4	16.7
31	6	8	4	192	6	194	6	Personnel should be informed regularly	2	7	2	28	51.3

[a]O: Occurrence, S: Severity, D: Detectability, P: Prioritization, RPN: Risk priority number, FRPN: fuzzy risk priority number, IRPN: Improved risk priority number, IFRPN: Improved fuzzy risk priority number.

The failure modes which would occur during transportation and storage were: traffic accidents (with a fuzzy RPN value of 259), the occurrence of dust (with a fuzzy RPN value of 208), and the explosion of cement trailer discharge hose (with a fuzzy RPN value of 194). The suggested risk-decreasing events were to assign traffic by a controller, use appropriate protective equipment, regularly inspect the discharge hose, and personnel training that emphasizes being careful. With those suggestions, the expected improvement rates were over 73% (see Fig. 10 and Table 11).

The failure modes which received high fuzzy RPN values on utilities were, respectively: the explosion of a compressor, exposure to chemicals or dust, and air leak. The following remedies were suggested: do not place compressors near other devices, using a filtered dust mask, and the device change with a periodical control if it is necessary. With those suggestions, the expected improvement rates were over 76% (see Fig. 11 and Table A.6). Not using an appropriate personal protector and exposure to traffic accidents and chemicals were failure modes at the quality control laboratory (with a fuzzy RPN value of 174). The following remedies were suggested: personnel training, an employment and a traffic controller, and the use of protective equipment. With those suggestions, the expected improvement rates were over 70% (see Fig. 13 and Table A.9). At the wastewater pool and the recycling facilities, the only failure mode with a fuzzy RPN value over 162 was a poisonous insect sting. The suggestion to prevent this was regular disinfestations. The obtained anticipated improvement percentage was calculated as 80.19% (please see Fig. 13 and Table A.10).

Table 11
Fuzzy RPN and RPN values in materials transportation and storage.

No.	Before planned actions							Planned actions	After planned actions				
	O	S	D	RPN	[a]P	FRPN	[a]P		O	S	D	IRPN	IFRPN
1	5	6	4	120	13	97.4	16	An indicator should be assigned to regulate vehicles' traffic in facility	2	3	3	18	16.7
2	5	5	5	125	12	125	10	It should be worked with seat-belt	2	3	3	18	16.7
5	7	7	3	147	7	125	11	Making a check-list related to establish pump, making an installation procedure with this check-list while pump is installed	2	2	3	12	16.7
6	4	5	4	80	18	97.4	17	Making a check-list related to establish pump, making an installation procedure with this check-list while pump is installed	1	1	3	3	13.3
7	5	8	4	160	6	145	6	Ground is controlled by expert workers	2	6	2	24	51.3
9	7	5	5	175	4	208	2	Controlling wedge and settlement of wedge by expert workers	2	2	2	8	16.7
18	4	5	6	120	14	145	7	Application of earthing should be made	2	3	3	18	16.7
19	5	9	4	180	3	148	5	Making a check-list related to establish pump, making an installation procedure with this check-list while pump is installed	2	8	2	32	51.3
20	6	5	4	120	15	145	8	An indicator should be assigned to regulate vehicles' traffic in facility	2	4	2	16	51.3
22	7	8	5	280	1	259	1	Handcuffs' safety pin should be controlled by expert workers, application of handcuffs pin control, opening and gathering boom should be added on check-list	2	6	3	36	51.3
23	7	7	3	147	8	125	12	Pipes should be controlled with three-month periods	2	2	3	12	16.7
26	7	6	4	168	5	145	9	Personnel training	2	5	2	20	51.3
27	8	6	4	192	2	194	3	Protective material should be used	2	6	2	24	51.3
28	5	4	5	100	16	125	13	Protective material should be used	1	4	3	12	16.7
29	5	5	4	100	17	97.4	18	Warning sign should be put	2	3	3	18	16.7
30	5	7	4	140	10	125	14	Vaccine should be made regularly	2	6	2	24	51.3
34	6	7	3	126	11	125	15	An indicator should be assigned to regulate vehicles' traffic in facility	2	4	2	16	51.3
35	8	9	2	144	9	194	4	It should be worked with seat-belt	3	6	2	36	51.3

[a]O: Occurrence, S: Severity, D: Detectability, P: Prioritization, RPN: Risk priority number, FRPN: fuzzy risk priority number, IRPN: Improved risk priority number, IFRPN: Improved fuzzy risk priority number.

5. Discussion and conclusion

The highest potential failure mode during this study was falling from a height at dumping places. Stretching building net to floors where there is work was suggested to mitigate this kind of failure mode. The fuzzy RPN value for this failure mode reaches an acceptable level with this suggestion. There is a potential risk of falling from a height in a production plant and recycling with wastewater facilities. The use of seat-belts was suggested for these facilities. The second highest potential failure mode was trapping a limb in rotary portions in the production plant. The potential accident risk for trapping a limb to rotary portions occurs at other parts of a ready-mixed concrete plant. The suggestion to address this was to include protective equipment in the procedures for this activity. The third highest potential failure mode was a traffic accident in dumping places, the production plant, and laboratory areas, in addition to transportation and storage areas. So, it was suggested that two traffic controllers be employed at the ready-mixed concrete plant and assigned to the production plant and dumping places. With the suggestion, the potential of this failure mode was much decreased.

The fourth highest failure mode was health problems which arise from noise. As it is not possible to decrease the source of noise, it was suggested that employees use ear-protective equipment and that personnel be trained about the use of protective equipment. On the studies which were made, the problems from noise, at 8.7%, were among the factors that affected the physical and emotional health of employees [12]. Thus, it was suggested that personnel be informed about using ear-protective equipment as a risk-preventing event. Another high-potential

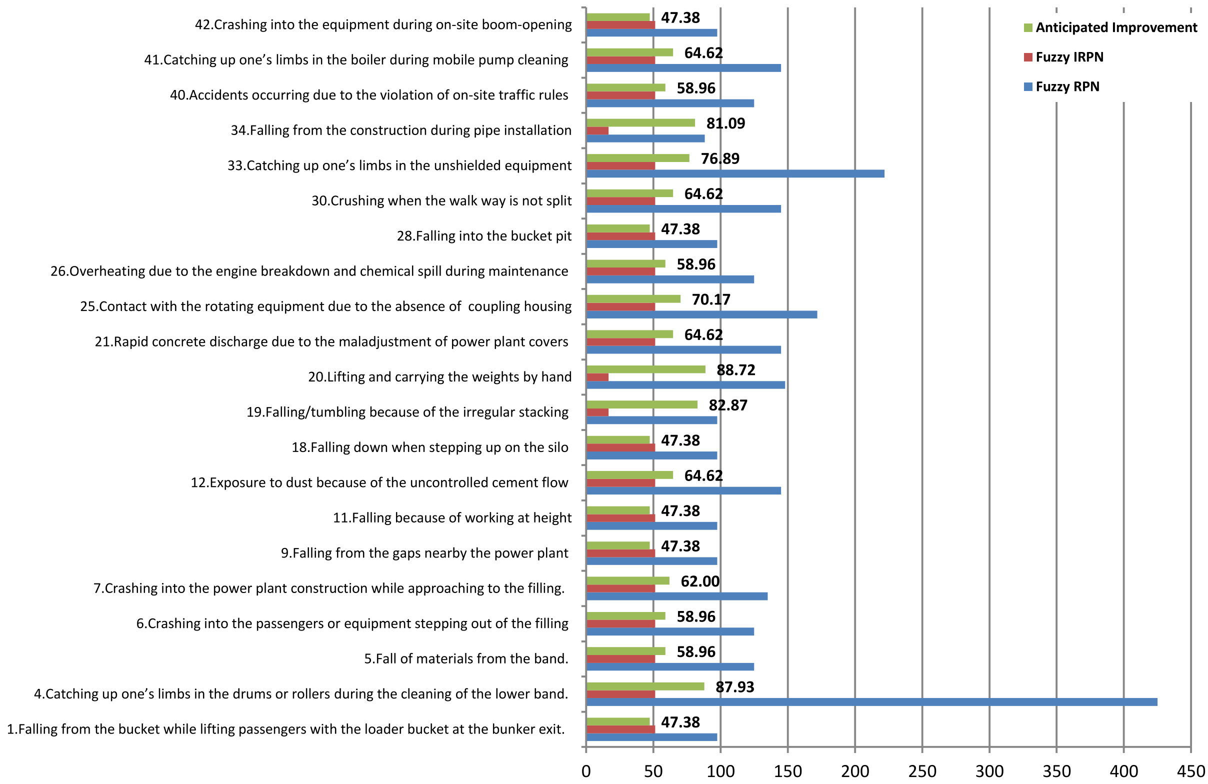

Fig. 7. Anticipated improvement rates in production plant if the proposed preventive measures are realized.

failure mode was exposure to dust or chemicals. On studies which were made, the exposure to chemicals, dust, gas, and fumes, at 14.1%, was another factor that affected the physical and emotional health of employees [12]. Thus, it was suggested that employees use appropriate personal protective equipment such as glasses, gloves, and masks, and it was also suggested that seminars be held to encourage workers to use them. Another point was to find potential failure modes related to workplace procedures, such as setting a compressor; cleaning, oiling, grinding, and montage/demontage works; and installing a pump. It was suggested that checklists be prepared as risk-decreasing event and to follow proper procedures. With that suggestion, the potential accident risk would decrease a great deal in those failure modes. The following cases were suggested for other potential error types: regular disinfestations to prevent poisonous insect stings; electrical grounding, routine control of electrical systems, and applying insulation to prevent electrical shock; and posting signs in offices that illustrate appropriate working and stance positions to address ergonomics problems.

This study which conducted at a ready-mixed concrete plant provided an opportunity to compare crisp FMEA and fuzzy FMEA methods. The point which first attracted attention for the research is that there were differences in the procedure to determine risk-prone activities which could be assigned fuzzy RPN values and crisp RPN values. For example, the RPN value for trapping a limb was 128 and the RPN value for violating traffic rules in the boiler during mobile pump cleaning in a production plant was 140. Thus, violating the traffic rules was a higher priority failure mode when crisp RPN value is considered. But the value of trapping a limb in the boiler was 140 and the value of violating traffic rules during mobile pump cleaning was 125 when fuzzy RPN values are considered. When fuzzy RPN laid down criteria, trapping a limb in a boiler is a higher potential failure mode. This result comes from not paying attention to relative importance in the crisp RPN method [26]. Another point is to calculate the slippery ground failure mode as 88.4 on social facilities [(O:4)*(S:4)*(D:2)] when its RPN value is 32 when evaluated by the fuzzy method. As expected, the fuzzy RPN value of a failure mode that received a very low RPN value using crisp FMEA revealed over 88.3 critical values. Indeed, the result is a risky failure mode for fuzzy FMEA when it is not a dangerous failure mode according to the crisp method. The O, S, and D values of RPN, which were disadvantages of

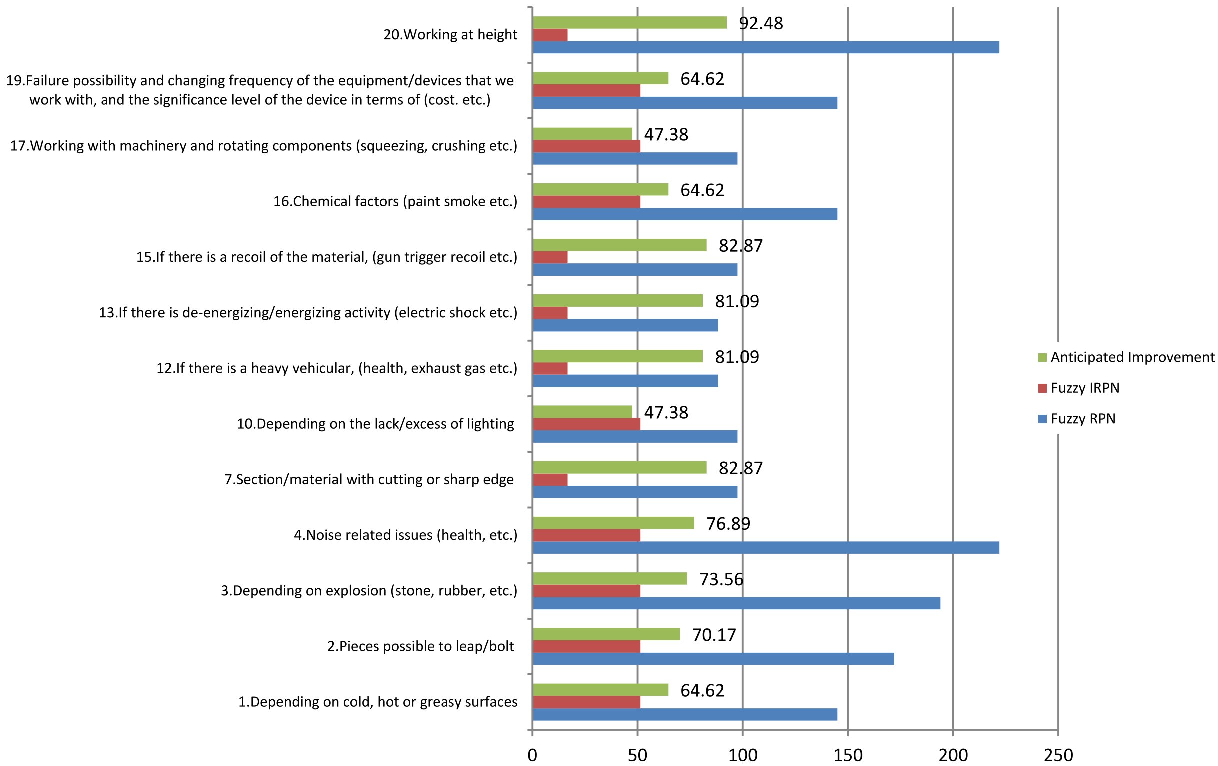

Fig. 8. Anticipated improvement rates in workshop and maintenance if the proposed preventive measures are realized.

crisp FMEA, received different combinations, which caused the result [30]. Fuzzy FMEA removes a disadvantage of classical FMEA as it allows using possibility, strength, and establishable values as subjective.

On the other hand, the ranking of failure modes by fuzzy RPN (given in column 5 of Table 12) and the ranking by the RPN, TOPSIS [4], and GRA [14] approaches are compared by taking the differences between them. Application details of the TOPSIS method and GRA method are provided in Appendices C and D [55]. The rankings and the differences in the rankings of failure modes are provided in Table 12. To determine the statistical significance of the differences in rankings by the fuzzy approach Spearman's rank-correlation test was used. In Spearman's test, the similarity of the rankings can be evaluated by two separate test statistics, r_s and Z, which are calculated with Eqs. (4) and (5) [41]. The test statistic r_s is a relative measure that varies from +1, implying a perfect positive relationship between the two sets of rankings, to −1, implying a perfect negative relationship between the two sets of rankings. The closer r_s is to + or −1, the stronger the relationship between rankings [55]. On the other hand, the test statistic Z is compared with a pre-determined level of significance α value. Generally, 1.645 which is the value that corresponds to the level of significance of $\alpha = 0.05$ is taken as the pre-determined value. Then, if the calculated Z value exceeds 1.645, it can be concluded that there is evidence of a positive relationship between the two sets of rankings [55]. Otherwise, the two rankings can be accepted as dissimilar. In the Eqs. (4) and (5), d_j represents the ranking difference of the feasible NTMP j, K is the number of feasible NTMPs to be compared.

$$r_s = 1 - \left[\frac{6 \times \sum_{j=1}^{K} \left(d_j\right)^2}{K \times \left(K^2 - 1\right)} \right] \tag{4}$$

$$Z = r_s \sqrt{K - 1} \tag{5}$$

In the 10, 13, and 14th rows of Table 12, the calculated r_s values are given as 0.691, 0.823, and 0.783 respectively. The calculated r_s value is close to +1 and the Z values are higher than 1.645. Both test statistics show that the rankings obtained by the RPN, FRPN, TOPSIS, and GRA approaches are statistically similar to each other. Based

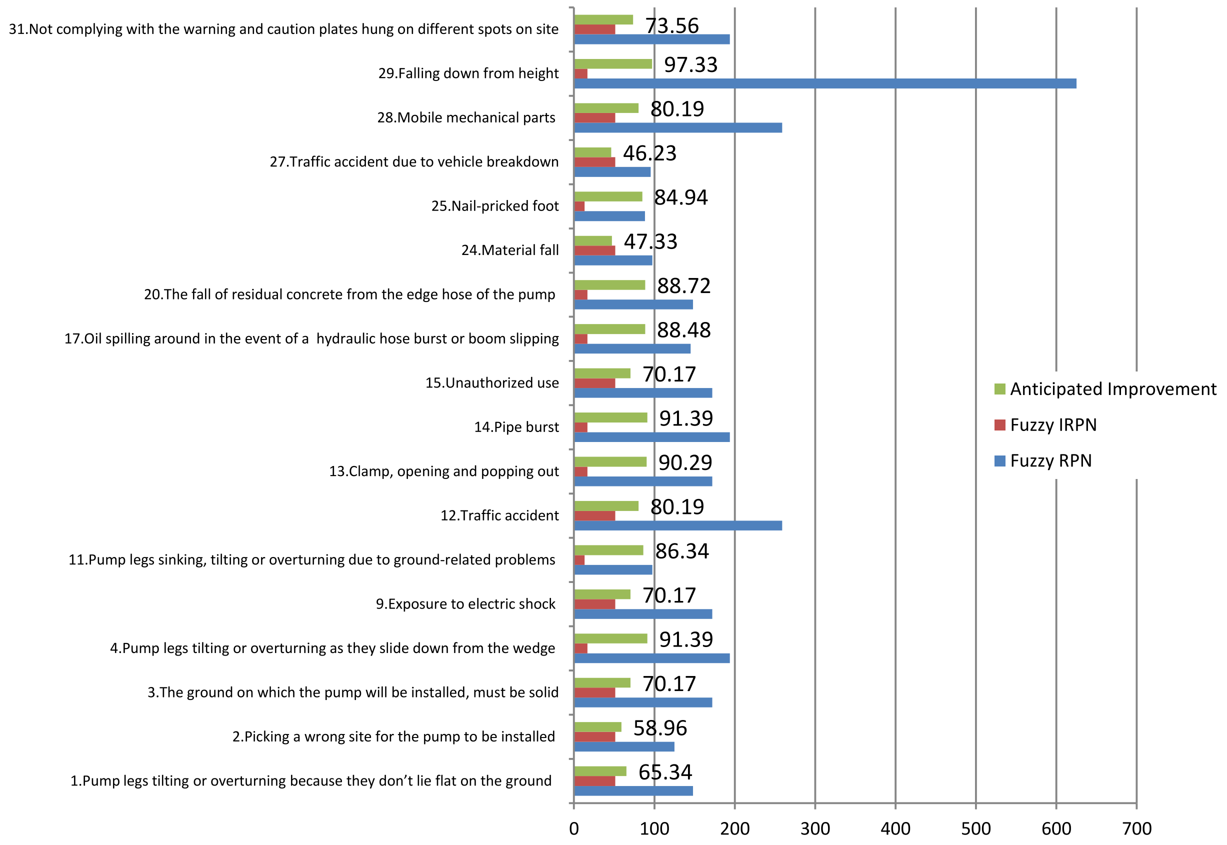

Fig. 9. Anticipated improvement rates in dumping grounds if the proposed preventive measures are realized.

on the statistical analysis of the ranking results it can be concluded that the fuzzy RPN provides ranking results that were statistically similar compared to the other approaches.

In this study, the possible failure modes were determined with specialists and employees at the ready-mixed concrete plant, the risk assessment of the current case was made especially with employees, the risk-decreasing suggestions were provided for the potential failure mode that involved accident risk, and the expected improved rates were calculated. Fuzzy RPN values can be raised to acceptable levels with the suggestions made for all error types. The results showed that the proposed Fuzzy FMEA methodology is effective in determining risk-prone areas in a concrete manufacturing plant. Suggestions were shared with all companies which helped to prepare questions for the company where the study was conducted.

Acknowledgements

The authors would like to thank Concrete Manufacturer Company name of which has been kept confidential upon request for providing facilities to carry out the risk assessment application at their work site. Otherside, the authors would also thank to occupational safety specialists of the ready mixed concrete plant for the questionnaire preparation.

Appendix A

Potential failure modes, effect and causes in utilities, administrative office, social facilities, quality control laboratory and wastewater pool and recycling facilities. RPN and Fuzzy RPN values in current condition, proposed activity for risk reduction, RPN and Fuzzy RPN values after if corrective actions occur in utilities, administrative office, social facilities, quality control laboratory and wastewater pool and recycling facilities.

See Tables A.1–A.10.

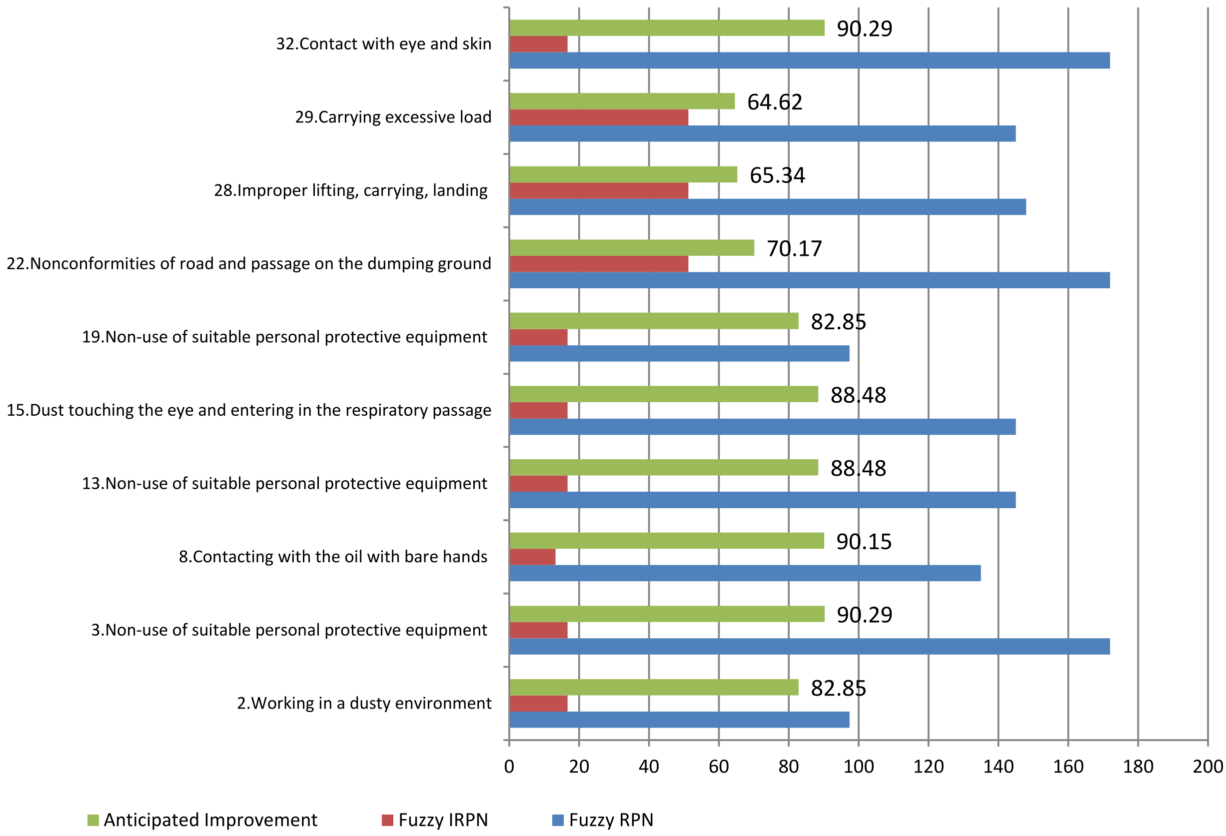

Fig. 10. Anticipated improvement rates in transportation and storage if the proposed preventive measures are realized.

Appendix B. Fuzzy rules

See Fig. B.1.

Appendix C. TOPSIS method

Step 1: Development of the decision matrix with O, S, and D values *(y_{ij}; $i = 1, 2, \ldots,$ number of alternatives (m), $j = 1, 2, 3$* O, S, and D values are placed in matrix form as shown in Eq. (C.1)).

$$D = \begin{bmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ \ldots & & \\ y_{m1} & y_{m2} & y_{m3} \end{bmatrix} \tag{C.1}$$

Step 2: The normalized decision matrix is constructed using Eq. (C.2) [64–66].

$$y^*_{ij} = \frac{y_{ij}}{\sqrt{\sum_{i=1}^{m} y^2_{ij}}} \quad \mathrm{i} = 1, 2, \ldots, \mathrm{m}, \quad \mathrm{j} = 1, 2, 3. \tag{C.2}$$

Step 3: The weighted normalized decision matrix is obtained:

$$V = \left[X_{ij}\right]_{mxr} \quad \mathrm{i} = 1, 2, \ldots, \mathrm{m}, \quad \mathrm{j} = 1, 2, 3. \tag{C.3}$$

$$X_{ij} = y^*_{ij} w_j \tag{C.4}$$

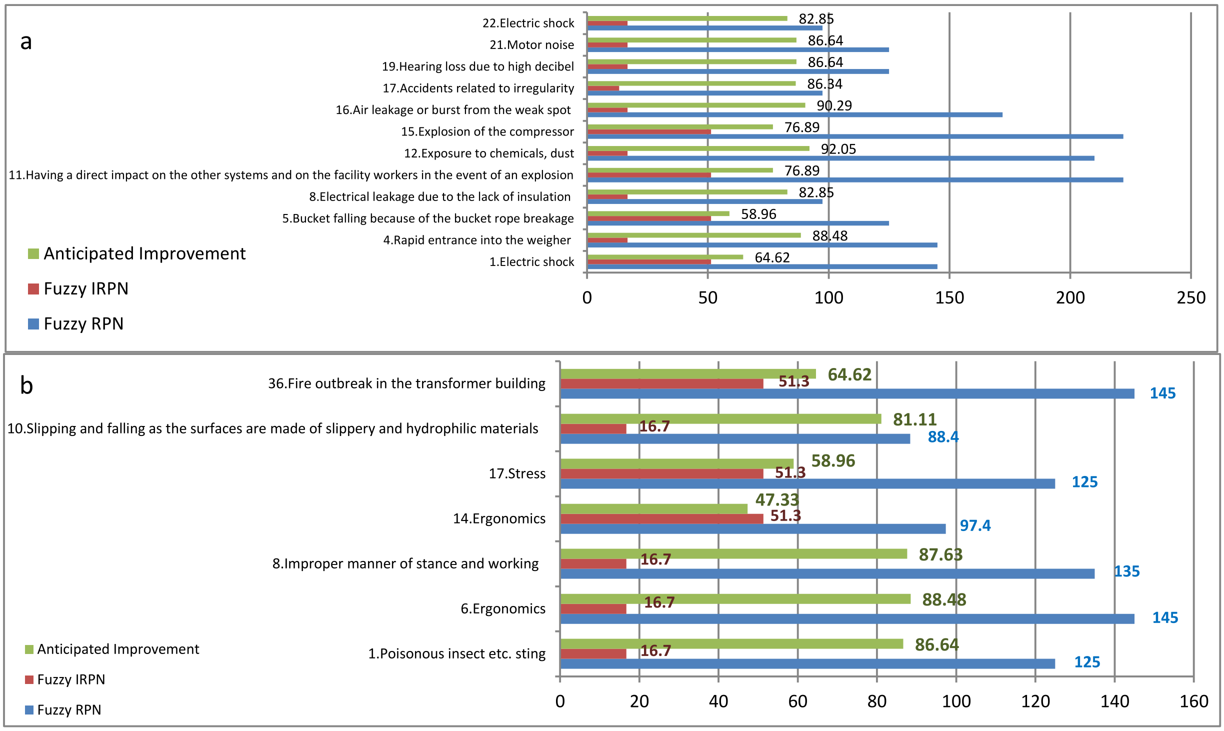

Fig. 11. Anticipated improvement rates if the proposed preventive measures are realized (a) in utilities, (b) administrative office and social facilities.

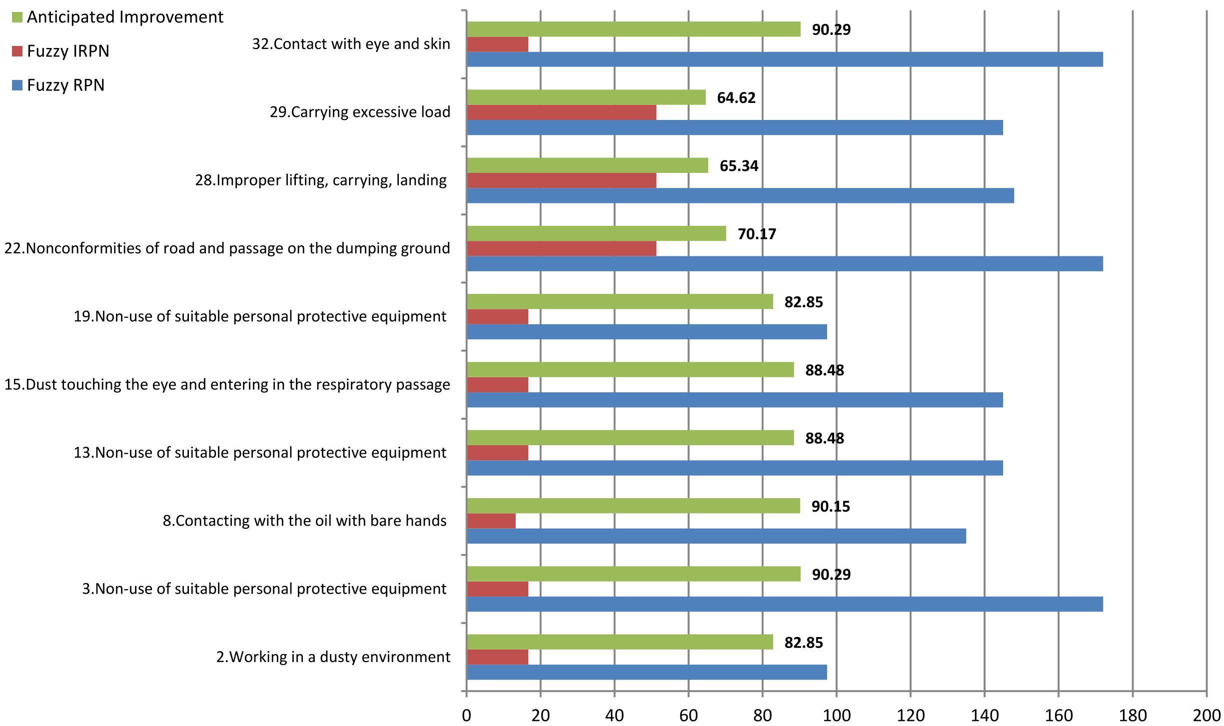

Fig. 12. Anticipated improvement rates if the proposed preventive measures are realized: quality control laboratory.

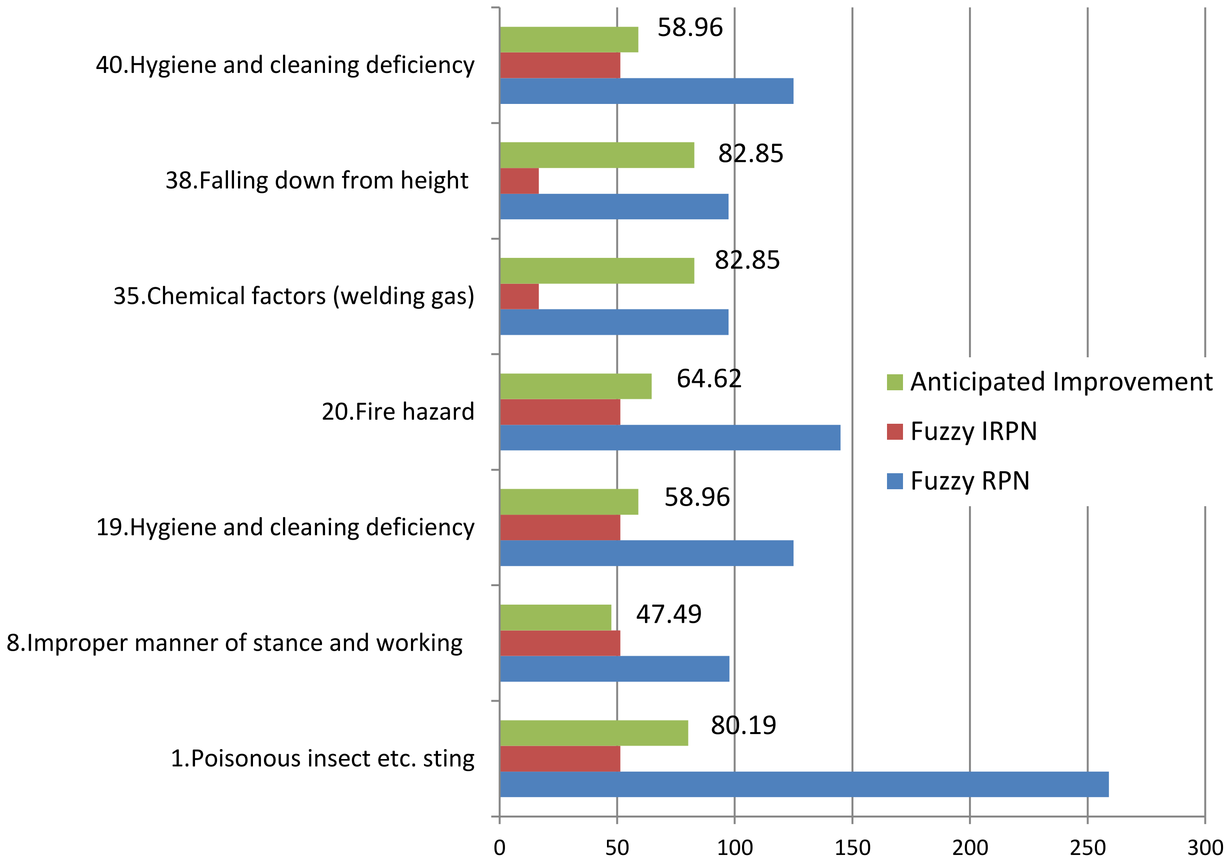

Fig. 13. Anticipated improvement rates if the proposed preventive measures are realized: wastewater pool and recycling facilities.

$$W = [w_1, w_2, w_3] \tag{C.5}$$

Step 4: Determine the ideal and negative-ideal solutions: Larger O, S, and D values are preferred. So the ideal solution (A^*) and negative-ideal solution (A^-), which represent the maximum and minimum O, S, and D values of all alternatives, are as follows:

$$A^* = \left(X_1^*, X_2^*, X_3^*\right) \tag{C.6}$$

$$\overset{*}{X}_j = \left\{\left(\max_i X_{ij} \,|j \in J\right) i = 1, \ldots .m\right\} \tag{C.7}$$

$$A- = \left(X_1^-, X_2^-, X_3^-\right) \tag{C.8}$$

$$\overset{-}{X}_j = \left\{\left(\min_i X_{ij} \,|j \in J\right) i = 1, \ldots .m\right\} \tag{C.9}$$

Step 5: The distance of an alternative i to the ideal solution (d_i^*), and from the negative ideal solution (d_i^-) are calculated using Eqs. (C.10) and (C.11) [64–66].

$$d_i^* = \sqrt{\sum_{j=1}^{3}(X_{ij} - X_j^*)^2} \quad \mathrm{i} = 1, 2, \ldots, \mathrm{m} \tag{C.10}$$

$$d_i^- = \sqrt{\sum_{j=1}^{3}(X_{ij} - X_j^-)^2} \quad \mathrm{i} = 1, 2, \ldots, \mathrm{m} \tag{C.11}$$

Table 12
Comparison of RPN rankings.

No	Rankings								Spearman Rank Correlation Test					
	RPN		FRPN		TOPSIS		GRA		RPN-FRPN	RPN-TOPSIS	RPN-GRA	FRPN-TOPSIS	FRPN-GRA	TOPSIS-GRA
	Score	Rank	Score	Rank	Score	Rank	Score	Rank						
1	108	14	97.5	14	0.464	11	0.59596	4	0	3	10	3	10	7
4	378	1	425	1	0.809	1	0.851852	1	0	0	0	0	0	0
5	150	5	125	10	0.516	5	0.503367	11	-5	0	-6	5	-1	-6
6	126	9	125	11	0.447	12	0.51339	10	-2	-3	-1	-1	1	2
7	96	17	135	9	0.405	17	0.4617	17	8	0	0	-8	-8	0
9	120	11	97.5	15	0.441	14	0.52972	8	-4	-3	3	1	7	6
11	90	20	97.5	16	0.348	20	0.446387	18	4	0	2	-4	-2	2
12	120	12	145	5	0.442	13	0.479557	14	7	-1	-2	-8	-9	-1
18	108	15	97.5	17	0.406	16	0.480057	13	-2	-1	2	1	4	3
19	120	13	97.5	18	0.427	15	0.469697	16	-5	-2	-3	3	2	-1
20	96	18	148	4	0.478	7	0.59596	4	14	11	14	-3	0	3
21	144	6	145	7	0.539	3	0.532967	7	-1	3	-1	4	0	-4
25	168	3	172	3	0.528	4	0.6163	3	0	-1	0	-1	0	1
26	125	10	125	12	0.474	8	0.479557	14	-2	2	-4	4	-2	-6
28	96	19	97.5	19	0.376	19	0.446387	18	0	0	1	0	1	1
30	160	4	145	8	0.513	6	0.55303	6	-4	-2	-2	2	2	0
33	240	2	222	2	0.668	2	0.63961	2	0	0	0	0	0	0
34	60	21	88.3	21	0.298	21	0.429293	21	0	0	0	0	0	0
40	140	7	125	13	0.472	9	0.50303	12	-6	-2	-5	4	1	-3
41	128	8	145	6	0.466	10	0.52972	8	2	-2	0	-4	-2	2
42	100	16	97.5	20	0.383	18	0.445887	20	-4	-2	-4	2	0	-2
								d^2	476	184	426	272	334	220
								r_s	0.691	0.881	0.723	0.823	0.783	0.857
								Z	***3.090***	***3.938***	***3.235***	***3.682***	***3.502***	***3.833***

Step 7: The ranking score (C_i^*) is calculated using Eq. (C.12).

$$C_i^* = d_i^- / (d_i^- + d_i^*), \quad i = 1, 2, \ldots, m \tag{C.12}$$

See Table C.1.

Appendix D. GRA method

Grey relational analysis is used to calculate the relationship between reference sequence $x_0^{(o)}(j)$ and comparability sequence $x_i^{(o)}$ (j), i = 1, 2, … , m; j = 1, 2, … , r, respectively.

Step 1: Development of the decision matrix with O, S, and D values.

Step 2: Normalization

A linear normalization of the O, S, and D values in the range between zero and unity is also called as the grey relational generation [64]. Eq. (D.1) is used for larger-the-better attribute. Note that the O, S, and D values are the larger-the-better attribute. Therefore, the proposed GRA method uses Eq. (D.1) for grey relational generating.

$$Y_i(j) = \frac{\eta_i^0(j) - \min \eta_i^0(j)}{\max \eta_i^0(j) - \min \eta_i^0(j)} \tag{D.1}$$

Step 3: Determination of deviation sequences, Δ_{0i} (j)

Table A.1
Potential failure modes, effect and causes in utilities.

No.	Activity	Failure cause and mode	Failure effect
1	Switching on/off via the wall frame	Electric shock	Serious injury, death
2	Pumping gasoline into the vehicles	Vehicle crashing into the pumper due to its movement	Serious injury, death
3	Refuelling for the gasoline tank	Fire outbreak because of static electricity	Minor lacerations
4	Entrance–exit and dispatch note of the facility weigher	Rapid entrance into the weigher	Financial loss
5	Scraper Unit	Bucket falling because of the bucket rope breakage	Injury, death
6	Transformer Building	Fire outbreak due to the leakage of electricity	Financial loss, minor lacerations
7	Maintenance and cleaning of the generator room	Loud working space	Hearing loss
8	On-site power lines	Electrical leakage due to the lack of insulation	Injury, death
9	Dump sites	Spalling due to inadequate insulation	Skin and eye diseases
10	Acid storage ground	Spalling due to inadequate insulation	Skin and eye diseases
11	Deployment of the compressors in a closed area along with other equipment	Having a direct impact on the other systems and on the facility workers in the event of an explosion	Serious injury, death
12	Maintenance of the compressors	Exposure to chemicals, dust	Minor lacerations
13	Water disposal while the compressor is on	Relief screw popping out under sudden pressure	Injury, death
14	Compressor manometers	Compliance of manometers	Injury, death
15	Check valve failure	Explosion of the compressor	Injury, death
16	Wearing of compressor tank	Air leakage or burst from the weak spot	Injury, death
17	Inconvenient storage in the compressor room	Accidents related to irregularity	
18	Compressor belt housing	Mobile equipment	Injury
19	Compressor noise	Hearing loss due to high decibel	Permanent diseases
20	Oil leakage from the compressor	Sliding down because of stepping on oil, machinery failure	Injury
21	Generator	Motor noise	Hearing loss
22	Generator	Electric shock	Injury
23	Generator	Emission	Air pollution, respiratory diseases
24	Generator fuel deposing	Fire	Equipment failure
25	Transformer	High voltage, electric shock	Injury
26	Transformer	Fire	Injury, equipment failure
27	Electrical system, panels	Electric shock due to improper earthing	Injury
28	Electrical system, panels	Fire due to short-circuit	Equipment failure
29	Electrical system, panels	Open cables, panels, socket/switches	Injury
30	Generator room cleaning	Improper storage	Fire
31	Battery charge	Electric shock due to the absence of cover	Electric shock
32	Generator running	Heat-related failures	Fire
33	Starting the generator	Line conflict due to the improper start-up of the generator	Electric shock

The deviation sequence, Δ_{0i} (j) is the absolute difference between the reference sequence x_0^* (j) and the comparability sequence x_i^*(j) after normalization. It is determined using Eq. (D.2) as,

$$\Delta_{0i}(k) = \left|Y_o^*(k) - Y_i^*(k)\right| \tag{D.2}$$

Step 4: Calculation of grey relational coefficient (GRC)

GRC for all the sequences expresses the relationship between the ideal (best) and actual normalized O, S, and D values. If the two sequences agree at all points, then their grey relational coefficient is 1. The grey relational

Table A.2
Potential failure modes, effect and causes in administrative office.

No.	Activity	Failure cause and mode	Failure effect
1	Garden/Green zones	Poisonous insect etc. sting	Intoxication
2	Passenger car wash/Parking lots	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
3	Use of office machinery–equipment	Crashing into objects	Injury
4	Use of office machinery–equipment	Object fall	Injury
5	Use of office machinery–equipment	Electric shock	Serious injury, death
6	Use of office machinery–equipment	Ergonomics	Backache
7	Use of office machinery–equipment	Causing injury while working with machinery and tools	Injury
8	Use of office machinery–equipment	Improper manner of stance and working	Neckache
9	Use of tea houses	Hygiene and cleaning deficiency	Microbic illness
10	General office work	Crashing into objects	Injury
11	General office work	Object fall	Injury
12	General office work	Working with screened vehicles	Permanent eye diseases
13	General office work	Electric shock	Serious injury
14	General office work	Ergonomics	Backache
15	General office work	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
17	General office work	Stress	Stress
18	General office work	Improper manner of stance and working	Neckache
19	Potable water supply	Hygiene and cleaning deficiency	Microbic illness
20	Paying no attention to the potable water, tea, dining hall hygiene	Hygiene and cleaning deficiency	Microbic illness
21	Fire precautions for the administrative building, dining hall and archive	Fire hazard	Financial loss
22	Parking lots for trucks /construction equipment	Traffic accident	Financial loss
23	Office ground remaining wet after cleaning	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
24	Use and cleaning of public fountain	Hygiene and cleaning deficiency	Microbic illness
25	Services–Personnel Transport	Traffic accident	Financial loss
26	Maintenance and repair of the sanitary system	Crashing into objects	Injury
27	Maintenance and repair of the sanitary system	Electric shock	Serious injury, death
28	Maintenance and repair of the sanitary system	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
29	Maintenance and repair of the sanitary system	Improper manner of stance and working	Neckache,Backache
30	Maintenance and repair of the sanitary system	Falling down from height	Serious injury, death
31	Paying no attention to Use of cleaning materials during cleaning works	Exposure to chemical materials	Gas poisoning
32	On-site carriage and walk ways	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
33	Installation/welding repair	Crashing into objects	Injury
34	Installation/welding repair	Electric shock	Serious injury
35	Installation/welding repair	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
36	Installation/welding repair	Chemical factors (welding gas)	Gas poisoning
37	Installation/welding repair	Use of portable hand tools	Injury
38	Installation/welding repair	Improper manner of stance and working	Neckache, Backache
39	Installation/welding repair	Falling down from height	Serious injury
40	Load-carrying within the units (box, package,seat etc.)	Falling due to the reasons such as accident, slipping, tripping etc.	Injury

(*continued on next page*)

Table A.2 (*continued*).

No.	Activity	Failure cause and mode	Failure effect
41	Catering and tea house personnel paying no attention to the personnel care and hygiene	Hygiene and cleaning deficiency	Microbic illness

Table A.3
Potential failure modes, effect and causes in social facility.

No.	Activity	Failure cause and mode	Failure effect
1	Dining Hall	Not having the subcontractor company's catering personnel subjected to health examination	Infectious diseases
2	Dining Hall	Cleaning the kitchenware used in the meal, with hot water and unhygienic materials	Infectious diseases
3	Dining Hall	Insufficient ventilation in the dining halls, moisture and mould formation due to the lack of sunlight	Bacterial growth
4	Dining Hall	Trash bins left open in dining halls	Insect, infectious diseases
5	Dining Hall	Electric shock and fire outbreak due to the inconvenience of the electrical wiring of the dining hall	Injury, death
6	Dining Hall	Short-circuit and fire outbreak because the lighting equipment in the dining halls, are not waterproof	Injury, death
7	Dressing rooms	Inadequacy of heating unit	İllness
8	Dressing rooms	Inconvenience of ventilation conditions	Illness
9	Toilets and showers	Consequence of bad ventilation	Insect
10	Toilets and showers	Slipping and falling as the surfaces are made of slippery and hydrophilic materials	Fracture
11	Toilets and showers	Electric shock, short-circuit and fire outbreak due to the unfeasibility of the electrical wiring	Serious accident
12	Toilets and showers	Use of electrical and gaseous heating methods in the showers	Fire, Explosion
13	Toilets and showers	Because of the insufficient cleaning	Insect
14	Toilets and showers	Toilets being close to water reservoirs	Illness
15	Toilets and showers	Cesspools being close to clear water reservoirs and conducting pipes	Illness
17	Toilets and showers	Slipping risk due to the wet floor at the toilet entrance	Injury
18	Driver's Room	Accidents and hazards arising from the unfeasibility of the driver's room	Illness
19	Driver's Room	Placing a water dispenser in the driver's room	dissatisfaction
20	Driver's Room	Airlessness due to aspirator failure	Anxiety
21	Dining hall	Diseases related to the environmental pollution	Illness
22	Dining hall, Tea house	Consequence of the untidiness of helmets	Accident
23	Toilets and showers	Syphons are not working	Pollution
24	Room Heater Chamber	Accidents and fire outbreak arising from the environmental untidiness and technical deficiencies (Velimeşe Accident)	Fire
25	Dressing rooms	Not being clean or fitting the bill	Pollution, illness
26	Toilets and showers	Pollution and untidiness	Illness
27	Toilets and showers	The entrance being dark	Injury
28	Dining hall	Diseases related to the environmental pollution	Illness
29	Use of dressing rooms	Accidents that might happen due to the non-use of dressing rooms	Illness, Injury
30	Use of lockers	Accidents that might happen because of not repairing the failures in the closets	Cut
31	Entrance to facility	External visitor entering into the production area	Injury
32	Entrance to facility	Irrelevant person coming from outside and entering into the facility site	Injury
33	Entrance to facility	Third person coming along with the suppliers, entering into the facility site	Injury
34	Entrance to facility	External (visitors, suppliers etc.) entering into the production area at the evening hours	Injury

(*continued on next page*)

Table A.3 (*continued*).

No.	Activity	Failure cause and mode	Failure effect
35	Transformer building	Fire splashing towards the transformer building in a possible fire outbreak	Injury
36	Transformer building	Fire outbreak in the transformer building	Injury
37	Catering vehicle	Catering vehicle being hygienic	Infectious diseases
38	Catering vehicle	Ensuring that the catering vehicle brings food in closed containers	Infectious diseases
39	Catering vehicle	Ensuring that the catering vehicle follows the on-site traffic rules	Infectious diseases

Table A.4
Potential failure modes, effect and causes in quality control laboratory.

No.	Activity	Failure cause and mode	Failure effect
1	Taking aggregate sample	Use of wheelbarrow	Muscular and skeleton diseases
2	Taking aggregate sample	Working in a dusty environment	Breathing passage irritation
3	Taking aggregate sample	Non-use of suitable personal protective equipment	Skin diseases, Breathing passage irritation
4	Taking aggregate sample	Car crash	Injury, death
5	Taking concrete simple from the transit-mixer into the wheelbarrow	Taking the samples in an inconvenient way	Skin diseases, Breathing passage irritation
6	Taking concrete simple from the transit-mixer into the wheelbarrow	Non-use of suitable personal protective equipment	Skin diseases, Breathing passage irritation
7	Taking concrete simple from the transit-mixer into the wheelbarrow	Concrete splashing	Skin diseases, Breathing passage irritation
8	Lubricating the concrete sample cubes	Contacting with the oil with bare hands	Skin diseases
9	The heater in the curing pool, being electrical	Electric shock	Injury, death
10	Piling the samples extracted from the curing pool on the poolside	Samples overturning	Injury
11	Extraction of concrete samples from the mould by compressed air	Mould popping out off the sample	Injury
12	Taking cement simple off the cement trailer	Taking the samples in an inconvenient way	Skin diseases, Breathing passage irritation
13	Taking cement simple off the cement trailer	Non-use of suitable personal protective equipment	Skin diseases, Breathing passage irritation
14	Taking cement simple off the cement trailer	Working at height	Injury, death
15	Conducting sieve analysis (MANUALLY)	Dust touching the eye and entering in the respiratory passage	Breathing passage irritation, eye diseases
16	Harvesting the sample	Sample piece splashing	Injury
17	Harvesting the sample	Non-use of suitable personal protective equipment	Injury
18	Taking sample from the dumping ground	Taking the samples in an inconvenient way	Breathing passage irritation, skin diseases
19	Taking sample from the dumping ground	Non-use of suitable personal protective equipment	Breathing passage irritation, skin diseases
20	Taking sample from the dumping ground	Insufficient organization and order of the dumping ground	Injury
21	Taking sample from the dumping ground	Dumping ground having insufficient lighting	Injury
22	Taking sample from the dumping ground	Nonconformities of road and passage on the dumping ground	Injury
23	Use of tube stove in the laboratory	Gas leakage	Explosion, poisoning
24	Use of electric radiator in the laboratory	Fire	Injury, death
25	Use of computer in the laboratory	Looking at the computer screen for a long time	Eye diseases

(*continued on next page*)

Table A.4 (*continued*).

No.	Activity	Failure cause and mode	Failure effect
26	Use of computer in the laboratory	Stance disorder	Backache
27	Use of computer in the laboratory	Tripping hazard due to the untidiness of computer cables	Backache
28	Transport of concrete samples	Improper lifting, carrying, landing	Neckache, backache
29	Transport of concrete samples	Carrying excessive load	Neckache, backache
30	Transport of concrete samples	Sample fall	Injury
31	Wet floor in the section where the curing pools are located	Sliding down due to the slippery ground	Injury
32	Performing chemical admixture experiments	Contact with eye and skin	Injury
33	Conducting experiments	Standing all the time	Muscular and skeleton diseases
34	Use of laboratory device and equipment	The absence of conservation and cover under proper protection	Injury
35	Cleaning of the laboratory space and removal of device and equipment	Testing sites being untidy and unclean	Injury, death

Table A.5
Potential failure modes, effect and causes in wastewater pool and recycling facilities.

No.	Activity	Failure cause and mode	Failure effect
1	Garden/Green zones	Poisonous insect etc. sting	Poisoning
2	Passenger car wash/Parking lots	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
3	Use of office machinery–equipment	Crashing into objects	Injury
4	Use of office machinery–equipment	Object fall	Injury
5	Use of office machinery–equipment	Electric shock	Serious injury, death
6	Use of office machinery–equipment	Ergonomics	Neckache, backache
7	Use of office machinery–equipment	Causing injury while working with machinery and tools	Injury
8	Use of office machinery–equipment	Improper manner of stance and working	Neckache, backache
9	Use of tea houses	Hygiene and cleaning deficiency	Microbic illness
10	General office work	Crashing into objects	Injury
11	General office work	Object fall	Injury
12	General office work	Working with screened vehicles	Eye diseases
13	General office work	Electric shock	Serious injury
14	General office work	Ergonomics	Backache
15	General office work	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
16	General office work	Stress	Stress
17	General office work	Improper manner of stance and working	Neckache, backache
18	Potable water supply	Hygiene and cleaning deficiency	Microbic illness
19	Paying no attention to the potable water, tea, dining hall hygiene	Hygiene and cleaning deficiency	Microbic illness
20	Fire precautions for the administrative building, dining hall and archive	Fire hazard	Microbic illness
21	Parking lots for trucks /construction equipment	Traffic accident	Financial loss, injury
22	Office ground remaining wet after cleaning	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
23	Use and cleaning of public fountain	Hygiene and cleaning deficiency	Microbic illness
24	Services–Personnel Transport	Traffic accident	Financial loss
25	Maintenance and repair of the sanitary system	Crashing into objects	Injury
26	Maintenance and repair of the sanitary system	Electric shock	Serious injury
27	Maintenance and repair of the sanitary system	Falling due to the reasons such as accident, slipping, tripping etc.	Injury

(*continued on next page*)

Table A.5 (*continued*).

No.	Activity	Failure cause and mode	Failure effect
28	Maintenance and repair of the sanitary system	Improper manner of stance and working	Neckache
29	Maintenance and repair of the sanitary system	Falling down from height	Serious injury
30	Paying no attention to Use of cleaning materials during cleaning works	Exposure to chemical materials	Gas poisoning
31	On-site carriage and walk ways	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
32	Installation/welding repair	Crashing into objects	Injury
33	Installation/welding repair	Electric shock	Serious injury
34	Installation/welding repair	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
35	Installation/welding repair	Chemical factors (welding gas)	Gas poisoning
36	Installation/welding repair	Use of portable hand tools	Injury
37	Installation/welding repair	Improper manner of stance and working	Neckache, backache
38	Installation/welding repair	Falling down from height	Serious injury
39	Load-carrying within the units (box, package,seat etc.)	Falling due to the reasons such as accident, slipping, tripping etc.	Injury
40	Catering and tea house personnel paying no attention to the personnel care and hygiene	Hygiene and cleaning deficiency	Microbic illness, poisoning

Table A.6
Fuzzy RPN and RPN values in utilities.

No.	Before planned actions					Planned actions	After planned actions				
	O	S	D	RPN	FRPN		O	S	D	IRPN	IFRPN
1	4	9	4	144	145	Electric system should be controlled routinely	2	8	2	32	51.3
4	4	6	5	120	145	Traffic is regulated by an indicator	1	5	2	10	16.7
5	5	6	5	150	125	Regular control and change of rope	2	6	2	24	51.3
8	5	6	4	120	97.4	Insulation and electrical grounding control of all electrical panels	1	5	2	10	16.7
11	5	6	8	240	222	Not setting compressors with another devices	2	5	3	30	51.3
12	8	5	5	200	210	Filtered dust mask will be used	2	3	3	18	16.7
15	6	6	6	216	222	Regular check valve control and periodical change	2	5	2	20	51.3
16	7	7	4	196	172	Periodical device change	2	2	2	8	16.7
17	4	6	5	120	97.4	Making compressor array in a plan and updating this plan as hanging on storage area	1	5	3	15	13.3
19	6	7	3	126	125	The use of appropriate ear-protective	1	4	3	12	16.7
21	5	5	5	125	125	The use of appropriate ear-protective	1	5	2	10	16.7
22	4	6	4	96	97.4	Insulation and electrical grounding control of all electric panels	1	4	2	8	16.7

Table A.7
Fuzzy RPN and RPN values in administrative office.

No.	Before planned actions					Planned actions	After planned actions				
	O	S	D	RPN	FRPN		O	S	D	RPN	FRPN
1	5	5	5	125	125	Regular disinfestations should be done	2	3	2	12	16.7
6	6	4	5	120	145	Proper posture visual should be hung on the office	2	2	2	8	16.7

(*continued on next page*)

Table A.7 (*continued*).

No.	Before planned actions					Planned actions	After planned actions				
	O	S	D	RPN	FRPN		O	S	D	RPN	FRPN
8	6	4	4	96	135	Proper posture visual should be hung on the office	2	3	3	18	16.7
14	4	5	5	100	97.4	Proper posture visual should be hung on the office	2	4	2	16	51.3
17	5	7	5	175	125	Giving information to employee about overcoming the stress techniques	4	5	2	40	51.3

Table A.8
Fuzzy RPN and RPN values in social facility.

No.	Before planned actions					Planned actions	After planned actions				
	O	S	D	RPN	FRPN		O	S	D	RPN	FRPN
10	4	2	2	16	88.4	Placing warning signs after cleaning	2	2	2	8	16.7
36	4	9	4	144	145	Transformers should be controlled regularly by the authorized companies.	2	8	2	32	51.3

Table A.9
Fuzzy RPN and RPN values in quality control laboratory.

No.	Before planned actions					Planned actions	After planned actions				
	O	S	D	RPN	FRPN		O	S	D	RPN	FRPN
2	4	5	4	80	97.4	Filter dusk mask should be used	2	2	3	12	16.7
3	5	7	6	210	172	Employee training on the use of personnel protective equipment	2	3	2	12	16.7
8	6	4	4	96	135	Employee protective equipment should be used	5	1	1	5	13.3
13	6	6	4	144	145	Employee training on the use of personnel protective equipment	2	2	2	8	16.7
15	6	5	4	120	145	Employee training on the use of personnel protective equipment	2	2	2	8	16.7
19	5	6	3	90	97.4	Employee training on the use of personnel protective equipment	2	3	2	12	16.7
22	6	7	4	168	172	Regulating vehicle traffic	2	6	2	24	51.3
28	7	5	4	140	148	Proper lifting tools should be used	2	4	2	16	51.3
29	6	4	5	120	145	Proper lifting tools should be used	2	5	2	20	51.3
32	6	5	5	150	172	Employee protective equipment should be used	2	3	2	12	16.7

Table A.10
Fuzzy RPN and RPN values in wastewater pool and recycling facilities.

No.	Before planned actions					Planned actions	After planned actions				
	O	S	D	RPN	FRPN		O	S	D	RPN	FRPN
1	8	7	5	280	259	Regular disinfestation should be done	2	5	3	30	51.3
8	4	5	5	100	97.7	Proper posture visual should be hung on the office	2	4	3	24	51.3
19	6	7	3	126	125	Personal training and a check-list should be done for regular hygiene controlling	2	5	2	20	51.3
20	4	8	4	128	145	Giving fire training to all employees	2	7	2	28	51.3
35	5	6	4	120	97.4	Respiratory protective equipment should be used	3	3	2	18	16.7
38	5	5	4	100	97.4	Seatbelt should be used working at height	2	2	2	8	16.7
40	6	7	3	126	125	Personal training and a check-list should be done for regular hygiene controlling	2	6	2	24	51.3

1. If (Occurance is VeryLow) and (Severity is VeryLow) and (Detection is VeryHigh) then (RPN is None) (1)
2. If (Occurance is VeryLow) and (Severity is VeryLow) and (Detection is High) then (RPN is None) (1)
3. If (Occurance is VeryLow) and (Severity is VeryLow) and (Detection is Moderate) then (RPN is None) (1)
4. If (Occurance is VeryLow) and (Severity is VeryLow) and (Detection is Low) then (RPN is None) (1)
5. If (Occurance is VeryLow) and (Severity is VeryLow) and (Detection is VeryLow) then (RPN is None) (1)
6. If (Occurance is VeryLow) and (Severity is Low) and (Detection is VeryHigh) then (RPN is None) (1)
7. If (Occurance is VeryLow) and (Severity is Moderate) and (Detection is VeryHigh) then (RPN is None) (1)
8. If (Occurance is VeryLow) and (Severity is High) and (Detection is VeryHigh) then (RPN is None) (1)
9. If (Occurance is VeryLow) and (Severity is VeryHigh) and (Detection is VeryHigh) then (RPN is None) (1)
10. If (Occurance is VeryLow) and (Severity is Low) and (Detection is High) then (RPN is None) (1)
11. If (Occurance is VeryLow) and (Severity is Low) and (Detection is Moderate) then (RPN is None) (1)
12. If (Occurance is VeryLow) and (Severity is Low) and (Detection is Low) then (RPN is None) (1)
13. If (Occurance is VeryLow) and (Severity is Low) and (Detection is VeryLow) then (RPN is None) (1)
14. If (Occurance is VeryLow) and (Severity is Moderate) and (Detection is VeryHigh) then (RPN is None) (1)
15. If (Occurance is VeryLow) and (Severity is Moderate) and (Detection is High) then (RPN is None) (1)
16. If (Occurance is VeryLow) and (Severity is Moderate) and (Detection is Moderate) then (RPN is None) (1)
17. If (Occurance is VeryLow) and (Severity is Moderate) and (Detection is Low) then (RPN is None) (1)
18. If (Occurance is VeryLow) and (Severity is Moderate) and (Detection is VeryLow) then (RPN is VeryLow) (1)
19. If (Occurance is VeryLow) and (Severity is High) and (Detection is VeryHigh) then (RPN is None) (1)
20. If (Occurance is VeryLow) and (Severity is High) and (Detection is High) then (RPN is None) (1)
21. If (Occurance is VeryLow) and (Severity is High) and (Detection is Moderate) then (RPN is None) (1)
22. If (Occurance is VeryLow) and (Severity is High) and (Detection is Low) then (RPN is VeryLow) (1)
23. If (Occurance is VeryLow) and (Severity is High) and (Detection is VeryLow) then (RPN is VeryLow) (1)
24. If (Occurance is VeryLow) and (Severity is VeryHigh) and (Detection is VeryHigh) then (RPN is None) (1)
25. If (Occurance is VeryLow) and (Severity is VeryHigh) and (Detection is High) then (RPN is None) (1)
26. If (Occurance is VeryLow) and (Severity is VeryHigh) and (Detection is Moderate) then (RPN is VeryLow) (1)
27. If (Occurance is VeryLow) and (Severity is VeryHigh) and (Detection is Low) then (RPN is VeryLow) (1)
28. If (Occurance is VeryLow) and (Severity is VeryHigh) and (Detection is VeryLow) then (RPN is Low) (1)
29. If (Occurance is Low) and (Severity is VeryLow) and (Detection is VeryHigh) then (RPN is None) (1)
30. If (Occurance is Low) and (Severity is VeryLow) and (Detection is High) then (RPN is None) (1)
31. If (Occurance is Low) and (Severity is VeryLow) and (Detection is Moderate) then (RPN is None) (1)
32. If (Occurance is Low) and (Severity is VeryLow) and (Detection is Low) then (RPN is None) (1)
33. If (Occurance is Low) and (Severity is VeryLow) and (Detection is VeryLow) then (RPN is None) (1)
34. If (Occurance is Low) and (Severity is Low) and (Detection is VeryHigh) then (RPN is None) (1)
35. If (Occurance is Low) and (Severity is Low) and (Detection is High) then (RPN is None) (1)
36. If (Occurance is Low) and (Severity is Low) and (Detection is Moderate) then (RPN is VeryLow) (1)
37. If (Occurance is Low) and (Severity is Low) and (Detection is Low) then (RPN is VeryLow) (1)
38. If (Occurance is Low) and (Severity is Low) and (Detection is VeryLow) then (RPN is Low) (1)
39. If (Occurance is Low) and (Severity is Moderate) and (Detection is VeryHigh) then (RPN is None) (1)
40. If (Occurance is Low) and (Severity is Moderate) and (Detection is High) then (RPN is VeryLow) (1)
41. If (Occurance is Low) and (Severity is Moderate) and (Detection is Moderate) then (RPN is VeryLow) (1)
42. If (Occurance is Low) and (Severity is Moderate) and (Detection is Low) then (RPN is Low) (1)
43. If (Occurance is Low) and (Severity is Moderate) and (Detection is VeryLow) then (RPN is Low) (1)
44. If (Occurance is Low) and (Severity is High) and (Detection is VeryHigh) then (RPN is None) (1)
45. If (Occurance is Low) and (Severity is High) and (Detection is High) then (RPN is VeryLow) (1)
46. If (Occurance is Low) and (Severity is High) and (Detection is Moderate) then (RPN is Low) (1)
47. If (Occurance is Low) and (Severity is High) and (Detection is Low) then (RPN is Low) (1)
48. If (Occurance is Low) and (Severity is High) and (Detection is VeryLow) then (RPN is HighLow) (1)
49. If (Occurance is Low) and (Severity is VeryHigh) and (Detection is VeryHigh) then (RPN is None) (1)
50. If (Occurance is Low) and (Severity is VeryHigh) and (Detection is High) then (RPN is VeryLow) (1)
51. If (Occurance is Low) and (Severity is VeryHigh) and (Detection is Moderate) then (RPN is Low) (1)

Fig. B.1. Fuzzy rules obtained by the expert suggestion.

52. If (Occurance is Low) and (Severity is VeryHigh) and (Detection is Low) then (RPN is HighLow) (1)
53. If (Occurance is Low) and (Severity is VeryHigh) and (Detection is VeryLow) then (RPN is LowMedium) (1)
54. If (Occurance is Moderate) and (Severity is VeryLow) and (Detection is VeryHigh) then (RPN is None) (1)
55. If (Occurance is Moderate) and (Severity is VeryLow) and (Detection is High) then (RPN is None) (1)
56. If (Occurance is Moderate) and (Severity is VeryLow) and (Detection is Moderate) then (RPN is None) (1)
57. If (Occurance is Moderate) and (Severity is VeryLow) and (Detection is Low) then (RPN is None) (1)
58. If (Occurance is Moderate) and (Severity is VeryLow) and (Detection is VeryLow) then (RPN is VeryLow) (1)
59. If (Occurance is Moderate) and (Severity is Low) and (Detection is VeryHigh) then (RPN is None) (1)
60. If (Occurance is Moderate) and (Severity is Low) and (Detection is High) then (RPN is None) (1)
61. If (Occurance is Moderate) and (Severity is Low) and (Detection is Moderate) then (RPN is Low) (1)
62. If (Occurance is Moderate) and (Severity is Low) and (Detection is Low) then (RPN is Low) (1)
63. If (Occurance is Moderate) and (Severity is Low) and (Detection is VeryLow) then (RPN is HighLow) (1)
64. If (Occurance is Moderate) and (Severity is Moderate) and (Detection is VeryHigh) then (RPN is None) (1)
65. If (Occurance is Moderate) and (Severity is Moderate) and (Detection is High) then (RPN is VeryLow) (1)
66. If (Occurance is Moderate) and (Severity is Moderate) and (Detection is Moderate) then (RPN is Low) (1)
67. If (Occurance is Moderate) and (Severity is Moderate) and (Detection is Low) then (RPN is HighLow) (1)
68. If (Occurance is Moderate) and (Severity is Moderate) and (Detection is VeryLow) then (RPN is Low) (1)
69. If (Occurance is Moderate) and (Severity is High) and (Detection is VeryHigh) then (RPN is None) (1)
70. If (Occurance is Moderate) and (Severity is High) and (Detection is High) then (RPN is Low) (1)
71. If (Occurance is Moderate) and (Severity is High) and (Detection is Moderate) then (RPN is Low) (1)
72. If (Occurance is Moderate) and (Severity is High) and (Detection is Low) then (RPN is HighLow) (1)
73. If (Occurance is Moderate) and (Severity is High) and (Detection is VeryLow) then (RPN is LowMedium) (1)
74. If (Occurance is Moderate) and (Severity is VeryHigh) and (Detection is VeryHigh) then (RPN is None) (1)
75. If (Occurance is Moderate) and (Severity is VeryHigh) and (Detection is High) then (RPN is VeryLow) (1)
76. If (Occurance is Moderate) and (Severity is VeryHigh) and (Detection is Moderate) then (RPN is HighLow) (1)
77. If (Occurance is Moderate) and (Severity is VeryHigh) and (Detection is Low) then (RPN is LowMedium) (1)
78. If (Occurance is Moderate) and (Severity is VeryHigh) and (Detection is VeryLow) then (RPN is Medium) (1)
79. If (Occurance is High) and (Severity is Low) and (Detection is VeryHigh) then (RPN is None) (1)
80. If (Occurance is High) and (Severity is Low) and (Detection is High) then (RPN is VeryLow) (1)
81. If (Occurance is High) and (Severity is Low) and (Detection is Moderate) then (RPN is VeryLow) (1)
82. If (Occurance is High) and (Severity is Low) and (Detection is Low) then (RPN is Low) (1)
83. If (Occurance is High) and (Severity is Low) and (Detection is VeryLow) then (RPN is HighLow) (1)
84. If (Occurance is High) and (Severity is Moderate) and (Detection is VeryHigh) then (RPN is None) (1)
85. If (Occurance is High) and (Severity is Moderate) and (Detection is High) then (RPN is VeryLow) (1)
86. If (Occurance is High) and (Severity is Moderate) and (Detection is Moderate) then (RPN is HighLow) (1)
87. If (Occurance is High) and (Severity is Moderate) and (Detection is Low) then (RPN is HighLow) (1)
88. If (Occurance is High) and (Severity is Moderate) and (Detection is VeryLow) then (RPN is LowMedium) (1)
89. If (Occurance is High) and (Severity is High) and (Detection is VeryHigh) then (RPN is VeryLow) (1)
90. If (Occurance is High) and (Severity is High) and (Detection is High) then (RPN is Low) (1)
91. If (Occurance is High) and (Severity is High) and (Detection is Moderate) then (RPN is HighLow) (1)
92. If (Occurance is High) and (Severity is High) and (Detection is Low) then (RPN is LowMedium) (1)
93. If (Occurance is High) and (Severity is High) and (Detection is VeryLow) then (RPN is HighMedium) (1)
94. If (Occurance is High) and (Severity is VeryHigh) and (Detection is VeryHigh) then (RPN is VeryLow) (1)
95. If (Occurance is High) and (Severity is VeryHigh) and (Detection is High) then (RPN is HighLow) (1)
96. If (Occurance is High) and (Severity is VeryHigh) and (Detection is Moderate) then (RPN is LowMedium) (1)
97. If (Occurance is High) and (Severity is VeryHigh) and (Detection is Low) then (RPN is HighMedium) (1)
98. If (Occurance is High) and (Severity is VeryHigh) and (Detection is VeryLow) then (RPN is LowHigh) (1)
99. If (Occurance is VeryHigh) and (Severity is VeryLow) and (Detection is VeryHigh) then (RPN is None) (1)
100. If (Occurance is VeryHigh) and (Severity is VeryLow) and (Detection is High) then (RPN is None) (1)
101. If (Occurance is VeryHigh) and (Severity is VeryLow) and (Detection is Moderate) then (RPN is VeryLow) (1)
102. If (Occurance is VeryHigh) and (Severity is VeryLow) and (Detection is Low) then (RPN is Low) (1)

Fig. B.1. (*continued*).

103. If (Occurance is VeryHigh) and (Severity is VeryLow) and (Detection is VeryLow) then (RPN is Low) (1)
104. If (Occurance is VeryHigh) and (Severity is Low) and (Detection is VeryHigh) then (RPN is None) (1)
105. If (Occurance is VeryHigh) and (Severity is Low) and (Detection is Moderate) then (RPN is HighLow) (1)
106. If (Occurance is VeryHigh) and (Severity is Low) and (Detection is Low) then (RPN is HighLow) (1)
107. If (Occurance is VeryHigh) and (Severity is Low) and (Detection is VeryLow) then (RPN is LowMedium) (1)
108. If (Occurance is VeryHigh) and (Severity is Moderate) and (Detection is VeryHigh) then (RPN is VeryLow) (1)
109. If (Occurance is VeryHigh) and (Severity is Moderate) and (Detection is High) then (RPN is Low) (1)
110. If (Occurance is VeryHigh) and (Severity is Moderate) and (Detection is Moderate) then (RPN is HighLow) (1)
111. If (Occurance is VeryHigh) and (Severity is Moderate) and (Detection is Low) then (RPN is LowMedium) (1)
112. If (Occurance is VeryHigh) and (Severity is Moderate) and (Detection is VeryLow) then (RPN is HighMedium) (1)
113. If (Occurance is VeryHigh) and (Severity is High) and (Detection is VeryHigh) then (RPN is Low) (1)
114. If (Occurance is VeryHigh) and (Severity is High) and (Detection is High) then (RPN is HighLow) (1)
115. If (Occurance is VeryHigh) and (Severity is High) and (Detection is Moderate) then (RPN is LowMedium) (1)
116. If (Occurance is VeryHigh) and (Severity is High) and (Detection is Low) then (RPN is HighMedium) (1)
117. If (Occurance is VeryHigh) and (Severity is High) and (Detection is VeryLow) then (RPN is High) (1)
118. If (Occurance is VeryHigh) and (Severity is VeryHigh) and (Detection is VeryHigh) then (RPN is Low) (1)
119. If (Occurance is VeryHigh) and (Severity is VeryHigh) and (Detection is High) then (RPN is LowMedium) (1)
120. If (Occurance is VeryHigh) and (Severity is VeryHigh) and (Detection is Moderate) then (RPN is HighMedium) (1)
121. If (Occurance is VeryHigh) and (Severity is VeryHigh) and (Detection is Low) then (RPN is High) (1)
122. If (Occurance is VeryHigh) and (Severity is VeryHigh) and (Detection is VeryLow) then (RPN is VeryHigh) (1)

Fig. B.1. (*continued*).

Table C.1
TOPSIS method's result.

No.	Decision matrix			Normalized decision matrix			Weighted normalized decision matrix			d_i^*	d_i^-	C_i^*
	O	S	D	O	S	D	O	S	D			
1	3	9	4	0.122	0.295	0.205	0.041	0.098	0.068	0.085	0.074	**0.464**
4	6	9	7	0.245	0.295	0.359	0.082	0.098	0.120	0.027	0.115	**0.809**
5	5	6	5	0.204	0.197	0.256	0.068	0.066	0.085	0.063	0.067	**0.516**
6	6	7	3	0.245	0.229	0.154	0.082	0.076	0.051	0.077	0.062	**0.447**
7	6	4	4	0.245	0.131	0.205	0.082	0.044	0.068	0.080	0.054	**0.405**
9	5	8	3	0.204	0.262	0.154	0.068	0.087	0.051	0.080	0.063	**0.441**
11	5	6	3	0.204	0.197	0.154	0.068	0.066	0.051	0.086	0.046	**0.348**
12	6	5	4	0.245	0.164	0.205	0.082	0.055	0.068	0.073	0.058	**0.442**
18	6	6	3	0.245	0.197	0.154	0.082	0.066	0.051	0.081	0.055	**0.406**
19	5	6	4	0.204	0.197	0.205	0.068	0.066	0.068	0.073	0.055	**0.427**
20	8	3	4	0.327	0.098	0.205	0.109	0.033	0.068	0.083	0.076	**0.478**
21	4	6	6	0.163	0.197	0.308	0.054	0.066	0.103	0.066	0.077	**0.539**
25	7	8	3	0.286	0.262	0.154	0.095	0.087	0.051	0.071	0.079	**0.528**
26	5	5	5	0.204	0.164	0.256	0.068	0.055	0.085	0.069	0.062	**0.474**
28	4	6	4	0.163	0.197	0.205	0.054	0.066	0.068	0.082	0.049	**0.376**
30	5	8	4	0.204	0.262	0.205	0.068	0.087	0.068	0.066	0.070	**0.513**
33	5	8	6	0.204	0.262	0.308	0.068	0.087	0.103	0.046	0.092	**0.668**
34	5	6	2	0.204	0.197	0.103	0.068	0.066	0.034	0.100	0.043	**0.298**
40	5	7	4	0.204	0.229	0.205	0.068	0.076	0.068	0.069	0.062	**0.472**
41	4	8	4	0.163	0.262	0.205	0.054	0.087	0.068	0.076	0.066	**0.466**
42	5	5	4	0.204	0.164	0.205	0.068	0.055	0.068	0.079	0.049	**0.383**
Weight	**0.33**	**0.33**	**0.33**			A*	0.108866	0.098268	0.119697			
						A^-	0.040825	0.032756	0.034199			

coefficient γ (Y_0 (j), Y_i (j)) can be expressed by Eq. (D.3) [64].

$$\gamma(Y_0(j), Y_i(j)) = \frac{\Delta \min + \zeta \Delta \max}{\Delta_{0i}(j) + \Delta \max} \tag{D.3}$$

Table D.1
GRA method's result.

No.	O	S	D	Normalization			Deviation sequence $\Delta_{0i}(j) = \lvert Y_o^*(j) - Y_i^*(j)\rvert$			Grey relational coefficient $\gamma(Y_0(j) - Y_i(j))$			Weighted grey relational grade
1	3.000	9.000	4.000	0.000	1.000	0.400	1.000	0.000	0.600	0.111	0.333	0.152	0.596
4	6.000	9.000	7.000	0.600	1.000	1.000	0.400	0.000	0.000	0.185	0.333	0.333	0.852
5	5.000	6.000	5.000	0.400	0.500	0.600	0.600	0.500	0.400	0.152	0.167	0.185	0.503
6	6.000	7.000	3.000	0.600	0.667	0.200	0.400	0.333	0.800	0.185	0.200	0.128	0.513
7	6.000	4.000	4.000	0.600	0.167	0.400	0.400	0.833	0.600	0.185	0.125	0.152	0.462
9	5.000	8.000	3.000	0.400	0.833	0.200	0.600	0.167	0.800	0.152	0.250	0.128	0.530
11	5.000	6.000	3.000	0.400	0.500	0.200	0.600	0.500	0.800	0.152	0.167	0.128	0.446
12	6.000	5.000	4.000	0.600	0.333	0.400	0.400	0.667	0.600	0.185	0.143	0.152	0.480
18	6.000	6.000	3.000	0.600	0.500	0.200	0.400	0.500	0.800	0.185	0.167	0.128	0.480
19	5.000	6.000	4.000	0.400	0.500	0.400	0.600	0.500	0.600	0.152	0.167	0.152	0.470
20	8.000	3.000	4.000	1.000	0.000	0.400	0.000	1.000	0.600	0.333	0.111	0.152	0.596
21	4.000	6.000	6.000	0.200	0.500	0.800	0.800	0.500	0.200	0.128	0.167	0.238	0.533
25	7.000	8.000	3.000	0.800	0.833	0.200	0.200	0.167	0.800	0.238	0.250	0.128	0.616
26	5.000	5.000	5.000	0.400	0.333	0.600	0.600	0.667	0.400	0.152	0.143	0.185	0.480
28	4.000	6.000	4.000	0.200	0.500	0.400	0.800	0.500	0.600	0.128	0.167	0.152	0.446
30	5.000	8.000	4.000	0.400	0.833	0.400	0.600	0.167	0.600	0.152	0.250	0.152	0.553
33	5.000	8.000	6.000	0.400	0.833	0.800	0.600	0.167	0.200	0.152	0.250	0.238	0.640
34	5.000	6.000	2.000	0.400	0.500	0.000	0.600	0.500	1.000	0.152	0.167	0.111	0.429
40	5.000	7.000	4.000	0.400	0.667	0.400	0.600	0.333	0.600	0.152	0.200	0.152	0.503
41	4.000	8.000	4.000	0.200	0.833	0.400	0.800	0.167	0.600	0.128	0.250	0.152	0.530
42	5.000	5.000	4.000	0.400	0.333	0.400	0.600	0.667	0.600	0.152	0.143	0.152	0.446
Weight	**0.33**	**0.33**	**0.33**										

where, $\Delta_{\max}$ will be equal to 1 and $\Delta_{\min}$ will be equal to 0, and ζ is the distinguishing coefficient. It will be 0.5 generally [64].

Step 5: Determination of weighted grey relational grade (GRG)

The grey relational grade is sum of the grey relational coefficients which is defined as follows,

$$\gamma(Y_0, Y_i) = \sum_{j=1}^{r} \gamma(Y_0(j), (Y_i(j)) \tag{D.4}$$

where γ (Y_0, Y_i) is the grey relational grade for the *i*th alternative and *r* the number of attributes (O, S, and D values). Furthermore, based on the influence of the attributes, the weights are given to the individual GRGs, and the resultant GRG is termed as weighted grey relational grade as shown in Eq. (D.5) [64]:

$$\gamma(Y_0, Y_i) = \sum_{j=1}^{r} w_1[\gamma(Y_0(j), (Y_i(j))] + w_2[(Y_0(j), Y_i(j))] + \cdots + w_r[(Y_0(j), Y_i(j))] \tag{D.5}$$

where w_1, w_2, and w_r are the weights associated with the individual attributes.

See Table D.1.

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