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Evaluating the academic scientific laboratories' safety by applying failure mode and effect analysis (FMEA) at the public university in Lebanon

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ABSTRACT

Workers at scientific academic laboratories are at risk of potential exposure to different types of hazards. The study's purpose was to assess the potential failure modes (FMs) of hazards facing them through the application of the Failure Mode and Effect Analysis (FMEA) method to propose corrective actions preventive actions (CAPA) to mitigate them and to improve the safety outcomes in these workplaces (WP) at the Lebanese public University (PbU). The potential FMs leading to accident occurrence in biological and chemical labs were identified and prioritized, their causes and effects were determined by applying two surveys, and the risk priority number (RPN) for each failure was calculated. A total of 24 FMs were identified. The most alarming FM having the highest RPN scores (80) was found in the workplace 'category requiring an emergency for corrective actions (CA), it is related to the unavailability of a hazard pictogram plot and the lack of labeling of chemicals and waste containers according to their categories. The FMs having RPN scores (75-60) requiring an urgent CA were assigned to other hazards of the WP, chemical, biological, and failure of the educational system. The need to program for the remaining FMs (RPN scores 20–48) is related to the safety, biological, physical, and radioactive categories 'hazards. It is recommended to apply continuously FMEA and implement the CA proposed for each detected FM in the scientific laboratories of the PbU in order to support the decision-makers to improve laboratory safety.

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1. Introduction

Academic scientific laboratories are environments devoted to learning and research with potential exposures to different types of hazards making them high-risk workplaces (WP) that might expose lab workers to accidents, and health problems and have negative effects on the environment [1–3].

These accidents could be due to negligence in performing risk assessment methods, failure to report all injuries, and the lack of training on proper safety in these labs [2,4].

Universities need to develop policies and programs to identify, measure, evaluate, and reduce work-related risks and to maintain a safe and healthy environment in their settings [5]. They also have to establish a proactive approach that integrates lab practices and associated risk mitigation through an effective risk management (RM) program [6]. In the context of health and safety and according to the Canadian Centre for Occupational Health and Safety (CCOHS), a hazard is “any of the sources of the potential damage that harms or has adverse health effects on something or someone” [7]. Besides, according to the Occupational Health and Safety Organization (OHSA), and regardless of the kind of the WP, the common hazards can be categorized into six core types: safety hazards (SH), biological hazards (BH), chemical hazards (CH), physical hazards (PH), ergonomic hazards (EH), and radioactive hazards (RH) [8].

Risk is described as a “probability or likelihood of developing a disease or getting injured, whereas hazard refers to the agent responsible” [9]. It is also defined as uncertainty about the occurrence and severity of the consequences of an activity with respect to something that humans value often focusing on negative or undesirable consequences [10]. According to International Organization for Standardization (ISO) 31,000, the risk management (RM) process is a “systematic application of management policies, procedures, and practices to the tasks of communication, consultation, establishing the context, identifying, analyzing, evaluating, treating, monitoring and reviewing risks” [11].

The identification of the potential risks in an organization is the most critical step in the whole process. It must be followed by the evaluation of the quality management process such as Failure Mode and Effect Analysis (FMEA).

Besides, an international standard was first published in 2004, with the most recent update coming in April 3, 2020, and primarily used in industries where the consequences of failures can be significant, such as automotive, aerospace, healthcare, manufacturing, and various other engineering sectors. It is developed by the International Electrotechnical Commission (IEC). This reference IEC 60812 provides a systematic method for identifying modes of failure together with their effects on the item or process and guidance on FMEA, including the failure modes, effects and criticality analysis (FMECA) variant, is planned, performed, documented and maintained [12].

FMEA offers a proactive approach to detecting failures in contrast to incident analysis and root cause analysis which are performed retrospectively [13].

It was originally developed as a reliability analysis tool by the United States (U.S) military in the 1940s, it was used by the National Aeronautics and Space Administration (NASA) in the 1960s and addressed security issues. It is a team-based, and structured process that includes diagramming or “mapping” the steps in a process, identifying the potential failure points and consequences of each, and ultimately determining the corrective actions (CA) to take actions to reduce its occurrence [6,14]. Its ultimate goal is to prevent the harm of potential hazards from reaching some laboratory personnel, reducing their frequency and severity, to make the systems safer [6,11,14].

In this regard, FMEA depends on prioritizing each FM on three factors: its frequency of occurrence (O), severity (S), and the detectability (D) using a well-defined scale for each factor according to three categories (critical, major, and minor). The critical and major FMs will then be monitored and their performance will be assessed following the application of the corrective measures [15].

A systemic study was conducted in Malaysia to provide a review of the risk assessment methods applied in the academic laboratory to identify the type of hazard commonly found and to address various control measures applied to overcome or eliminate the hazard. It was shown that the combination of qualitative and quantitative risk assessment methods such as bowtie and FMEA may be required to enhance the risk assessment process by utilizing the positive aspect of the both methods [16].

Moreover, due to the uncertainties, subjectivity, and linguistic judgment of the traditional FMEA approach for the evaluation of the FMs of each risk, two approaches were proposed based on the degree of match and fuzzy rule-base for prioritizing FMs, specifically intended to overcome such limitations of traditional FMEA [17].

In a recent study, an integrated novel approach was proposed and based on multi-criteria decision-making (MCDM) methods by combining Fuzzy Analytical Hierarchy Process (FAHP) with the modified Fuzzy Multi-Attribute Ideal Real Comparative Analysis (modified FMAIRCA), aiming to improve the risk assessment and overcome the drawbacks of the FMEA tool [18].

On the other hand, a case study of a university chemical laboratory has proposed an approach for risk assessment using incorporated several methodologies such as the FMEA, interval type-two fuzzy sets (IT2FSs), analytic hierarchy process (AHP) and Vlse Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) to identify, evaluate FMs and to calculate the risks scores, prioritize them and suggest their potential control measures [19].

Working in an academic laboratory environment is very challenging since students and researchers are exposed to various risks that can lead to an increasing rate of accidents having harmful effects on their health and productivity. In Lebanon, there is no national study highlighting the importance of the identification, analysis, and controlling of the potential hazards facing academic laboratory workers that can effectively contribute to reducing and anticipating these risks and increasing their productivity. Moreover, this study will enable lab personnel to participate in the promotion of a proactive risk management approach to effectively manage risks and to propose corrective and preventive actions when needed and in a further step to an effective guideline for good safety practices in scientific laboratories in respect to the international OHSA standards.

The main purpose of the present study is to assess and classify the potential risks/hazards in the scientific laboratories of the PbU in Lebanon through the application of the traditional FMEA method as a performance improvement tool and to determine, the effective CA or controls required to eliminate or mitigate these risks/hazards. This study could help develop specific laboratory safety guidelines, including a detailed description, and effective proactive strategies visualizing necessary control processes.

2. Materials and methods

2.1. Study design

The project was done in the research and practical scientific laboratories of the PbU in Lebanon from February 2020 to July 2021.

2.2. Team selection

A multidisciplinary team of 5 members with diverse expertise in the domain of RM and quality assurance in scientific laboratories was chosen. It consisted of a team leader or the facilitator (Ph.D. candidate), an epidemiologist with biostatistical skills, two researchers, and an expert in the RM domain and quality assurance. Their main responsibilities were the observation, analysis, and scoring of all possible processes of potential FMs and the development of the corresponding CAPA.

2.3. Data collection and targeted population

After obtaining approval from the Doctoral School of Science and Technology (DSST) to conduct this study, the potential hazards were identified using a survey done by face to face interviews in biological and chemical laboratories that were chosen as a good model of FMEA analysis in the present study. They were the most active laboratories exposed to several types of hazards including; chemical substances, biological agents, radioactive products, physical risks, and general hazards related to the WP and workers' activities in the laboratories. The observed population includes researchers, laboratory assistants, and master's degree and Ph.D. candidates of both genders working at either research or practical laboratories of scientific faculties of the PbU. Two hundred twenty participants were recruited. Undergraduate students and other fields of laboratories were excluded.

2.4. Ethical considerations

Before starting the study, a permission letter was addressed from the Dean of DSST to the direction of each faculty (ID-18-757) to facilitate access to the targeted scientific laboratories, and ethical approval was granted by the American University of Beirut and its Institutional Review Board (IRB ID-SBS-2019-0384). Informed consent was taken from the participants. Anonymity, privacy, and confidentiality were respected throughout the study, and participant's data was registered only under a code.

2.5. Analysis methods

The study consists of 9 steps (Supplementary Fig. 1) [6]. Regrouped into four main stages, the first stage includes the process mapping that identifies activity steps in the scientific laboratories as described in the flow diagram (Supplementary Fig. 2). The second stage lists the potential hazards facing scientific laboratory workers that are known to be problem-prone or having potential risk.

The process mapping of the FMEA was created according to the International Standard ISO 31000:2018 Risk Management Guidelines [20]. It was reviewed and validated by an expert in the RM of scientific laboratories.

The FMEA team members identified the potential FMs related to the labs and classified them by categories using as reference "the laboratory safety principles OHSA standards" [21].

The third stage identifies all possible reasons for the occurrence of failures and their effects. It was followed by prioritizing the potential FMs based on the specific risk priority numbers (RPN) and deciding the threshold/Cut-off of these FMs.

The estimated frequency of O, S, and the likelihood of D scores of the failures were assessed by using the numerical scores ranging from 1 to 5 as described in Table 1 [22].

The overall RPN was calculated as follows: RPN=S x O x D. According to the defined scale in Table 2, the RPN ranged from 1 to 125.

Table 1
FMEA scores of occurrence, severity, and detectability of potential hazards in the scientific laboratories.

Occurrence (% of the time)		Severity		Detectability	
Score	Description	Score	Description	Score	Description
1	Rare (<10 %)	1	Insignificant	1	Almost certain
2	Unlikely (10–25 %	2	Minor	2	High
3	Possible (25–45)	3	Moderate	3	Moderate
4	Likely (45–65 %)	4	Major	4	Low
5	Almost certain to certain (65–90 %)	5	Catastrophic	5	Remote

Source:(Sellappan & Palanikumar, 2013; Rah et al., 2016; Bozdag et al., 2015)

Table 2
Risk matrix determination in academic laboratories.

S / O × D	1	2	3	4	5
5	5	10	15	20	25
10	10	20	30	40	50
15	15	30	45	60	75
20	20	40	60	80	100
25	25	50	75	100	125

The mean of RPNs of each category of the potential FMs was also calculated [23,24].

In addition, the range of risk acceptability was determined. The prioritization of the most critical potential FMs was selected based on the RPN scores of each category. Then, the periodization of intervention for the identified FMs was categorized into four different areas as follows [25]. The FMs with RPN ≥ 80 highlighted in red, required an emergency of CA (risk elimination), then, the FMs 40 ≤ RPN ≤ 75 highlighted in orange, require an urgent CA for intervention (programming & controlling), and the FMs having 20 ≤ RPN ≤ 39 highlighted in yellow need to program CA (programming & controlling), while FMs with RPN < 20 highlighted in green color need to be monitored (accepted).

At the final stage, once the FMs of the potential hazards have been prioritized according to the RPNs means of each hazard category and its RPN score, the team developed strategies and proposed to implement the CA plans for FMs RPN's greater than 20 [25].

Table 3
Ranking of the potential CH category facing laboratory workers at the academic scientific laboratories.

Failure Mode#	Causes	Effects	O	S	D	RPN Score	CA	PA
FM1–Splashing /exposure to chemical liquid	– Improper transportation, handling, storage of chemicals – Non-compliance with lab safety precautions – Wearing not easily removable lab coats in case of accident – Wearing open-toed shoes	– Short term health effects: poisoning, skin burn – Long term health effects: irreversible destruction of living tissues, carcinogen asbestos – Spontaneous fire and explosions from flammable chemicals –	5	5	3	**75**	– Use the smallest amount of chemical required for the experiment – Substitute hazardous chemicals with low-toxic chemicals – Manipulate experiments involving hazardous or volatile materials in a fume hood	– Ensure the availability and use of appropriate PPE (chemically resistant laboratory coats, safety shields, splash goggles, gloves) – Develop SOPs for the safe use, handling, storage, and transport of CH – Prohibit wearing of sandals or open-toed shoes
FM2–Exposure to chemical solid	– Improper handling and storage of chemical solid – Unfamiliarity with CH	– Skin/eye irritation – Burns	3	4	3	**36**	– Follow safe procedures when handling hazardous solid material in the manner prescribed by the MSDS	– Ensure the availability and use of appropriate PPEs – Develop SOPs for the safe use, handling, storage, and transport of CH
FM3- Exposure to flammable or oxidizing gases	– Improper handling and storage of flammable or oxidizing gas – Unavailability of the fume hood – Using toxic and corrosive gases	– Serious poisoning – Chronic irritation of the respiratory system – Destruction of the skin and eye tissue – Deterioration of materials	2	5	3	**30**	– Conduct a refresher training – Manipulate experiments involving hazardous or volatile materials in a fume hood	– Follow safe procedures when handling flammable or oxidizing gases in the manner prescribed by the MSDS – Ensure the availability and use of appropriate PPEs
FM4- Exposure to high levels of radioactive materials	– Using radioactive materials without lab safety precautions – inhaling, ingesting, or absorbing radioactive chemicals	– Harmful effects on humans and the environment – Acute radiation syndrome – Long-term health effects	1	5	3	**15**		-Use proper radiation shields -Wear radiation monitor badges when appropriate. -Use time, distance, shielding, and containment -Label contaminated items and containers of radioactive material

Table 4
Ranking of the potential BH category facing laboratory workers at the academic scientific laboratories.

Failure Mode #	Causes	Effects	O	S	D	RPN Score	CA	PA
FM5- Exposure to microbial agents	– Working with microorganisms or contaminated biological fluid specimens without safety measures – Splashing of contaminated biological fluid – Unavailability of biosafety cabinets	– Bacterial infection based upon the suspected existing pathogens in the specimen	3	5	3	**45**	– Conduct a biosafety program and provide a formal biosafety manual – Provide appropriate HK – Decontaminate and monitor periodically the environmental WP to determine the extent of exposure to airborne biological or surface contamination	– Ensure the availability of a biosafety cabinets, a lockable door and appropriate PPEs – Develop SOPs for safe handling, storage, transport of BH and disposal of biological waste
FM6- Contact with contaminant biological fluid			3	4	4	**48**	– Use of appropriate PPEs	– Provide training regarding the lab practice safety measures according to OHSA standards to reduce the likelihood of biological fluid exposure
FM7- Exposure to animal bites during Lab works	- Use of animals without safety measures and without approval by the animal experimentation committee	- Potential risk of zoonotic diseases and allergies - Bacterial disease affecting the nervous system (Tetanus)	1	4	1	**4**	– Reduce skin contact with animal products by using gloves, lab coats, and approved particulate respirators with face shields	– Practicing good personal hygiene – Follow proper sharps management practices

3. Results

In the academic scientific laboratories of the PbU, we have identified 24 FMs facing laboratory workers with RPN scores ranging from 4 to 80, they are related to six categories of potential hazards (CH, BH, PH, SH, FES, WP) (Tables 3–8).

Table 3 showed 4 FMs in the CH category. The accidental splashing/exposure to chemical liquid had the highest RPN (75) that needs urgent intervention, and 2 other FMs had 20<RPN<40 that need to program CA programmed, they were due to the exposure to solid chemical, flammable or oxidizing gases, mainly due to the improper handling. These FMs have short or long-term health effects mainly on the respiratory system, skin, and eyes. They may also have a harmful effect on the environment and destructive effects on the WP materials (corrosion, explosion). It is required to follow the safety procedures when handling these hazardous chemicals in the manner prescribed by the MSDS, ensure the availability and the use of appropriate PPEs, and develop SOPs.

The 4th FM in this category was due to the exposure to a high level of radioactive materials with RPN >20 highlighted in green color that needs to be monitored (accepted).

As for the BH category (Table 4), 3 FMs were detected, two of them were caused by exposure to microbial agents (RPN = 45), and contaminant biological fluid (RPN = 48) without safety measures and unavailability of biosafety cabinets. These FMs can lead to bacterial infections. They need an urgent CA to be programmed and controlled such as; ensuring the availability of biosafety cabinets, appropriate use of PPEs, conducting a biosafety program, developing SOPs for safe handling, storage, and transport of biological hazards, and ensuring periodic monitoring of environmental WP. The third FM (RPN = 4) was related to animal bites during the research experiment that was accepted and needs to be monitored.

Regarding the PH (Table 5), 6 FMs were identified. Two of them were caused by the excessive noise from equipment at the WP (RPN = 48) and the exposure to dust fume due to chemical explosion (RPN = 40). These FMs can lead to temporary or permanent hearing loss, severe headaches, depression, irritability, productivity, and increased errors at work. Their causes were mainly due to working noisy equipment, inadequate hearing protection, and lacking lab equipment maintenance. They need urgent CA (programming & controlling) such as; monitoring the noise level, use of proper hearing protection devices, conducting strict maintenance of the equipment, post the ear protection safety symbol to indicate that lab workers are in a dangerously high decibel noise range, use of appropriate PPEs, manipulate chemical experiments under a fume hood and follow the basic OHSA requirements for best practices, regular inspection, and maintenance of the fume hood. However, the FMs related to thermal chemical or electrical contact, injuries by sharp instruments, thermal stress from overheating, and dust fumes exposure due to chemical reactions (30>RPN>20) need to be programmed by taking adequate and necessary safety measures. These FMs can lead to burning infection, and complications, skin wounds, heat stroke, exhaustion, cramps or rashes, and respiratory problems.

Regarding the SH (Table 6), 5 FMs were identified. The most critical was the respiratory sensitization by inhalation of volatile

Table 5
Ranking of the potential PH category facing laboratory workers at the academic scientific laboratories.

Failure Mode #	Causes	Effects	O	S	D	RPN Score	CA	PA
FM8-Exposure to excessive noise from equipment at the WP	— Working with noisy equipment — Inadequate hearing protection or prolonged exposure to noise — Lack of maintenance of lab equipment	— Temporary or permanent hearing loss, severe headache — Depression; irritability; — Decreased focusing in the WP and productivity — Tinnitus — Increased errors in works —	4	3	4	**48**	— Use of proper hearing protection devices — Post the ear protection safety symbol to indicate that lab workers are in a dangerously high decibel noise range	— Monitor the level of noise in the WP — Conduct a strict maintenance of equipment
FM9- Exposure to thermal chemical, or electrical contact	— Hastily or improper handling of hot items — Contact with radiation, chemical products — Electrical contact with imperfect wiring — Poor engineering control at lab	— Burn infection — Severe local and systemic burn complications	3	5	2	**30**	— Conduct a refresh training on fire and electrical shock incidents to be able to evacuate personnel and call for emergency assistance — Inspect wiring of equipment before each use — Repair all damaged receptacles and portable electrical equipment before placing them back into service	— Ensure safe work practices when handling electrical equipment — Make sure that all the electrical equipment is properly grounded — Keep electrical equipment away from water/chemical or their spills
FM10- Injuries by sharp instruments	— Working under stressful situation, poor concentration, and carelessness — Negligence of safety precautions and wearing of cut resistant gloves	— Skin wound contact with hazardous materials — Increase infection's risk	3	4	2	**24**	— Educate lab workers about the safe use of sharp instruments — Ensure the availability and the use of cut resistant or mesh gloves in the lab	-
FM11- Thermal stress from overheating	— Working in extreme hot or cold temperatures — Direct physical contact with hot objects — Mechanical failures of steam or water hammer	— Heat stroke, heat exhaustion, heat cramps or heat rashes	3	3	4	**36**	— Instruct lab workers to recognize heat stress — Isolate the source of heat and or humidity by environmental controls — Wear proper reflective clothing to prevent heat stress	— Encourage lab workers to maintain physical fitness and take rest breaks in a cool, well-ventilated area — Inspect the use of engineering controls (ventilation systems)
FM12- Dust fumes exposure due to chemical reaction, heating, detonation	— Heat or mix of chemicals, with poor ventilation — Negligence to use PPEs — Lack of regular maintenance of the fume hood	— Health respiratory complications: Bronchitis, asthma and in extreme cases lung cancer	2	3	4	**24**	— Ensure the availability of a closed handling systems	— Ensure that the engineering controls (e.g. ventilation) are operating
FM13- Dust fumes exposure due to chemical explosion			2	5	4	**40**	— Follow basic OHSA requirements for best practices, regular inspection, testing, and maintenance of the fume hood	— Ensure the use of appropriate PPEs — Ensure to manipulate chemical experiments under fume hood

chemical or harmful gas fumes (RPN = 60), followed by 2 other FMs related, to skin corrosion by CH or BH and eye irritation (RPN = 40). They need an urgent CA. Their main causes were poorly ventilated space, not working under the fume hood, neglecting to wear PPE, and unavailability of eyewash or shower station. Their effects were respiratory disorders, and skin or eye irritation. They require to perform manipulations in a fume hood, wear appropriate respiratory protection, provide adequate ventilation in storage areas, especially for toxics with high vapor pressures, train laboratory workers on the proper procedures for opening windows, using ventilation fans, and using equipment to measure the amount of gas emission in a room, ensure the storage of toxic chemicals in unbreakable chemically-resistant containers and perform periodic environmental monitoring of the pollutants to measure pollution levels according to Air Quality Index (AQI), and ensure that every laboratory worker is familiar with the location, and types of hazards to which they will be exposed.

Besides, a need to program CA was proposed for the FM regarding the handling of sharp tools (RPN = 36) that leads to health hazards, and possible exposure to secondary microbial infections. It requires making available proper PPE, training regarding the safe storage, handling, and disposal of sharp tools and sharps containers, filling incident reports and laboratory safety, and communicating the hazard categories through the plot of hazard pictogram. The accepted FM regarding the oral ingestion of a toxic dose of a substance (RPN = 15) needs to be monitored.

Regarding the FES (Table 7), we have noticed one FM (RPN = 60) related to the inadequacy and inefficiency of training regarding measures and risks related to the WP, the lack of MSDS, and posted lab safety instructions. This is due to the lack of regular training on lab safety measures, protocols, and procedures and the absence of a lab safety officer/Environmental Health & Safety Office. This FM can lead to the lack of awareness and skills required to safely use equipment, hazardous products and supplies, unsafe work environments, and increasing injury and accident occurrences. An urgent CA is needed to be programmed and controlled by conducting initial training of laboratory workers prior to their research activities, providing interactive training through critical reading, evaluating and using MSDS and other authority safety information sources, and performing repeated simulations to ensure the proper functioning of the biannual "white plan".

Regarding the WP category (Table 8), 5 FMs were identified. Where the most alarming FMs were caused by the unavailability of

Table 6
Ranking of the potential SH category facing laboratory workers at the academic scientific laboratories.

Failure Mode #	Causes	Effects	O	S	D	RPN Score	CA	PA
FM14- Respiratory sensitization by inhalation of volatile, chemical or harmful gas fumes	- Poorly ventilated space - Not working under the fume hood	- Respiratory disorders - Respiratory failure, spasm, bronchitis - Pulmonary congestion, oedema of the larynx, headaches, nausea, and even fainting	5	4	3	**60**	- Wear appropriate respiratory protection - Provide adequate ventilation in storage areas especially for toxics with high vapour pressures - Train laboratory workers on the proper procedures for opening windows, using ventilation fans and equipment to measure the amount of gas emission in a room	- Ensure the storage of toxic chemicals in unbreakable chemically-resistant containers - Ensure periodic inspections of work operations - Perform manipulations in a chemical fume hood - Perform periodic environmental monitoring of the pollutants to measure pollution levels according to AQI
FM15- Handling sharp tools	- Mishandling sharps tools during lab experiments - Carelessness and lack of precautions	- Health hazards - Possible exposure to secondary microbial infections (wound infections)	3	3	4	**36**	- Provide proper PPEs - Provide training for safe storage, handling, and disposal of laboratory sharp tools - Fill incident report - Substitute glassware with plastic ware, desiccators, wherever it is possible	- Communicate the hazard categories through the plot of hazard pictograms - Check the glassware to ensure the absence of cracks or scratches
FM16- Oral ingestion of toxic dose of substance	- Eating/handling food in areas where toxic substances are used or eating food without washing hands - Mouth pipetting - Storage of food or beverage in the laboratory refrigerators and freezers	- Severe damage to the digestive system	1	5	3	**15**	- Work under the fume hood when handling chemicals and avoid mouth pipetting - Review the MSDS for each of chemicals to determine the consequences in case of accident or exposure - Train personal on hand washing	- Respect the PELs established by OSHA
FM17- Skin corrosion by chemicals or biological hazards	- Neglecting to wear PPE - Unavailability of eyewash or shower station	- Irritation of the skin - Eczematous lesions	5	4	2	**40**	- Use carefully the biological hazard specimen and use only approved containers to transfer potentially irritating chemicals - Perform a regular inspection by superiors of appropriate use of PPEs	- Ensure that every laboratory worker is familiar with the location, types of hazard to which they will be exposed - Ensure the availability of appropriate PPEs
FM18- Eyes irritation	- Neglecting to wear PPE - Splashing of harmful products	- Irritation of eyes - Serious eye damage	5	4	2	**40**	- Provide and check the use of appropriate PPEs	

Table 7
Ranking of the potential FES hazard category facing laboratory workers at the academic scientific laboratories.

Failure Mode #	Causes	Effects	O	S	D	RPN Score	CA	PA
FM19- Inadequacy and inefficiency of training regarding measures and risks related to the WP	- Lack of regular training on lab safety measures - Lack of protocols and procedures - Absence of lab safety officer/ Environmental Health & Safety Office	- Lack of the awareness and skills required to safely use equipment, hazardous products and supplies - Unsafe work environments - Increasing of injury and accident occurrences	5	4	3	**60**	- Conduct an initial training of laboratory workers prior to their research activities - Provide interactive training in through critical reading, evaluate and use of MSDS and other authority safety information sources	- Perform repeated simulations to ensure the proper functioning of the biannual "white plan"

Table 8
Ranking of the potential WP hazard category facing laboratory workers at the academic scientific laboratories.

Failure Mode #	Causes	Effects	O	S	D	RPN Score	CA	PA
FM20- Unavailability of hazard pictogram plot	- Neglecting and ignoring the importance to post the hazard pictogram plot on the labs wall - Inappropriate storage of chemicals	- Missing of quick indication of the hazards risk - Fire and explosions - Unfamiliarity of the staff with the pictograms and hazard codes	5	4	4	**80**	- Provide and post a plot of hazard pictograms in each laboratory using hazardous chemicals	- Ensure that the staff are familiar with the pictogram and hazard codes to mark risks
FM21- Lack of MSDS and posted lab safety instructions	- Ignoring of the importance of MSDS and posting lab safety instructions	- Increase the potential of exposure to hazards and incidence leading to illness and injuries - Increase of equipment damage - Missing of safety information	5	3	4	**60**	- Warning signs with the appropriate safety symbols should be posted at the laboratory entrance and inside the working area	- Ensure the availability and accessibility at the labs of hard or soft copies of MSDS for hazardous substances from the manufacturer, or supplier
FM22- Lack of Labelling of chemical and waste containers according to their categories	- Lack of training regarding the proper labelling of hazardous wastes - Inappropriate management of chemicals	- Increasing the threats on the occupational hazards - Spontaneous fire and explosions	5	4	4	**80**	- Collect wastes in specific bins with appropriate labels and signs and keep it inside the fume hood to be treated later	- Ensure the proper labelling of waste containers according to their categories - Ensure that all chemicals, biological, or radioactive materials are identified and labelled
FM23- Lack of first aid kit	- Lack of emergency trolley and its regular inspection	- A simple injury could become severe fatalities	5	5	3	**75**	- Provide an emergency trolley and check it regularly	- Apply a laboratory first aid checklist according to OHSA requirements
FM24-Unavailability of devices to detect the fire	- Financial shortage - Lack of smoke detector or fire extinguisher - Lack of fire "simulation" in regular time - Keeping fire extinguishers malfunctioning	- Lack of early detection of a fire and early warning for emergency action - Delay of rapid and safe evacuation - Increasing the incidence of fatalities, injuries, and environmental damage	4	4	3	**48**	- Ensure the installation of smoke detectors at chemical labs and storage area	- Conduct regular inspection, and maintenance of smoke detectors and fire extinguishers - Conduct a periodic fire evacuation drills

hazard pictogram plots on the lab walls and the lack of labeling of chemical and waste containers according to their categories (RPN = 80). These FMs require urgent intervention. Their main effects were: the unfamiliarity of the staff with the pictograms and hazard codes, increasing potential exposure to hazards occupational hazards, and spontaneous fire and explosions. The proposed CA were to provide and ensure that the staff is familiar with the pictogram and hazard codes, and ensure the proper collection and labeling of chemicals and waste containers according to their categories. In addition, the other FMs in the category were related to the lack of MSDS and lab safety instructions (RPN = 60), the unavailability of a first aid kit (RPN = 75), and the improper functioning of the fire detector (RPN = 48). Their causes were mainly due to ignoring the importance of MSDS and posting lab safety instructions, lack of emergency trolley and its regular inspection, financial shortage, smoke detector or fire extinguisher, fire "simulation" in regular time, and keeping fire extinguishers malfunctioning. Their main effects were increasing the potential of exposure to hazards and incidence leading to illness and injuries, equipment damage, lack of early detection of a fire, delay of rapid and safe evacuation, and increasing the incidence of fatalities, injuries, and environmental damage. These FMs need urgent intervention through the installation of smoke detectors at chemical labs and storage areas, regular inspection, maintenance of smoke detectors and fire extinguishers, and conducting periodic fire evacuation drills.

4. Discussion

In the scientific laboratories of the PbU, we have identified 24 potential FMs to be taken into consideration related to 6 categories. Their possible causes and effects were stated, and we have suggested their related CA improve the safety in these Labs. The most critical FMs categories were FES, WP, CH, and to a lesser extent SH, BH, PH, and RH.

An emergency for CA was assigned for the highest RPN scores (≥80) related to the unavailability of hazard pictogram plots, unlabeled chemical containers, and waste containers according to their categories. This is consistent with a study done in a chemical laboratory at the National Defense University of Malaysia (NDUM) showing that the incorrect labeling of chemicals had led to minor explosion and that performing lab experiments using chemicals with unknown status would lead to harmful effects and unwanted chemical reactions [26]. This is due to the unavailability of shower and eyewash stations, which are in line with previous studies indicating that the majority of their academic laboratories were not equipped with safety showers, eyewash stations, and even biological safety cabinets (BSCs). They were often ignored due to the lack of a safety culture [27]. This will increase exposure to biohazards and cross-contamination [28].

On other hand, an urgent CA was assigned to the accidental splashing/exposure to chemical liquid and the unavailability of a first aid kit. Our previous study [29]. Showed that laboratory workers were exposed to several potential hazards including chemical (corrosive flammable, toxic) hazards. Another study reported that few laboratories have first-aid and emergency spill kits [30].

Besides, respiratory sensitization by inhalation of volatile chemicals or harmful gas fumes has required an urgent CA. Our result was in concordance with a study showing identical potential accidents due to the inhalation of harmful gases leading to skin irritation/eye and burns [31].

The inadequacy and inefficiency of training on ESE and safety measures shown in our results were in agreement with studies stating that the lab personnel's unfamiliarity with chemical warning signals and the lack of personnel training on ESE management had led to laboratory accidents [32,33].

In addition, previous studies [34,35]. Revealed a limited comprehension of safety hazard symbols among chemical engineering students due to the lack of safety knowledge and limited safety training. This was due to the low compliance in the research labs of the PbU with MSDS and the posting of the lab safety signage and emergency hazards cautions [29]. Another study conducted in chemical laboratories of the Kingdom of Saudi Arabia (KSA) University reported that their labs mentioned the lack of posting emergency contact numbers, MSDSs, and a lack of lab hazard signs required to minimize accidents from exposure to chemicals [36].

Our findings were also consistent with a previous study showing that laboratory workers are exposed to several potential hazards including chemicals. These FMS can be avoided by good lab safety knowledge and working practices [37].

Moreover, our results showed that FMs' causes were related to dust fumes, exposure from a chemical explosion, skin corrosion by chemicals or biological hazards, and eye irritation by the splashing of harmful products. They agreed with the data shown in a previous study [27].

Regarding the unavailability of smoke detectors observed in our study, there are emergency standards required by OHSA (29 CFR 1910. 140–164), to reduce fire deaths and injuries due to the fall of hazards in the work environment [35].

> Not posted safety instructions are an important FM that leads to accidents occurrence. It is required by OHSA to minimize the risks, and damages to the lab environment [https://www.osha.go].

Furthermore, a need to program was related to the following FMs: accidental exposure to chemical solids, flammable or oxidizing gases, and burn by exposure to thermal stress from overheating or electrical contact. These potential SH were also revealed by a study showing that laboratory accidents were frequently associated with chemicals [38]. The remaining causes were due to handling of sharp tools and cutting by sharp instruments, which are similar to a study conducted in chemistry laboratories of a Mexican university showing that handling hot or sharp materials due to missing safety education in academic research laboratories [38].

In similarity with our findings, the unavailability of chemical fume hoods, and fire extinguishers, and the lack of PPEs, were stated in a previous study [3].

Regarding FMs that were accepted but required monitoring, they were assigned to electrocution by contact with electric devices and the incompliance with SWM. The exposure to animal bites during the research experiment, exposure to a high level of radioactive materials, and acute toxicity by oral swallowing of a dose of substance. It is recommended by the OHSA guidelines that appropriate electrical installation practices ensure employee safety and maintain equipment integrity and that the proper management of unused or old chemical hazardous waste is required to decrease their harmful effects on health and the environment [32].

In order to sustain a safe WP and avoid accidents, the proposed CAPA suggested by our team members insisted on the importance of compliance with international safety regulations, the presence of lab safety guidelines and SOPs, the need to post lab safety symbols and emergency signage, the understanding of hazard communicated information about laboratory safety signs including specific hazardous agents (biological, chemical, radiological), PH (lasers, magnetic fields), the respect of stated precautions (no food or drink allowed), offering a refresher of safety training, the availability and best practices of MSDS, PPEs, and ESE, the regular inspection of chemical labeling and storage, the effective HWM of expired chemical storing, separation, and the labeling of chemical waste containers. All these strategies will ensure safety in the laboratories and ensure workers' health and protect the environment. Our results were similar to the results of a study showing that laboratory accidents at universities can be prevented by the engineering control systems [3]., and with another study reporting that the application of the following controlling measures can lead to mitigate the risk of chemical exposure among laboratory staff: safety training, posting of safety regulations in the laboratories, and good use of PPEs [35].

Moreover, our proposed CAPA regarding proper training on ESE and safety measures, conducting regular maintenance of ESE, the appropriate labeling of hazardous materials, the availability of PPEs, and the safe handling and storage of hazardous chemicals present in laboratory work areas were also in agreement with a study showing that participation of lab workers in safety training may increase their commitment to avoid the potential hazards and reduce laboratory's injuries [39]. and other studies were done in Southern Italy and PbU in Costa Rica reporting that the maintenance of laboratories' cleanliness, the functionality [40]. of safety equipment, the proper interpretation of labels of all hazardous chemicals; the availability of appropriate PPEs, the compliance to safety procedures during chemicals handling, the installation and the regular inspection of functioning of ESE, will greatly decrease the likelihood and severity of injuries [26,32,33,36].

Our study has meaningful strengths, it is the first initiative to evaluate the risks encountered and safety adopted in educational laboratories at Lebanon to improve the quality performance of academic laboratories' safety.

In addition, it provides academics labs with a guideline and insight into further application of the FMEA tool that can serve as a checklist for identification of FM, their effects, and the causes of the most critical failures for effectively improving environmental safety in scientific laboratories in concordance with international occupational and health standards and avoid the severity of different categories of laboratory potential hazards.

However, this study has some limitations that must be considered. It was difficult to make a direct comparison of the scores of FMs because of the lack of studies quantifying the RPNs scores using FMEA analysis in academic research laboratory settings. The mathematical accuracy of calculating RPN score values has been a concern for researchers as well and it is a known limitation of FMEA [24,35,40–43]. Subjectivity and inability to generalize the results are other limitations of this study, they are as also reported in another study [24]. It was a convenience sample. In this regard, It is great of importance to apply the novel approach for treating uncertainty in the multi-criteria decision-making process by introducing interval rough numbers to enable a more realistic presentation of the decision attribute values of the FMEA team members [44].

In addition, the limitation was due to the scope of the laboratory safety, which was rather general. The scope of laboratory safety at universities should cover other important aspects of potential hazards such as psychological, and ergonomic hazards [33]., legislative requirements, technical standards, procedures related to the work, health protection, and worksite ergonomics [19].

5. Conclusion

This study shows that the FMEA offers tools for predicting failure and for implementing changes to prevent its future occurrence. They are applied as lab safety processes to raise effectiveness and efficiency and to enhance compliance with lab safety measures.

Findings revealed that all potential hazards are categorized in the labs, the FMs are identified for each hazard category and all the possible causes and effects of these FMs were listed according to their rating. Based on the RPN analysis FM causes, CAPA was addressed to strictly adhere to the guidelines for safe practices in the laboratory setting. The refresher safety training is very important to increase lab workers' efficiency and awareness about the potential hazards so that correct precautions and safeguards are learned and practiced. Once the CAPA is applied, risk control review and monitoring activities are needed to assess the impact of the preventive actions in the same laboratories conducting an FMEA of the redesigned process to determine the percent reduction in FMs RPN [45].

We recommend establishing the University Environmental Health & Safety (UEHS) office to aid labs in achieving regulatory compliance and developing proactive strategies, and to apply the FMEA tool as a continuous project of RM in the academic scientific laboratories. This application is intended to help the decision-makers and the employees to reduce the inherent risks and to improve laboratory safety.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Inaam Nasrallah: Investigation, Resources, Visualization, Writing – original draft. **Ibtissam Sabbah:** Investigation, Methodology, Resources, Supervision, Visualization. **Chadia Haddad:** Formal analysis. **Lina Ismaiil:** Writing – review & editing. **Jana Kotaich:** Visualization, Writing – review & editing. **Pascale Salameh:** Data curation, Methodology. **Assem EL. Kak:** Project administration. **Rihab Nasr:** Conceptualization, Resources, Supervision. **Wafa Bawab:** Conceptualization, Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

[1] O. Al-Obaidi, M. Abdallh, W. Al-Dahhan, Risk assessment in postgraduate laboratories, J Pub Health Catalog 1 (3) (2018) 1–4, https://doi.org/10.35841/public-health-nutrition.1.3.82-85, 2 J Pub Health Catalog 2018 Volume 1 Issue. 2018;3:3.

[2] I.M. Nasrallah, A.K. El Kak, L.A. Ismaiil, R.R. Nasr, W.T. Bawab, Prevalence of Accident Occurrence Among Scientific Laboratory Workers of the Public University in Lebanon and the Impact of Safety Measures. Safety and Health at Work, 2022, https://doi.org/10.1016/j.shaw.2022.02.001.

[3] J.E. Steward, V.L. Wilson, W.-H. Wang, Evaluation of safety climate at a major public university, J. Chem. Health Saf. 23 (4) (2016) 4–12, https://doi.org/10.1016/j.jchas.2015.10.016.

[4] M.B. Mulcahy, C. Boylan, S. Sigmann, R. Stuart, Using bowtie methodology to support laboratory hazard identification, risk management, and incident analysis, J. Chem. Health Saf. 24 (3) (2017) 14–20, https://doi.org/10.1016/j.jchas.2016.10.003.

[5] A. Dehdashti, F. Fatemi, M. Jannati, F. Asadi, M.B. Kangarloo, Applying health, safety, and environmental risk assessment at academic settings, BMC Publ. Health 20 (1) (2020) 1–7, https://doi.org/10.1186/s12889-020-09419-5.

[6] A. Mascia, A. Cirafici, A. Bongiovanni, G. Colotti, G. Lacerra, M. Di Carlo, et al., A failure mode and effect analysis (FMEA)-based approach for risk assessment of scientific processes in non-regulated research laboratories, Accred Qual. Assur. 25 (5) (2020) 311–321, https://doi.org/10.1007/s00769-020-01441-9.

[7] E. O'Grady, Preventing further injury and illness in the lab, Can. J. Med. Lab Sci. 83 (3) (2021) 5–6.

[8] D. Michaels, G.R. Wagner, Occupational safety and health administration (OSHA) and worker safety during the COVID-19 pandemic, JAMA 324 (14) (2020) 1389–1390, https://doi.org/10.1001/jama.2020.16343.

[9] H.-C. Liu, L. Liu, N. Liu, Risk evaluation approaches in failure mode and effects analysis: a literature review, Expert Syst. Appl. 40 (2) (2013) 828–838, https://doi.org/10.1016/j.eswa.2012.08.010.

[10] A. Šotić, R. Rajić, The review of the definition of risk-online, Journal of Applied Knowledge Management (2015).

[11] R. Ivanova, ISO 31000–prerequisite for strategic risk management in the activities of organizations, Izvestia Journal of the Union of Scientists-Varna Economic Sciences Series 10 (1) (2021) 55–62.

[12] Commission IE, IEC 60812: 2018–Failure Modes and Effects Analysis (FMEA and FMECA),(International Standard vol. 3, IEC, Geneva, Switzerland, 2018. August 10.

[13] J.L. Anjalee, V. Rutter, N. Samaranayake, Application of failure mode and effects analysis (FMEA) to improve medication safety in the dispensing process–a study at a teaching hospital, Sri Lanka, BMC Publ. Health 21 (1) (2021) 1–13, https://doi.org/10.1186/s12889-021-11369-5.

[14] B. Dhillon, Failure modes and effects analysis—bibliography, Microelectron. Reliab. 32 (5) (1992) 719–731, https://doi.org/10.1016/0026-2714(92)90630-4.

[15] H. Sabati, A. Mohsenzadeh, N. Khelghati, Control of clinical laboratory errors by FMEA model, in: Contemporary Topics in Patient Safety-, vol. 1, IntechOpen, 2021.

[16] N.A.A. Wahab, N.A. Aqila, N. Isa, N.I. Husin, A.M. Zin, M. Mokhtar, et al., A systematic review on hazard identification, risk assessment and risk control in academic laboratory, Journal of Advanced Research in Applied Sciences and Engineering Technology 24 (1) (2021) 47–62, https://doi.org/10.37934/araset.24.1.4762.

[17] H. Gargama, S.K. Chaturvedi, Criticality assessment models for failure mode effects and criticality analysis using fuzzy logic, IEEE Trans. Reliab. 60 (1) (2011) 102–110, https://doi.org/10.1109/TR.2010.2103672.

[18] S. Boral, I. Howard, S.K. Chaturvedi, K. McKee, V.N.A. Naikan, An integrated approach for fuzzy failure modes and effects analysis using fuzzy AHP and fuzzy MAIRCA, Eng. Fail. Anal. 108 (2020), 104195, https://doi.org/10.1016/j.engfailanal.2019.104195.

[19] Y. Ozdemir, M. Gul, E. Celik, Assessment of occupational hazards and associated risks in fuzzy environment: a case study of a university chemical laboratory. Human and Ecological Risk Assessment, Int. J. 23 (4) (2017) 895–924, https://doi.org/10.1080/10807039.2017.1292844.

[20] ISO.ISO G, ISO 31000:2018 Risk management — Guidelines, 2022. https://www.iso.org/standard/65694.html.

[21] O. Safety, H. Administration, Laboratory Safety Guidance, Occupational Safety and Health Administration US OSHA, 2011.

[22] M. Lesbats, Précis de gestion des risques: L'essentiel du cours, fiches-outils et exercices corrigés, Dunod, 2012.

[23] D.C. Pangestuti, H. Nastiti, R. Husniaty, Failure mode and effect analysis (FMEA) for mitigation of operational risk, INOVASI 17 (3) (2021) 593–602.

[24] N. Sellappan, D. Nagarajan, K. Palanikumar, Evaluation of risk priority number (RPN) in design failure modes and effects analysis (DFMEA) using factor analysis, Int. J. Appl. Eng. Res. 10 (14) (2015) 34194–34198.

[25] F. Lopez, C.D. Bartolo, T. Piazza, A. Passannanti, J.C. Gerlach, B. Gridelli, et al., A quality risk management model approach for cell therapy manufacturing, Risk Anal.: Int. J. 30 (12) (2010) 1857–1871, https://doi.org/10.1111/j.1539-6924.2010.01465.x.

[26] E. Netto, T.R. Hamedon, Predictors of knowledge, attitude and practices on work related injuries among laboratory staffs in a public university in Malaysia, International Journal of Public Health and Clinical Sciences 4 (5) (2017) 139–157.

[27] M.M. Uy, The status of chemical safety and security in Universities in Mindanao, Philippines, J. Chem. Health Saf. 18 (6) (2011) 8–14, https://doi.org/10.1016/j.jchas.2011.06.002.

[28] M.A.M. Al-Ibadi, The chemical safety and security in the university of kufa: progress and challenges, Iraqi National Journal of Chemistry 16 (2) (2016).

[29] I.M. Nasrallah, P.R. Salameh, A.R. EL-Outa, A.K. Elkak, R.R. Nasr, W.T. Bawab, Availability of Safety Measures and Knowledge towards Hazardous Waste Management Among Workers in Scientific Laboratories of Two Universities in Lebanon, 2022, https://doi.org/10.33422/4th.icrsh.2021.10.220.

[30] K.-H. Chang, Y.-C. Chang, I.-T. Tsai, Enhancing FMEA assessment by integrating grey relational analysis and the decision making trial and evaluation laboratory approach, Eng. Fail. Anal. 31 (2013) 211–224, https://doi.org/10.1016/j.engfailanal.2013.02.020.

[31] T. Meyer, How about safety and risk management in research and education? Procedia Eng. 42 (2012) 854–864, https://doi.org/10.1016/j.proeng.2012.07.478.

[32] V.R.K.R. Galarpe, N.C. Lamela, R. Alcantara, Preliminary evaluation of laboratory practices in cebu doctors' university, Philippines, J. Chem. Health Saf. 20 (4) (2013) 25–30, https://doi.org/10.1016/j.jchas.2013.03.490.

[33] J. Mora, J. Sibaja, W. Umaña, G. Piedra, O. Molina, Safety equipment for storage and handling of chemicals in university laboratories, WIT Trans. Built Environ. 174 (2018) 345–356, https://doi.org/10.2495/SAFE170321.

[34] W. Al-Zyoud, A.M. Qunies, A.U. Walters, N.K. Jalsa, Perceptions of chemical safety in laboratories, Saf. Now. 5 (2) (2019) 21, https://doi.org/10.3390/safety5020021.

[35] F. Lestari, Budiawan, M.L. Kurniawidjaja, B. Hartono, Baseline survey on the implementation of laboratory chemical safety, health and security within health faculties laboratories at Universitas Indonesia, J. Chem. Health Saf. 23 (4) (2016) 38–43, https://doi.org/10.1016/j.jchas.2015.11.002.

[36] M. Abbas, A.M. Zakaria, M.A. Balkhyour, Investigation of safety facilities and safe practices in chemical laboratories of a Saudi university, Journal of Environment and Safety 7 (2) (2015) 141–147, https://doi.org/10.11162/daikankyo.E15RP1001.

[37] H. Bourji, H. Sabbah, A. Al'Jamil, R. Khamis, S. Sabbah, N. Droubi, et al., Evaluating the alarm fatigue and its associated factors among clinicians in critical care units, European Journal of Clinical Medicine 1 (1) (2020), https://doi.org/10.24018/clinicmed.2020.1.1.8.

[38] Z. Li, W. Wang, Lesson learned from an explosion during chemical synthesis: discussion and preventative strategies, ACS Chemical Health & Safety 27 (5) (2020) 272–278. https://pubs.acs.org/doi/10.1021/acs.chas.9b00028?goto=supporting-info.

[39] R. Papadopoli, C.G.A. Nobile, A. Trovato, C. Pileggi, M. Pavia, Chemical risk and safety awareness, perception, and practices among research laboratories workers in Italy, J. Occup. Med. Toxicol. 15 (1) (2020) 1–11, https://doi.org/10.1186/s12995-020-00268-x.

[40] M.D. Al-Tahat, A.K.M.A. Jawwad, Y.L.A. Nahleh, Ordinal logistic regression model of failure mode and effects analysis (FMEA) in pharmaceutical tabletting tools, Eng. Fail. Anal. 27 (2013) 322–332, 10.1016/j.engfailanal.2012.08.017.

[41] F. Rezaei, M.H. Yarmohammadian, A. Haghshenas, A. Fallah, M. Ferdosi, Revised risk priority number in failure mode and effects analysis model from the perspective of healthcare system, Int. J. Prev. Med. 9 (2018), 10.4103%2F2008-7802.224046.

[42] Z. Wang, Y. Ran, H. Yu, C. Jin, G. Zhang, Failure mode and effects analysis using function–motion–action decomposition method and integrated risk priority number for mechatronic products: FMEA using FMA decomposition method and IRPN for MPs, Qual. Reliab. Eng. Int. 37 (6) (2021) 2875–2899, https://doi.org/10.1002/qre.2895.
[43] X. Wu, J. Wu, The risk priority number evaluation of FMEA analysis based on random uncertainty and fuzzy uncertainty, Complexity (2021) 2021, https://doi.org/10.1155/2021/8817667.
[44] D. Pamučar, M. Mihajlović, R. Obradović, P. Atanasković, Novel approach to group multi-criteria decision making based on interval rough numbers: hybrid DEMATEL-ANP-MAIRCA model, Expert Syst. Appl. 88 (2017) 58–80, https://doi.org/10.1016/j.eswa.2017.06.037.
[45] Reliasoft, Examining Risk Priority Numbers in FMEA, HOTTINGER BRUEL & KJAER INC, 2022.