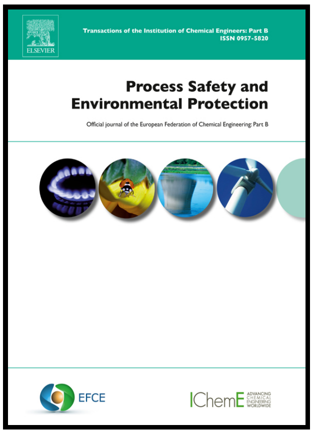

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A Comprehensive Framework for Risk Probability Assessment of Landfill Fire Incidents Using Fuzzy Fault Tree Analysis

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Abstract

Landfill fire is the most frequent type of incidents in the waste management complexes. This paper presents a new framework for risk probability evaluation of major fires in landfills using the fuzzy fault tree analysis. The framework starts with construction of the fault tree of landfill fire comprised of 38 basic and 22 intermediate events with the corresponding type of faults under managerial, executive, human, and environmental conditions. Fault tree quantitative analysis is carried out through a combination of fuzzy set theory and experts' judgements to overcome the lack of data limitation. Two new sensitivity analysis approaches are used to identify the critical fault type and critical paths in the fault tree. The proposed framework is demonstrated by its application to a real-world case of a landfill in Iran. The results show the probability of a major "fire incident" is 5.5% in which "fire occurrence" stands for 25% higher than "lack of preparation for controlling fire". In addition, "Waste's uncontrolled dumping" is recognised as the highest critical event by 6% for probability failure and 24% for importance degree. "Executive fault" also found as the most fault's critical type by frequency analysis of failure probability. The results also reveal the major impact of the experts' weights, especially for events related to human or management faults. These results can

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give decision-makers a profound insight into providing effective intervention strategies for minimising the risk of major landfill fire incidents.

Keywords: Comprehensive evaluation; Fuzzy fault tree analysis; Landfill fire incidents; Probability assessment; Sensitivity analysis

1 Introduction

Today, the ever-increasing global population growth coupled with significant industrial development and world trades has led to a constant increase in the production of waste all over the world. As such, managing waste in a sustainable manner is a desirable goal for all countries that can underpin their national standards and legislation (Nanda, and Berruti, 2021). Although there is a broad consensus that landfilling is the least preferred method in the hierarchy of the waste management options due to the negligence for recovery and recycling potentials, adverse impacts on soils, water pollution, and greenhouse gas emissions, landfilling is still applied widely in the world especially in developing countries, mainly due to its relatively low cost, low-technical requirements, and simple operation (Fazzo *et al.*, 2020). Furthermore, some waste materials such as ash as an output of thermal treatment method or non-recyclable hazardous material still need to be landfilled (Ahluwalia and Patel, 2018). All this shows that landfill still stands as a conclusive method of integrated solid waste management (Nanda, and Berruti, 2021).

This method however suffers from some serious incidents and controversial failures, including slope failure, excessive and rapid surface settlement, failure in engineering components (such as liner systems, leachate or gas collection systems, drainage systems, and final cover systems), and surface or subsurface fires (Jahanfar *et al.*, 2017; Koda *et al.*, 2019). Among these failures/incidents, the occurrence of fires is significantly important. Based on statistical reports of landfill incidents in different countries, fires are the most chronic and ongoing global issue related to all kinds of landfills that have occurred frequently over the decades in both developing and developed countries (Moqbel and Reinhart, 2017; Ibrahim, 2020). Reviewing some reported landfill fires can shed light on the expanse of this incident. Federal Emergency Management Agency data on fire incidents at municipal landfills in the US shows there were approximately 839 unique fire incidents each year from 2004 to 2010 (US Fire Administration, 2014). In Canada, Ontario, based on a survey of 43 landfill sites, 10% reported daily fires, 20% weekly, and 20% monthly (Chiblow, 2004). In the United Kingdom, in 2002, Approximately 57 waste fire incidents have reported to the environmental agency over a 10-month period, and 53% of them were attributed to landfill fires (44% non-inert landfill and 9% inert landfill) (Copping *et al*., 2007). In another study, over a period between 1998 and 2003, the Fire Service and Environment Agency reported 26 incidents of landfill fires within Northamptonshire, United Kingdom (Bates, 2004). In Sweden, millions of euros have been lost due to spontaneous waste fires (Ibrahim *et al*., 2020), and the environmental impact of such fires is estimated to be larger than the impact of all incineration plants (Hogland and Marques, 2003). Based on a research by Ibrahim (2020) in Sweden, 111 waste management sites were surveyed for detecting waste fires over a period of seven years 2012_2018 by remote sensing and GIS modelling. Results of this study reveal that landfills and recycle centres are respectively the major high-risk parts of Sweden's waste management chain for fire occurrence. In Poland, fire occurrence in the largest landfills and waste storage yards have been tripled from 23 incidents in 2010 to 79 incidents in 2018 (Bihałowicz *et al*., 2021). In New Zealand, a national review of all landfills by the Ministry for the Environment in 1995 indicates more than half of the landfill operators experienced landfill fires during previous years (Boyle, 2000). In most Asian and African countries, there is no comprehensive study to report on the number and the frequency of landfill fire occurrence. Therefore, for these countries, we can refer to only a few case studies of massive incidents that highlighted case-oriented disasters such as Philippine (Jafari *et al*., 2014), Indonesia (Koelsch *et al*., 2005), and Nigeria (Rim-Rukeh, 2014). These incidents are often followed by slope instabilities, landfill collapses and many more casualties caused by prolonged landfill fires. However, it goes without saying that certainly, the reported statistics only indicate a few percentages of all landfill fire incidents (LFI). In fact, the majority of landfill fires occur in general refuse disposal areas and dumps in open ground or extinguish by landfill operators without any report to the fire departments.

Landfill fires can be a source of pollution and producing significant amount of hazardous toxic pollutants as harmful combustion may produce substances with high concentrations which can be dispersed over long distances through dense clouds of noxious smoke (Toro and Morales, 2018). Furthermore, damaging the integrity of the waste bulk, damaging the cover materials or liner, and also causing elevated gas and leachate pressure may cause landfill fires to be a main trigger for the occurrence of other aforementioned failures in landfill, especially slope failures (Jahanfar *et al.*, 2017). A major fire in a landfill can have severe impacts on the environment, safety, and health. From an environmental standpoint, landfill fires have potential for contamination of the environment by producing toxic gases containing harmful compounds such as dioxins/furans and polynuclear aromatic hydrocarbons (Vaverková, 2019). Research in this field has confirmed the presence of pollution traces due to landfill fires and contamination emitted to air, water, soil, products, and vegetables in the affected areas (Escobar *et al.*, 2018; Cocean et al., 2020). From a safety and health standpoint, landfill fires, especially subsurface fires, produce burned pockets of charred waste damaging the integrity of landfill bodies and reducing the shear strength, which results in slope instability or sudden surface collapse (Stark *et al.*, 2012). Consequently, firefighters and workers at the scene are at risk of serious injury or death, both from exposure to the high concentration of toxic fumes produced by the fire and from possible collapse due to the weight of personnel and equipment on the fireground (Adetona *et al.*, 2020). A landfill fire can also pose a long-term threat to neighbouring communities' health by transferring and dispersing a considerable number of pollutants in the form of dense clouds of noxious smoke, which pollutes the surrounding air, water, soil, and local farming areas (Aderemi and Otitoloju, 2012). Additionally, in rural settlements that are close to landfills, a prolonged fire under the surface may result in the damage of the pile and the creation of a safety hazard for settlers by waste slides and collapses (Jahanfar *et al.*, 2017). For example, the Leuwigajah dumpsite slope failure in Bandung, Indonesia, in February 2005 caused 141 deaths due to significant rainfall and prolonged smouldering fire in the subsurface causing the failure of structural reinforcement in landfills (Koelsch *et al.*, 2005).

Hence, landfill fires pose a major hazard that needs to be considered in both planning and operational management of landfills. While techniques for detecting early fire in landfills have been developed recently, high priority should be given to developing plans for avoiding fire in landfills due to saving cost of detection, extinguishing the fire, cleaning up, and recovery (Radosavljevic *et al*., 2016; Milosevic *et al*., 2018).

In general, there have been some research works developed for the assessment of reliability, failure or risk in landfills such as slope failure, failures of unique design features, e.g. liner failure or gas/ leachate collection system failure. Pivato (2011) evaluated landfill liner failure by using traditional hydrological risk assessments and the Delphi technique. Huang *et al* (2013) also used the artificial neural network model with the first-order reliability method and Monte Carlo simulation to evaluate the reliability for the stability of landfills on the slope for different rainfall parameters. Xu *et al* (2014) proposed a holistic model for leakage risk assessment in landfills using the EPA's Composite Model for Leachate Migration model based on Monte Carlo method and Fault Tree Analysis (FTA). Jahanfar *et al* (2017) investigated the risk of slope failure in landfills by proposing a novel probabilistic risk assessment methodology to assess both hazard and vulnerability aspects of landfill slope failure using the Monte Carlo and Taylor series methods. Sadeghi *et al* (2020) used the failure mode method, effects analysis and analytic hierarchy process to assess the failure of the various design features in landfills. Finally, Xu *et al* (2021) proposed a new fibre-optic based large deformation transducer and numerical model for the stability analysis of landfills along with an early warning system. These attempts have taken great steps into consideration of safety approaches for managing failure occurrence in different engineering features of landfills during the design and operational phases. Although landfill fire can lead to the failure of other landfill features, little attention has been paid to the risk-based assessment of the LFI in the research communities in order to mitigate their risk and implement practical and effective safety measures.

There are several studies investigated risk assessment of fire incidents and relevant safety issues in various industries through the application of fire modelling and its integration to the risk-based design and operation of those industries to find effective strategies for risk mitigation and improve safety performance. Khan and Abbasi (1999) recapped major incidents including fire and explosion in chemical processing industries to understand the relevant damage potential used for risk assessment. Khan and Amyotte (2004) were amongst one of the first attempts to develop a conceptual framework of an integrated inherent safety index (I2SI) for loss prevention and risk management of fire, explosion and toxic hazards in process industries. Dadashzadeh *et al*. (2013) proposed a new integrated approach for modelling the interaction of fire and explosion accidents in processing facilities based on an evolving accident scenario by using computational fluid dynamics (CFD). Dadashzadeh *et al*. (2014) also used CFD to develop a new risk-based assessment for fire accidents of combustion products in confined or semi-enclosed facilities. Baalisampang *et al.* (2018) carried out a comprehensive review of fire and explosion accidents in marine transportation industry. They specifically analysed underlying causes and identified potential measures such as alternative fuels to prevent or minimise those fire and explosion accidents. Baalisampang *et al* (2019) developed a new risk-based approach for modelling an integrated impact of fire, explosion and combustion products within the accidental leakage of LNG (liquefied natural gas) in LNG processing facilities. Ding *et al* (2020) proposed a framework for qualitative risk management of material storage fire within the processes of industry plants based on Bow-tie analysis and relevant safety measures to reduce storage fire risk. Ding *et al* (2021) also proposed a novel risk management approach to reduce the fire-induced domino effect in chemical plants, by leveraging loading/unloading demands based on risk aggregation and inventory management. Similarly, Huang *et al* (2021) proposed a dynamic model for propagation of fire-induced domino effects in chemical process industries by using matrix calculation coupled with Monte Carlo simulation.

However, despite the frequent occurrence of fires in waste management industries especially fires in landfills with major adverse impacts, to the best of the authors' knowledge, the risk-based assessment of the LFI has been investigated by few cases. Dokas *et al.* (2009) developed a web-based expert system for early warning and emergency response system to any possible operational landfill problems and accidents including landfill fires. Furthermore, Obeid *et al* (2020) investigated the causes of ignition for surface fire in Malaysian landfills and assessed the consequence and health risk of this incident. Another study conducted by Sabrin *et al* (2021) investigated a risk-based analysis of subsurface elevated temperatures in landfills for a range of gas variables to find safe and unsafe ranges of gas variables and subsurface temperature. The current study aims to investigate both types of surface and subsurface fires in all types of landfills in order to develop a comprehensive framework for risk probability assessment of the LFI and identify their critical causes.

This study aims to present a novel approach for fault detection and categorisation, develops a fault tree for a major fire in a landfill, and uses fuzzy set theory and expert judgement to perform a quantitative analysis of landfill fire risk probability. Finally, as an important step, this study analyses the sensitivity of the fault tree to a variety of values (basic events, intermediate events, type of fault, minimal cut sets) in order to identify the critical variables that have the greatest effect on the final results. This paper is organised in the following three sections. First, the methodology including the details of fault tree construction and development of the Fuzzy FTA (FFTA) for landfill fire assessment is described in the next section. Then, the application of the proposed methodology on a real case study is demonstrated, and results are analysed and discussed. Finally, the conclusions are drawn with further recommendations for future research works.

2 Methodology

This paper presents a comprehensive framework for risk probability assessment of the LFI. The framework comprises three main steps as shown in Figure 1. The first step starts with developing the fault tree of the LFI through the identification of events and their corresponding types of faults, as well as determining events relationships in order to create branches. The second step consists of generating failure probabilities of basic events by using the combination of fuzzy set theory and experts' judgement with considering their weighting scores. The third step includes quantitative analysis for calculating the failure probability of events and measuring importance degree based on sensitivity analysis in three levels: (1) basic events and minimal cut sets (2) intermediate events to identify critical paths; and (3) groups of basic events in a particular fault for identifying the critical type of fault.

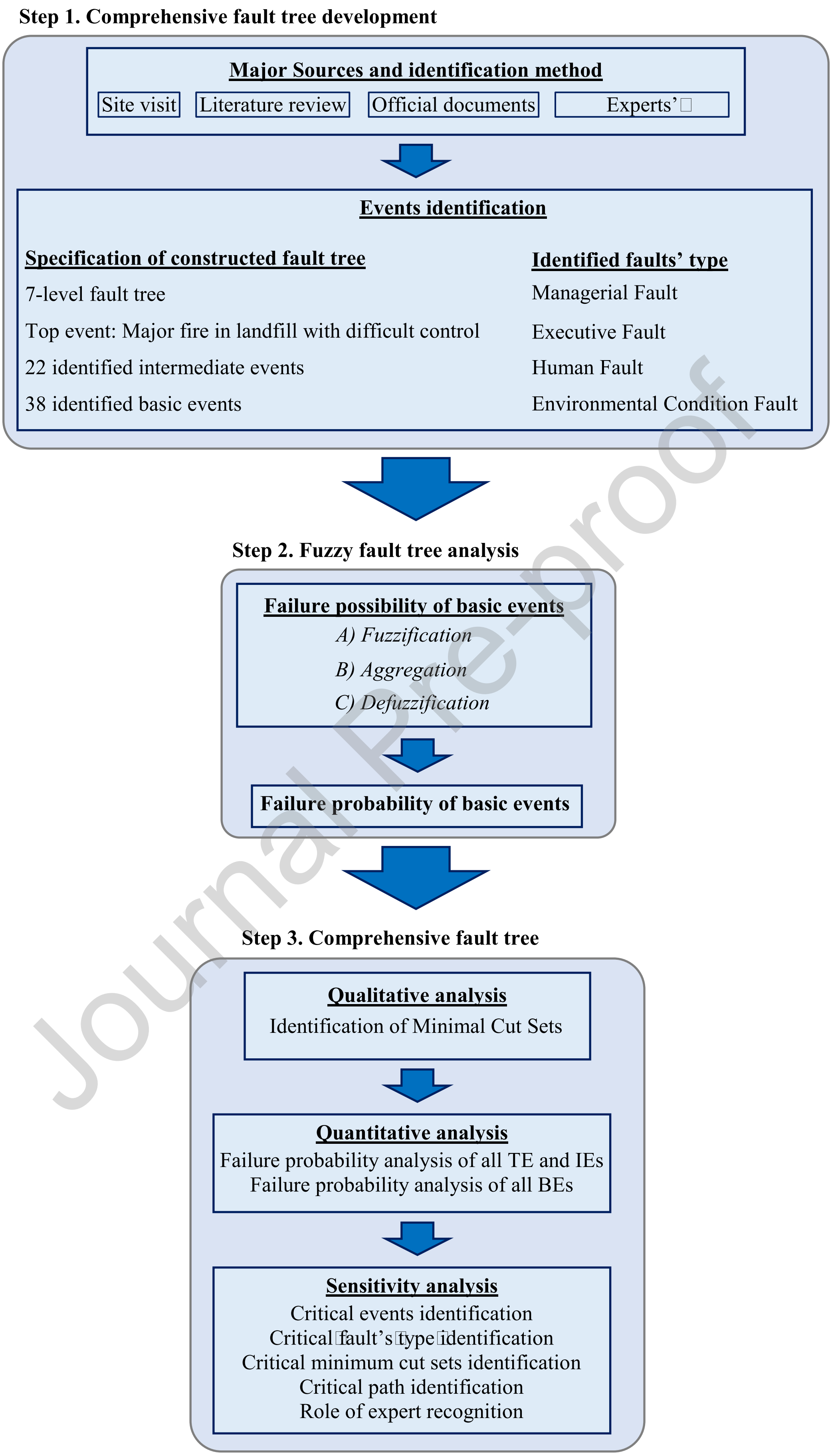


Figure 1. Proposed framework for comprehensive risked-based assessment of the LFI

2.1 Fault tree of Landfill Fire Incidents (LFI)

Among all techniques for reliability and failure assessment such as FTA, Event Tree Analysis (ETA), Hazard Analysis, Bayesian Analysis, or Cause and Effect Analysis, FTA is selected for this study as it has been used and recommended by many studies associated with risk analysis of similar studies due to its ability to (1) identify and model the failure path and relation of root causes, (2) estimate the safety and reliability of the complex systems, and (3) diagnose and describe undesired events (Kabir *et al*., 2019; Koda *et al*., 2019).

The FTA is constructed here based on a top-down approach starting from a top event (TE) i.e. landfill fire, continued by passing through layers of created intermediate events (IE) on a cause-effect basis, and finally ended to rout causes called basic events (BE). All events in the fault tree of the LFI here are identified based on the information collected from one of these sources: (1) site visits, (2) official documents such as consulting reports and other relevant articles (3) experts' judgement, and (4) scientific literature review. Based on the information collected from these sources, the landfill fire events can be classified under four main failure types including managerial, executive, human faults and faults due to environmental conditions. More specifically, Managerial Faults (MF) refer to those faults initiating from actions responsible by management or managerial team of the landfill. Executive Faults (EF) reflect those faults related to inappropriate executive measures which are not consistent with protocols and technical guidance. Human Faults (HF) are related to faults by landfill operators and employees due to either intentional/unintentional misconduct or negligence. Environmental Condition Faults (ECE) are natural-based issues such as inclement weather conditions.

Based on the information collected from the above sources, the fault tree for all possible LFI is constructed for this study as shown in Figure 2 including 22 intermediate events and 38 basic events with the details given in Table 1. Although great care was provided for creating a comprehensive structure for the LFI based on the most possible events that can apply for any types of landfills, the fault tree structure can be adjusted (i.e. either expanded to include more events or shortened to remove some events) based on the conditions that are either likely or unlikely to happen for any specific study area.

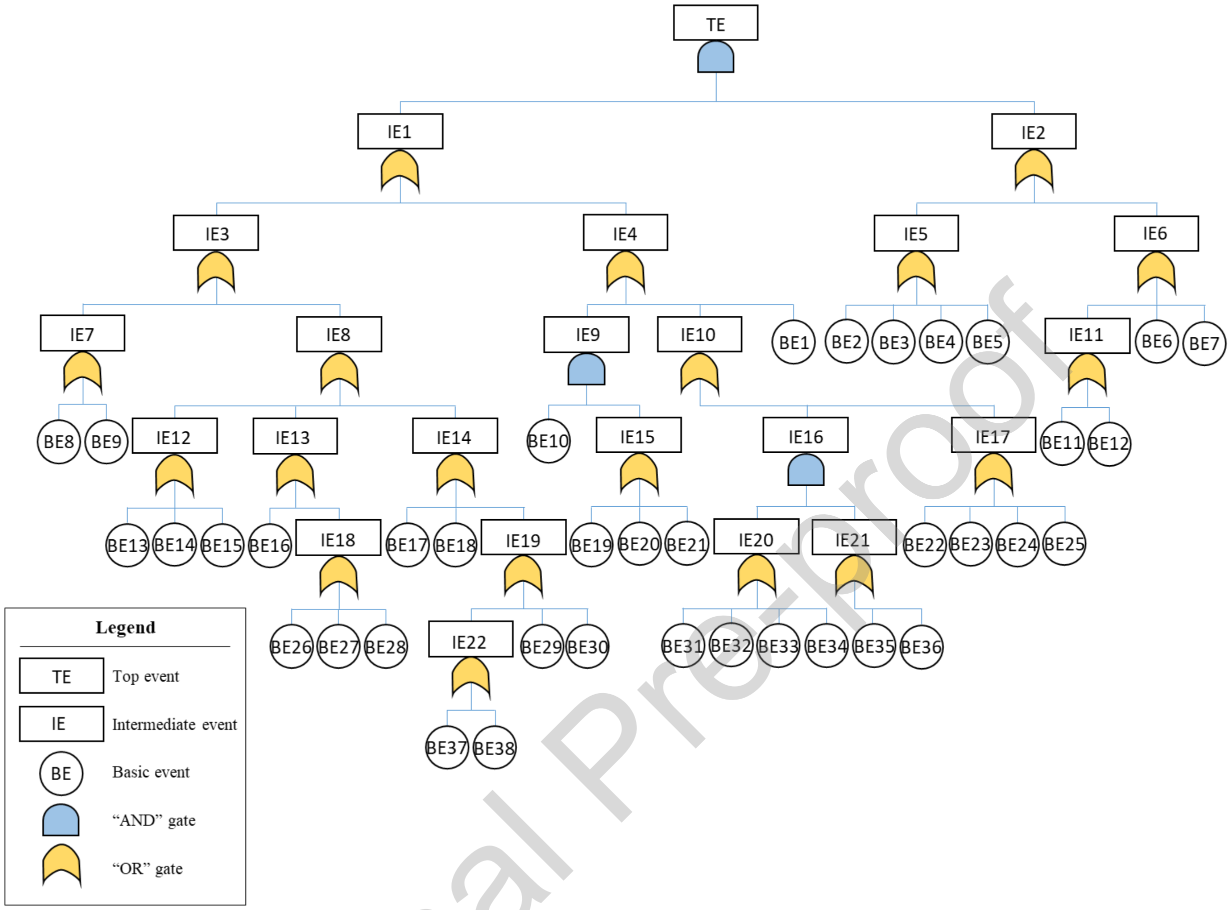


Figure 2. The fault tree structure proposed for the LFI

Table 1. Identified events for the fault tree of the LFI

Code	Description	Identification method				Type of fault	References
		SV[a]	LR[b]	OD[c]	EJ[d]		
TE	Major fire in landfill with difficult control					MX[*]	
IE1	Fire occurrence		•			MX	FEMA (2002)
IE2	Lack of preparation for controlling fire				•	MX	Proposed
IE3	Subsurface fire		•			MX	Jafari *et al.* (2017a)
IE4	Surface fire		•			MX	Dokas *et al.* (2009)
BE1	Deliberate arson fire		•			MF[1]	FEMA (2002)
IE5	Problem with firefighting operation			•		MX	EPA (2008)
BE2	Incomplete extinguishing operation and rekindling a fire from the previous fire		•			EF[2]	Ibrahim (2020)
BE3	Being in an inclement weather condition (e.g., extremely hot, cold or windy weather)	•				ECF[3]	Proposed
BE4	Negligence and delayed notification to the fire department by operator			•		HF[4]	Sperling (2002a)

Code	Description	Identification method				Type of fault	References
		SV[a]	LR[b]	OD[c]	EJ[d]		
BE5	The late arrival of the fire service				●	HF	Proposed
IE6	Problem with fire suppression equipment			●		MF	Sperling (2002b)
BE6	Lack of sufficient personal protective equipment for personnel to participate in firefighting operations	●				MF	Proposed
BE7	Lack of sufficient firefighting equipment on site			●		MF	USFA (2002)
IE7	Increasing the moisture content of landfill		●			EF	Jafari *et al.* (2017b)
BE8	Poorly design leachate-recirculation system		●			EF	Feng *et al.* (2018)
BE9	Poorly maintenance of the cap in the condition of heavy rain	●				EF	Proposed
IE8	The air intrusion into the landfill mass		●			MX	Reinhart *et al.* (2020)
IE9	Spontaneous fire		●			MX	Moqbel and Reinhart, (2017)
BE10	Poorly cover condition in shallow areas				●	EF	Proposed
IE10	Accidental fire			●		MX	BSLI (2014)
IE11	Problems with heavy equipment			●		MF	USFA (2002)
BE11	Problem with the manoeuvrability of the heavy equipment	●				MF	Proposed
BE12	Lack of access to require heavy equipment				●	MF	Proposed
IE12	Problems with the gas collection system		●			EF	Jafari (2015)
BE13	Applying an excessive vacuum in the gas collection system		●			EF	FEMA (2002)
BE14	Damaged gas wells		●			EF	Jafari (2015)
BE15	Abandoned open outlets of gas wells			●		EF	LMOP (2002)
IE13	Existence of voids within the waste mass		●			EF	Hall *et al.* (2007)
BE16	Inadequate interim covers	●				EF	Proposed
IE14	Problems with cap			●		MX	Sperling (2002a)
BE17	Poorly engineered cap especially on the side slope		●			EF	Jafari *et al.* (2017a)
BE18	Weak interconnection between caps on two wastes deposits cells				●	EF	Proposed
IE15	Formation of shallow hot spots		●			ECF	Moqbel *et al.* (2010)
BE19	Heat generation because of remaining waste in aerobic degradation phase		●			ECF	Bates (2004)
BE20	Heating from the sun during summer months	●				ECF	Proposed
BE21	Heating from exothermic reactions of chemical substances in contact with water		●			ECF	Ibrahim, (2020)
IE16	Surface catching fire			●		MX	USFA (2002)
IE17	Operational errors			●		EF	UN DESA (2018)
BE22	Deliberate fire by landfill operators to reduce the volume of waste	●				EF	Proposed
BE23	Uncontrolled dumping of reactive and flammable hazardous waste				●	EF	Proposed
BE24	Uncontrolled dumping of incompatible chemicals next to each other, which can ignite when mixed		●			EF	Martin *et al.* (2013)
BE25	Burial of hot or undetected smouldering		●			EF	Stark *et al.* (2012)

Code	Description	Identification method				Type of fault	References
		SV^a	LR^b	OD^c	EJ^d		
	loads (.e.g. melting slag or ash)						
IE18	Poorly compacted waste		●			EF	Chavan *et al.* (2019)
BE26	Improper waste placement				●	EF	Proposed
BE27	Inconsistency between the weight of compactor and incoming waste				●	EF	Proposed
BE28	Inadequate number of passages of compactor	●				EF	Proposed
IE19	Existence of fissures and cracks in the soil cover		●			MX	Chavan *et al.* (2019)
BE29	Settlement of waste surface		●			ECF	Idowu *et al.* (2019)
BE30	Landslide of slopes			●		EF	EPA (2008)
IE20	Existence of pilot ignition source			●		HF	USFA (2002)
BE31	Sparks from vehicles using the landfill		●			HF	Bates, (2004)
BE32	Discarding lit matches and cigarettes in landfill	●				HF	Proposed
BE33	Contact of hot parts of opening equipment with waste				●	HF	Proposed
BE34	Using the welding or electrical equipment on site			●		HF	USFA (2002)
IE21	Existence of exposed combustible material		●			EF	Moqbel *et al.* (2010)
BE35	Uncapped layers of waste in the working face		●			EF	Bates (2004)
BE36	Methane gas leaking from the header pipes of the landfill gas collection system			●		EF	Administration (2002)
IE22	Poorly maintenance of the cap in all weather conditions		●			ECF	Moqbel (2009)
BE37	Cap erosion after heavy rain		●			ECF	Koelsch *et al.* (2005)
BE38	Cap problem in windy weather condition	●				ECF	Proposed

*: Mixed e.g., event that consists of different types of faults in their sub level

a: Site Visit b: Literature Review c: Official Documents d: Experts Judgement

1: Managerial Fault 2: Executive Fault 3: Environmental Condition Fault 4: Human Fault

2.2 Development of FFTA

The fuzzy set theory is incorporated in the FTA technique, creating the FFTA, in order to eliminate the above-mentioned limitations and improve fault tree applications in an uncertain situation with imprecise and vague failure data (Yazdi and Kabir, 2017). FFTA is developed through two steps of failure possibility and failure probability of BEs as outlined below.

2.2.1 Failure possibility of BEs

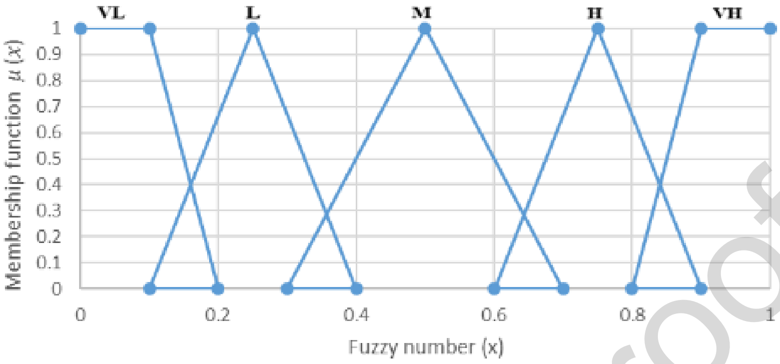
Possibility for an event is expressed subjectively in a qualitative manner while probability is usually expressed by using statistical indicators that can be calculated as a numeric ratio defining the rate of event occurrence. In cases of lack of statical data, instead of failure probabilities, failure possibilities can be extracted in a subjective state by using the experts' judgement and fuzzy set theory. These possibilities are then quantified and turn into failure probability rates in order to perform the quantitative analysis in the fault tree. Hence, failure possibility in the fuzzy environment is generated through three steps of (a) fuzzification, (b) aggregation, and (c) defuzzification that are defined below in detail.

2.2.1.1 Fuzzification

Failure possibilities of BEs in the LFI are specified here by the judgement of a number of experts using five linguistic terms (i.e. very high, high, medium, low and very low) given in Figure 3a. These qualitative expressions are mapped to corresponding quantitative fuzzy numbers by using different forms of fuzzy membership functions such as triangular, trapezoidal, and Gaussian-shape (Ardeshir *et al.*, 2017). Triangular fuzzy membership functions are adopted here for the five linguistic terms as shown in Figure 3 for fuzzy numbers ranging between 0 and 1 with their graphical representation (Piadeh *et al.*, 2018a). It should be noted that the triangular fuzzy number is widely used as it can be intuitively envisaged better by decision-makers and is easy to apply. Hence, the triangular shape can simply reflect the dispersion of the evaluation data and point to the highest possible failure of the LFI (Mahmood *et al.*,2013).

Possibility of occurrence in form of linguistic terms	Symbol	Possibility of occurrence in form of triangular fuzzy numbers
Very High	VH	(0.8,0.9,1)
High	H	(0.6,0.75,0.9)
Medium	M	(0.3,0.5,0.7)
low	L	(0.1,0.25,0.4)
Very Low	VL	(0,0.1,0.2)

(a)



(b)

Figure 3. (a) Triangular fuzzy numbers for five linguistic terms and (b) graphical representation of the corresponding triangular membership functions

2.2.1.2 Aggregation

Different fuzzy numbers of each BE are aggregated into one single fuzzy number in order to reach a consensus between experts' opinions. Several aggregation techniques are available such as fuzzy Delphi method, max and min Delphi method, similarly aggregation, voting, linear opinion pool, game theory, max-product, and sum-product (Mahmood *et al.*, 2013). However, there is no specific priority suggested by the literature for their application (Liu *et al.*, 2014). Hence, to combine the judgements of different experts with specific knowledge and experience, the aggreged fuzzy number (AFN) for BE *i* suggested by Clemen and Winkler (1999) is used here that can be calculated for each BE as below:

$$\mathrm{AFN_i} = \sum_{j=1}^{n} \mathrm{W_j}\, \mathrm{A_{ij}} \qquad (i = 1, 2, 3, \ldots, m) \qquad \mathbf{(1)}$$

where $\mathrm{W_j}$ is the relative weight of expert *j* and $\mathrm{A_{ij}}$ is the opinion of expert *j* as a fuzzy number about the possibility of occurrence for BE_i in the LFI, and *m* is the number of BEs and *n* is the number of experts.

The relative weight for each expert is calculated based on their personal characteristics i.e. educational degree, professional experience and job positions as given in Table 2 in this study (Piadeh et. Al, 2018b). Thus, the relative weight (W_j) for expert *j* is calculated as below.

$$\mathrm{W_j} = \frac{\mathrm{S_j}}{\sum_{j=1}^{n} \mathrm{S_j}} \tag{2}$$

where $\mathrm{S_j}$ is the sum of all weighting scores for expert *j* and *n* is the number of experts.

2.2.1.3 Defuzzification

The outcome of the aggregation process is the possibility of BEs as fuzzy numbers. These fuzzy numbers need to be converted into a single crisp value for each BE indicating the most likely score that an event may occur (Ahmadi *et al.*, 2017). The centre of area method proposed by Sugeno (1999) is used here for the defuzzification. If A= (*a*, *b*, *c*) is aggregated triangular fuzzy number of BE_i, CFP_i can be defuzzified as below:

$$\mathrm{CFP_i} = \frac{\int x\mu_A(x)dx}{\int \mu_A(x)dx} = \frac{\int_a^b \frac{x-a}{b-a} x dx + \int_b^c \frac{c-x}{c-b} x dx}{\int_a^b \frac{x-a}{b-a} dx + \int_b^c \frac{c-x}{c-b} dx} = \frac{1}{3}(a+b+c) \tag{3}$$

where $\mathrm{CFP_i}$ is the crisp failure possibility of $\mathrm{BE_i}$.

2.2.2 Failure probability of BEs

The crisp failure possibility (CFP) generated above needs to transfer to failure probability (FP) to be used for fault tree quantitative analysis. The following conversion function introduced by Onisawa (1990) is used here.

$$\mathrm{FP_i} = \begin{cases} \frac{1}{10^{K_i}}, & \mathrm{CFP_i} \neq 0 \\ 0. & \mathrm{CFP_i} = 0 \end{cases}, \qquad \mathrm{K_i} = \left[\left(\frac{1-\mathrm{CFP_i}}{\mathrm{CFP_i}}\right)^{1/3}\right] \times 2.301 \tag{4}$$

where $\mathrm{FP_i}$ represents the failure probability of BE_i.

2.3 Comprehensive fault tree analysis

Once the fault tree of the LFI is created, it can be analysed both qualitatively and quantitatively. qualitative analysis interprets the events' cause and consequence relationships and extracts the combinations of events leading to the TE. Quantitative analysis uses BEs' failure probability rates as input to provide valuable numerical results such as EI and TE failure probability and events importance degree by sensitivity analysis. Further details of these two FTA approaches are described below.

2.4.1. Qualitative analysis

Quantitative analysis is a non-numerical, subjective analysis that identifies all the combinations of events leading to the TE called "Cut Sets". When a cut set has many events, it is less likely to fail all of them than one with fewer events. Thus, among all cut sets, their minimal ones, called "Minimal Cut Sets" (MCSs), which contain too few events are more important combinations that may indicate a system vulnerability. MCSs are defined as the smallest combination of events that are minimal, necessary, and sufficient to cause the system to fail. For the MCS of order *n*, the top event will occur by the failure of *n* numbers of BEs in the cut set (Kabir and Papadopoulos, 2018).

2.4.2. Quantitative analysis

Fault tree quantitative analysis can compute relevant numerical values including failure probability values and importance degrees (Shi *et al*., 2018). Quantitative analysis determines the system reliability by computing relevant numerical indexes such as IEs and TE failure probabilities and identifying critical events through sensitivity analysis. This analysis entails having BEs failure probabilities. Although the crisp failure data for BEs, directly obtained from the system, are the most reliable source for fault tree quantitative analysis, it is almost inevitable to work with estimated data instead of precise data in some real-world engineering practices (Yazdi *et al*., 2019). This is mainly due to limitations such as lack of accurate and sufficient statistical records of data, vague behaviour of basic events (e.g. human-related subjective events), the ambiguous nature of the incidents, and variation in the system-operating environment (Yazdi and Kabir, 2017). Hence, the development of a fault tree in a fuzzy environment is a solution in this situation to overcome these limitations and generate failure probabilities for BEs.

2.4.2.1 Analysis of failure probability values

Failure probabilities of intermediate events with 'AND' or 'OR' gates can be calculated based on failure probabilities of BEs and using Boolean algebra as Equations (5) and (6):

$$P(E_O) = \prod_{i=1}^{n} P(BE_i) \qquad \text{For 'AND' gate} \qquad \textbf{(5)}$$

$$P(E_O) = 1 - \prod_{i=1}^{n} (1 - P(BE_i)) \qquad \text{For 'OR' gate} \qquad \textbf{(6)}$$

where *n* is the number of independent input events, $P(E_O)$ is the probability of the upper-level event of the gate (e.g. IEs or TE) and $P(BE_i)$ is the failure probability of lower level event *i* of the gate (e.g. BEs or IEs).

The same calculation can be subsequently used for failure probabilities of other upper level IEs until the failure probability of TE is obtained. Comparing the probability values of IEs in different branches of the tree and analysing TE probability value can shed light on the important parts of the incident and be a basis for reliability assessment and any measures to mitigate the overall LFI.

2.4.2.2 Sensitivity analysis

The sensitivity of the FFTA results to variation of input data needs to be analysed to identify importance degree of BEs and critical paths in the fault tree of the major fire in landfill. In fact, if changes in failure probabilities of one particular component, BE, IE, or MCS can drastically change the TE state, the system is extremely sensitive to this component and then this component is defined as critical. Therefore, critical components are the biggest contributors to the result and they can be an ideal candidate for improving system reliability. In addition to the sensitivity analysis of BEs and MCSs, this paper adopts sensitivity analysis based on IEs and several types of BEs faults.

There are different methods to measure BEs' importance degree for finding top contributors to system failure (Vesely, 2002). Here, the Fussell-Vesely importance method (FV-I) is adopted to rank critical BEs. This method prioritises all BEs based on their contribution to the occurrence of the top event. The FV-I of a BE can be calculated as:

$$\mathrm{I}_{\mathrm{BE_i}}^{\mathrm{FV}} = \frac{\mathrm{P(TE)} - \mathrm{P(TE)}^{\mathrm{P(BX_i)=0}}}{\mathrm{P(TE)}} \tag{7}$$

where $\mathrm{I}_{\mathrm{BE_i}}^{\mathrm{FV}}$ is the importance degree of $\mathrm{BE_i}$; and $\mathrm{P(TE)}^{\mathrm{P(BX_i)=0}}$ is the occurrence probability of the TE when the probability of $\mathrm{BE_i}$ is zero. A new sensitivity analysis is conducted here by setting the probabilities of all BEs associated with a given type of fault equal to zero and then calculating the probability of TE as:

$$\mathrm{I}_{\text{fault of type A}}^{\mathrm{FV}} = \frac{\mathrm{P(TE)} - \mathrm{P(TE)}^{(\text{all BEs of fault type A})=0}}{\mathrm{P(TE)}} \tag{8}$$

where $\mathrm{I}_{\text{fault of type A}}^{\mathrm{FV}}$ is the importance degree of fault type A; and $\mathrm{P(TE)}^{(\text{all BEs of fault type A})=0}$ is the occurrence probability of the TE when the probability of all BEs of fault type A is zero. It can also help to identify the type of BEs fault with the greatest impact on the occurrence of TE. Identifying the critical type of BEs fault provides a major step to prevent the TE occurrence because it involves a group of a certain number of BEs in all different tree branches.

The sensitivity analysis of IEs similar to BEs are prioritised based on their contribution to TE occurrence and can be calculated as.

$$\mathrm{I}_{\mathrm{IE_i}}^{\mathrm{FV}} = \frac{\mathrm{P(TE)} - \mathrm{P(TE)}^{\mathrm{P(IE_i)=0}}}{\mathrm{P(TE)}} \tag{9}$$

where $I_{IE_i}^{FV}$ is the importance degree of IE_i; and $P(TE)^{P(IE_i)=0}$ is the occurrence probability of the TE when the probability of IE_i is zero.

The critical path can be identified by comparing the importance degrees of IEs at each level of all branches to find the critical ones at each level, then connecting them in each particular branch to finally reach the TE. These paths indicate critical consecutive cause-consequence events from the bottom to the top of the fault tree.

The importance analysis for MCS identifies the most critical combination that leads to the occurrence of TE. MCS ranking is performed by calculating the ratio of MSC probability to the top event probability. This relative measure called the cut set importance (CSI) or Fussell-Vesely Importance (FV-I) (Lavasani *et al*., 2015) is calculated as.

$$\mathrm{I}_{\mathrm{j}}^{\mathrm{CS}} = \mathrm{P}\left(\mathrm{MCS}_{\mathrm{j}}\right)/\mathrm{P}(\mathrm{TE}) \quad \textbf{(10)}$$

where $\mathrm{P}\left(\mathrm{MCS}_{\mathrm{j}}\right)$ is the failure probability of $\mathrm{MCS}_{\mathrm{j}}$, P(TE) is the failure probability of TE and $\mathrm{I}_{\mathrm{j}}^{\mathrm{CS}}$ is measured importance degree of $\mathrm{MCS}_{\mathrm{j}}$.

3 Case study

The proposed framework is demonstrated by its application to a real case study of a landfill located in Qazvin city, Iran, as shown in Figure 4. The city is surrounded by many industrial towns and hence receives several types of chemical, pharmaceutical, and mainly industrial waste. The capacity of the landfill is 150,000 m^3 in total for the waste and daily/interim covers. With an almost annual loading of around 1,000 tons/year, this site has three closed industrial landfills and one in operation. This landfill site has experienced five major fires from 2015 to 2020, which spread through almost 70- 100 tons of industrial waste and entailed an arduous firefighting operation (ISIPO, 2020).

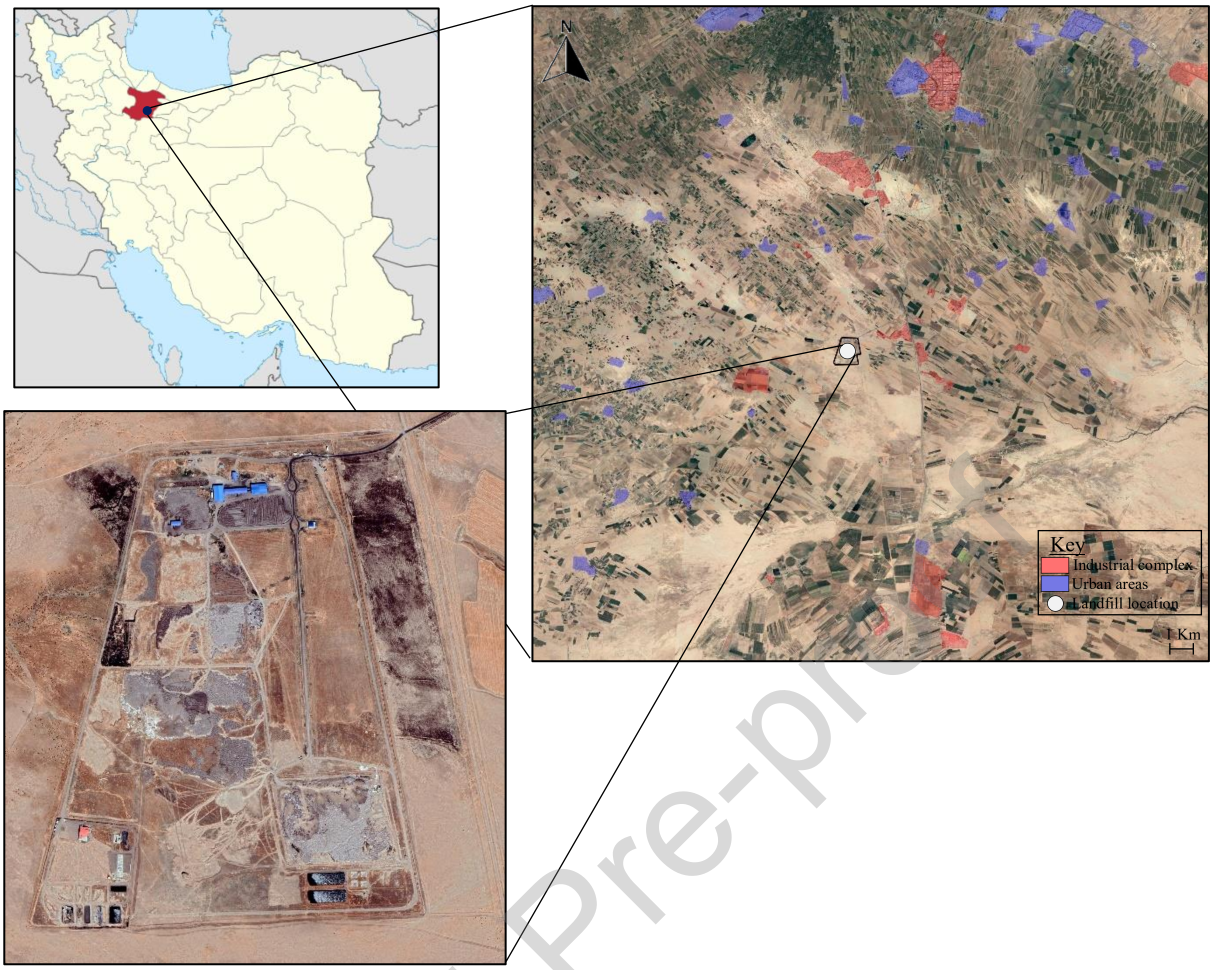


Figure 4. Layout of the case study's landfill

The fault tree and the framework developed for analysis in the case study are described here. First, all basic events listed in Table 1 are first reviewed for the case study. Among all, BEs #8, #13, and #36 are discarded due to the lack of a leachate circulation and gas collection system in the case study. Additionally, BEs #22, #27, and #28 are also discarded due to not being applicable of 'deliberate fire by landfill operators' and 'compactor' in the case study. By applying Boolean algebraic rules, the fault tree of the case study has 176 MCS, indicating that there are 176 paths to result in fire occurrence in this landfill. The total 176 MCSs include 56 MCSs of order 3 and 120 MCSs of order 2. The MCSs equation can be expressed as below:

$$\mathrm{T} = \mathrm{MCS}_1 + \mathrm{MCS}_2 + \cdots + \mathrm{MCS}_\mathrm{N} = \Big(\textstyle\sum_\mathrm{i} \mathrm{X}_\mathrm{i} \left(\mathrm{X}_1 + \mathrm{X}_9 + \mathrm{X}_{26} + \sum_\mathrm{k} \mathrm{X}_\mathrm{k} + \sum_\mathrm{l} \mathrm{X}_\mathrm{l} + \sum_\mathrm{m} \mathrm{X}_\mathrm{m} + \sum_\mathrm{n} \mathrm{X}_\mathrm{n}\right) + \sum_\mathrm{j} \mathrm{X}_\mathrm{j} \left(\mathrm{X}_1 + \mathrm{X}_9 + \mathrm{X}_{26} + \sum_\mathrm{k} \mathrm{X}_\mathrm{k} + \sum_\mathrm{l} \mathrm{X}_\mathrm{l} + \sum_\mathrm{m} \mathrm{X}_\mathrm{m} + \sum_\mathrm{n} \mathrm{X}_\mathrm{n}\right)\Big) + \left(\textstyle\sum_\mathrm{i} \mathrm{X}_\mathrm{i} \left(\sum_\mathrm{p} \mathrm{X}_\mathrm{p}\mathrm{X}_{10} + \sum_\mathrm{q} \mathrm{X}_\mathrm{q}\mathrm{X}_{35}\right) + \sum_\mathrm{j} \mathrm{X}_\mathrm{j} \left(\sum_\mathrm{p} \mathrm{X}_\mathrm{p}\mathrm{X}_{10} + \sum_\mathrm{q} \mathrm{X}_\mathrm{q}\mathrm{X}_{35}\right)\right) \quad \textbf{(11)}$$

where N is the serial number of MCS which is $1 \leq \mathrm{N} \leq 176$; X represents BE; $2 \leq \mathrm{i} \leq 7$; $11 \leq \mathrm{j} \leq 12$; $14 \leq \mathrm{k} \leq 18$; $23 \leq \mathrm{l} \leq 25$; $29 \leq \mathrm{m} \leq 30$; $37 \leq \mathrm{n} \leq 38$; $19 \leq \mathrm{p} \leq 21$; $31 \leq \mathrm{q} \leq 34$.

This indicates that there are 176 short ways, by combination just 2 or 3 events, resulting in landfill fire incidents in the case study. Therefore, it is necessary to identify the critical ones among these 176 MCSs through sensitivity analysis in the quantitative realm to focus on the important part. A fuzzy FTA based on experts' judgement is adopted here due to lack of access to statistical failure data. The five fuzzy membership functions presented in Figure 3 are used here with corresponding triangular membership functions for experts’ judgements. Experts used for judging the BEs are selected from various levels of job position, professional experience (number of years in service), educational degree to have a better diversity of opinions from all groups working in this sector (Piadeh *et al.*, 2018a). Hence, six experts from three fields were first selected as follows: two from those involved in the firefighting operations of the landfill, two from planning and management team, and two from the operation team. The six experts from all the available pool of experts attended the interview but they were fully aware of the case study and had detailed information about the historic landfill fires occurred at the site. Judgements of these six individual experts for each BE are combined based on Eqs. (1) and (2) to form a single failure probability for each BE by using the relative weights of experts calculated based on the scores criteria given in Table 2 related to three specifications of the experts as suggested by Piadeh *et al.* (2018b).

Table 2. Score of experts for job position, duration of professional experience and educational degree

Classification			Score
Job position	**Professional experience (years in service)**	**Educational degree**	
Professor / Chief Engineer / Director	more than 20	PhD	5
Associated professor / Manager	15 to 20	Master’s (MSc)	4
Engineer, supervisors	10 to 15	Bachelor’s (BSc)	3
Foreman, Technician	5 to 10	HND	2
Operator, Workers	<5	Secondary School	1

4 Results and discussion

The methodology outlined above is applied here for the reliability assessment of the LFI of the case study in Iran. First, the relative weights of the six experts participated in the interview is calculated based on the scores given in Table 2 related to three types of specifications as details shown in Table A1 of Appendix A. Note that the details of the direct interview collecting from the experts' judgements for the occurrence possibility of BEs of the LFI are shown in Table A2 of Appendix A.

Note that the AFN is obtained from Eqs. (1) and (2) based on applying the method of linear opinion pool. The defuzzification of the AFN is performed by using Eq. (3) to convert fuzzy numbers into crisp failure possibility (CFP) for each BE. Finally, Eq. (4) is used to transform CFP into the failure probability (FP) for each BE. The results of the FFTA processes and failure probabilities for each BEs are also shown in Table A2 of Appendix A. Figure 5 shows the results of the top ten BEs of the LFI with the highest failure probability in the case study. The results indicate BE23 "Uncontrolled dumping of reactive and flammable hazardous waste" is the basic event with the highest failure probability occurrence amongst others. Furthermore, exploring the type of fault shows while in general "Human Faults" seem to be the major basic events for many LFI, frequency analysis of the incidents in the study reveals that "Executive Faults" appear more in the top 10 identified basic events with the highest probability failure.

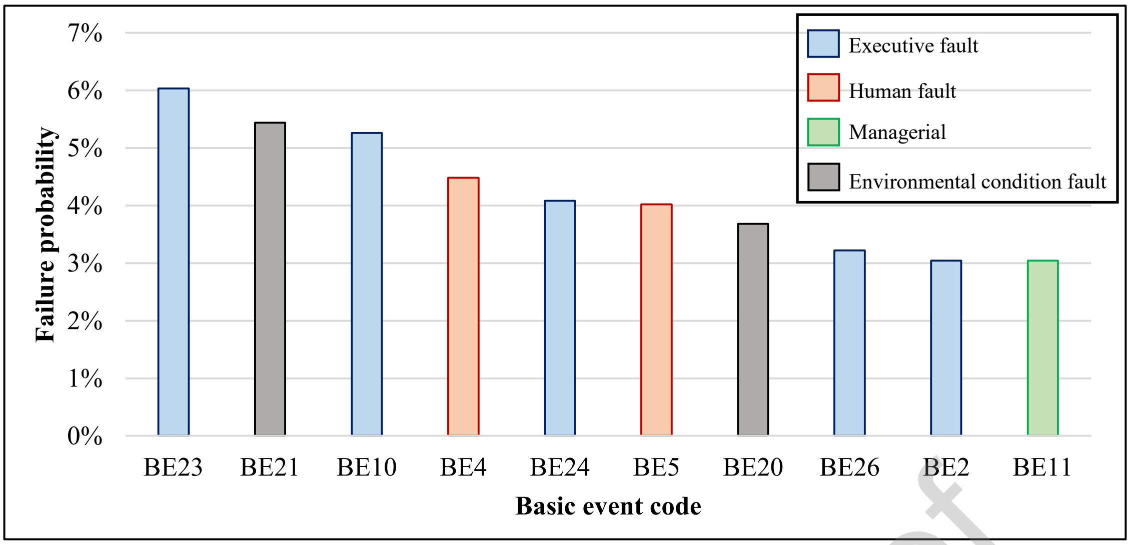


Figure 5. Top ten identified basic events with highest probability failure

4.1 Failure probability analysis

Figure 6 shows the results of the failure probability of the TE (i.e. Major fire in landfill with difficult control) and two top-level IEs i.e. IE1 (fire occurrence) and IE2 (lack of preparation for fire control) are calculated based on Eqs. (5) and (6). The two top-level IEs are shown here as they are directly connected to the TE by using a "AND" gate and are the head of the main branches in the tree for lower level events and hence their analysis related to the failure probabilities can be useful to understand the major causes of the LFI. As can be seen, it is evident that the probability of a major fire incident in the case study (i.e. TE) is quite low i.e. 5.51% although the probability of occurrence for both i.e. IE1 "fire occurrence" (25.4%) and IE2 "Lack of preparation for controlling fire" (21.7%) are both significantly higher than the TE (5.51%). This is due to the fact that the two IEs are required to occur simultaneously to have the occurrence of the TE and hence a multiplication of the failure probabilities for these two IEs would form the failure probability of major landfill fire. Additionally, the likelihood of surface fire is slightly more than subsurface fire in the landfill. In general, this is consistent with previous findings for landfill fire that indicates surface fire are more common in comparison to subsurface fires (Ibrahim, 2020). However, the importance of an event is based on its impact on the TE failure probability and not necessarily the failure probability of itself. The result of a sensitivity analysis for intermediate events is presented in the next section to determine whether the surface fire is more critical than subsurface fire.

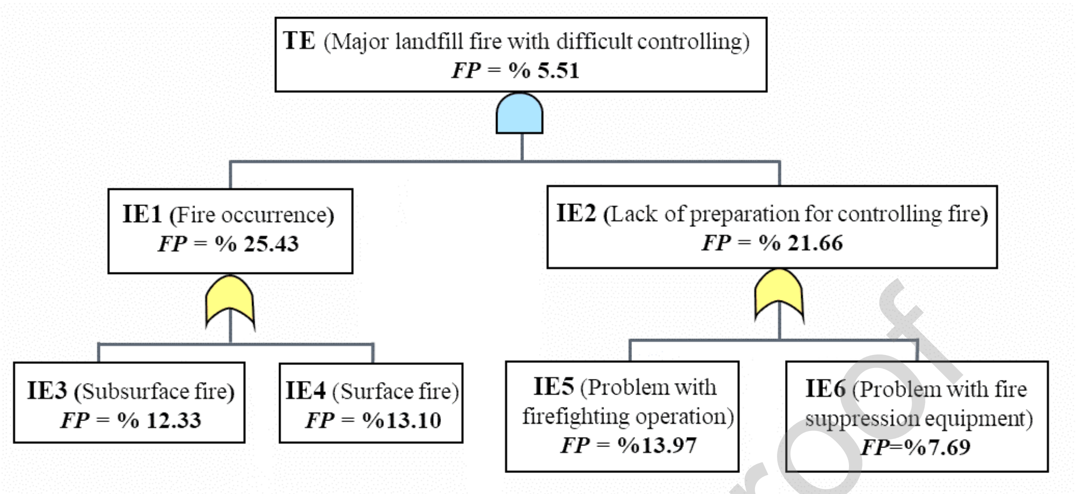


Figure 6. Failure probability of the top event and two top-levels of intermediate events

4.2 Sensitivity analysis

After calculating the TE failure probability, the importance degree of BEs is calculated by using the Fussell-Vesely importance method (FV-I) in Eq. (7) and presented in Tables B1 of Appendix B. Figure 7 also shows the importance degree of BEs ranked in descending order with corresponding failure probabilities for the landfill fire in the case study. The results show a relatively high direct correlation between the failure probabilities and importance degrees for the first 16 BEs. However, a few spikes for those ranked in the lower half of the list (i.e. BE10, BE21 and BE20) show inconsistency between these two indicators. More specifically, although failure probabilities of these BEs are quite high, their importance degrees are negligible compared to their failure probabilities. For example, BE21 "Heating from exothermic reactions of chemical substances in contact with water" and BE10 "Poorly cover condition in shallow areas" that are ranked the second and third BE with the highest failure probability are not amongst the top 15 BEs with highest importance degree. This indicates that regardless of their high failure probability rate, their impacts on the failure probability of TE can be negligible through the fault tree roots and in relation to other events. This result also demonstrates the fact that the high failure probability is not enough to consider an event as an important one and sensitivity analysis should be applied to reveal their actual critical ones. In addition, some BEs such as BE19, BE35 and BE32 have decent failure probability while their importance degrees are quite trivial that can be ignored when planning for any mitigation strategies. It is also evident that BE23 "Uncontrolled dumping of reactive and flammable hazardous waste" has the highest rate for both failure probability and importance degree which indicate the importance of this event that required an urgent mitigation measure.

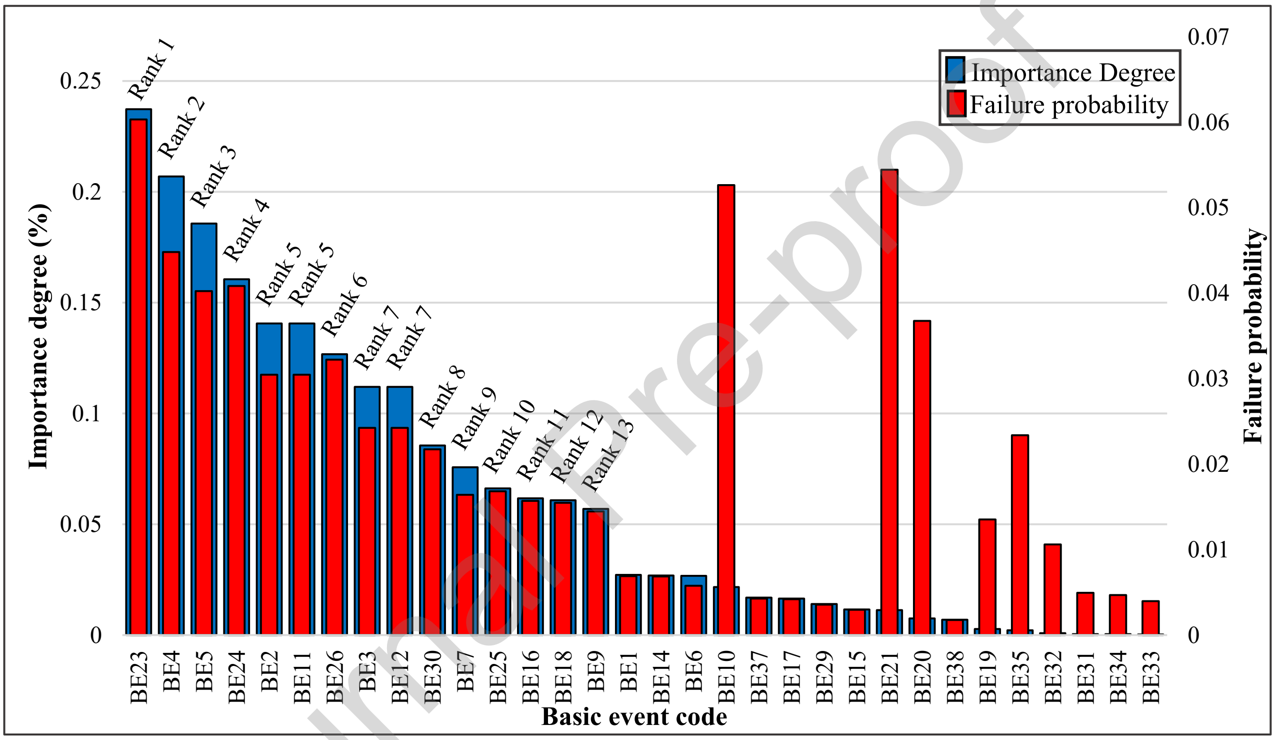


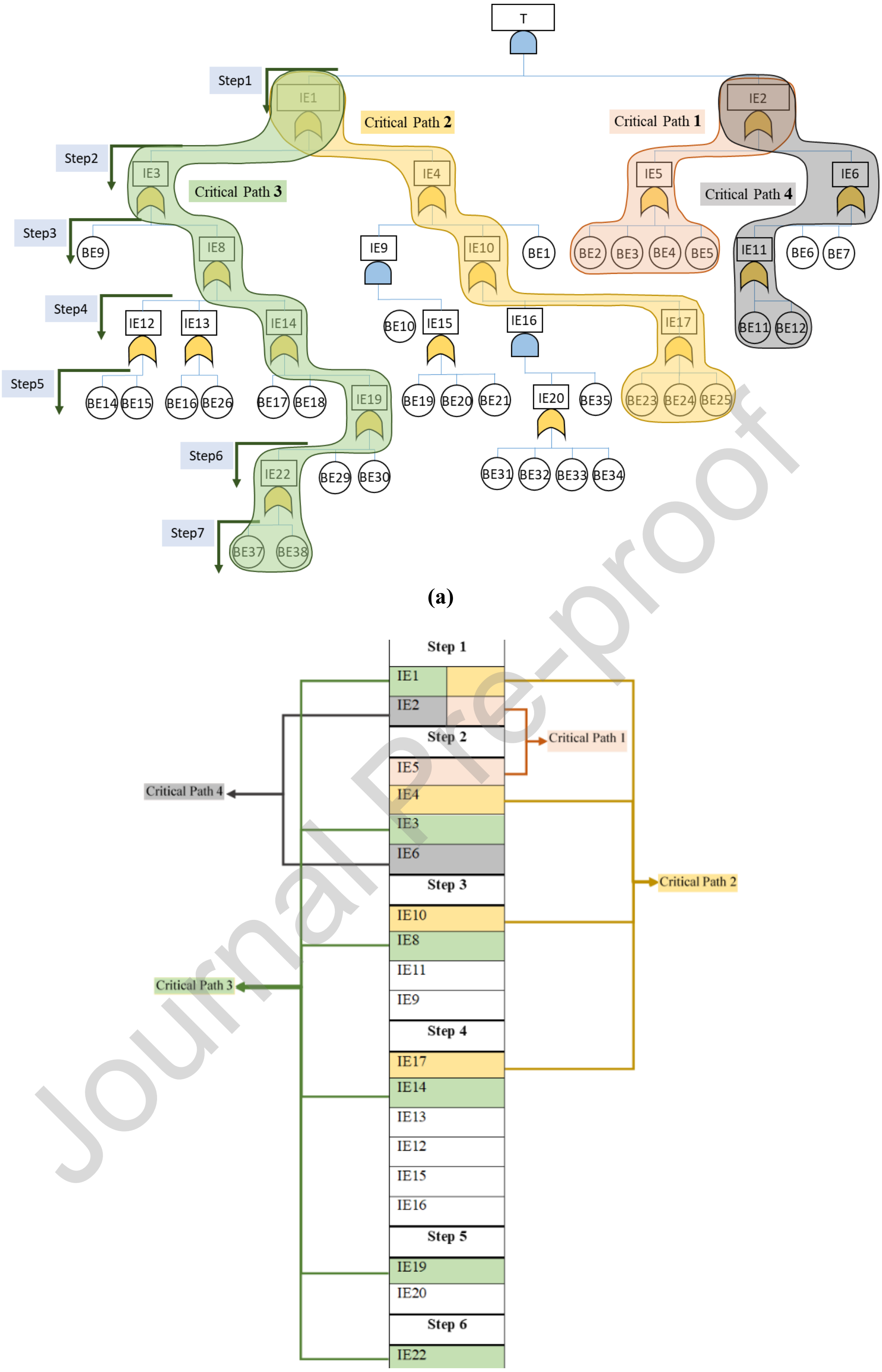
Figure 7. The importance degree and failure probability of BEs for landfill fire in the case study

Moreover, Table 3 presents the results of the sensitivity analysis for the ranking of the type of fault in BEs by using Eq. (8). Based on this ranking, the most critical types of fault can also be identified that can be followed by some recommendations and priorities for mitigation measures required for preventing fire in the future. As can be seen, executive fault (EF) is the most critical type of fault with the highest importance degree with a significant difference with other types of fault. This also indicates the high demand for critically reviewing and inspecting execution processes and technical documents in the site and checking with operators' functions against technical criteria. Human fault (HF) and managerial fault (MF) are placed in the next ranks with a relatively similar importance degree that can be considered at the same importance level for this site. Finally, environmental condition fault (ECF) is the lowest rank, and in general, due to the nature of this type of fault, they cannot be entirely eliminated and can only be undermined by some actions (for example, occurring heavy rain and performing immediate attempts to enhance cover condition on cap). In addition to ranking the type of fault in BEs, Table 3 also shows the critical BE related to each type of fault based on its importance degree and recommends several basic corrective actions. It is vital for decision makers to perform corrective actions for these BEs to reduce the TE occurrence probability in the case study.

The importance degree of IEs can also be determined to identify critical paths in the fault tree. The importance degrees are calculated for 22 IEs by Eq. (9) and presented in Tables B2 of Appendix B. In order to identify the critical paths of the LFI in the FTA, the importance degree of IEs for each step of the tree for all branches can be compared together. In this case study, identification of the basic events is extended to seven steps as shown in Figure 8a. According to the ranking of IEs in each step based on the importance degrees shown in Table B2, four main critical paths can be identified and highlighted in the fault tree as shown in Figure 8a. The first critical path (pink route) is for the branch related to the preparation for fire control. IE2 "Lack of preparation for controlling fire" and IE5 "Problem with firefighting operation" on this route show that the failure to successfully operate firefighting on time is the main reason that forms the first critical route leads to the major landfill fire in the site. Therefore, a priority should be given to this combination for developing plans for improvement of fire-fighting operations such as equipping an early detection by using fire detection technology or by planning shift schedules to have constant monitoring of the site by responsible operators, even during non-business hours; separating burning or smouldering loads from the rest of the waste bulk to prevent heading fire towards other cells; and carefully excavating and digging out the layers of burning or smouldering area for preventing from rekindled fire.

Table 3. The ranking of the type of fault in BEs for the LFI in the case study

Fault type	$I^{FV}_{fault\ of\ type\ A}$	Ranking	Critical BEs in fault	Recommended several basic corrective actions
EF	0.94399	1	BE23 (Uncontrolled dumping of reactive and flammable hazardous waste)	Providing labels for incoming waste include information about the material content, handling instruction, storage requirements, and disposal directions
HF	0.39386	2	BE4 (Negligence and delayed notification to the fire department by operator)	Using fire detection technology to provide early detection; Establishing shift schedules for continuous monitoring of the site, even during non-business hours;
MF	0.37246	3	BE11 (Problem with the manoeuvrability of the heavy equipment)	Planning equipment pathway by plotting the access point, the routs, and the proper movement and manoeuvres; Providing appropriate illuminate level of lighting based on guidelines in case of night time work; Planning to make workers clearly visible to drivers by using the appropriate type of garments; Training workers for being familiar with blind spots around each type of particular heavy equipment that could be used in the site in case of fire.
ECF	0.16491	4	BE3 (Being in an inclement weather condition)	Preparing plans by considering unusual inclement weather conditions in the area (for example, extremely windy or rainy months); Training workers for being familiar with the best clothing, driving techniques, and appropriate gear specific to the local weather-related safety hazard.



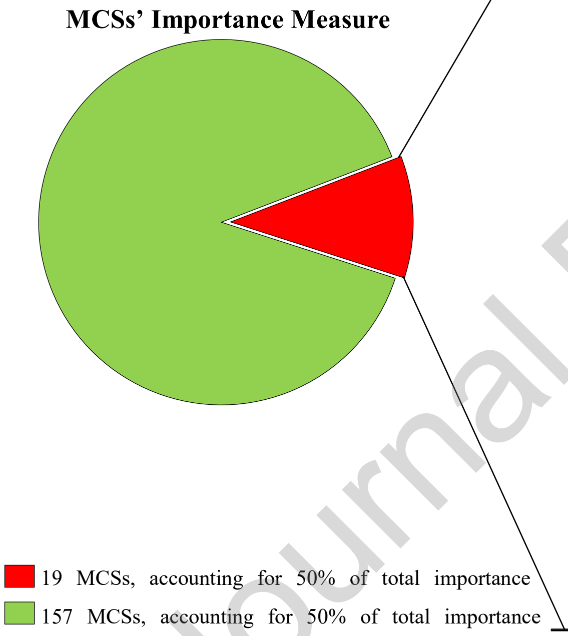
(a)

(b)

Figure 8. Critical paths of the fault tree: (a) routes of all critical paths; (b) critical intermediate events in each step

The second critical path (orange route) is related to the occurrence of surface fire, which is due to the accidental fire (IE10) by operational errors (IE17). Therefore, for preventing this critical path in the site, it is necessary to provide up-to-date documents of technical guidance for landfill operators. In addition, regular visual inspection by the head of the site should be performed for checking that landfilling follows based on the technical guidance and regulations. The third critical path (green route) is through a subsurface fire. Among the reasons leading to this type of fire incident, the air intrusion into the landfill mass (IE8) because of cap problems (IE14) is the reason to form the critical path in the fault tree of the case study. The problem of fissures and cracks in the soil cover (IE19) and poor maintenance of the cap in all weather conditions (IE22) in the site are weaknesses and should be solved by designing and implementation of daily and final covers with appropriate materials. Finally, the fourth critical path (grey route) is related to the fire suppression equipment branch. Based on this path, successful firefighting operations on the site are heavily dependent on how quickly and easily heavy machinery (bulldozers, excavators, etc.) are accessible and their manoeuvrability on the site. In addition, this machinery also plays a crucial role in the first critical path for excavating and separating the burning piles of waste. Designing the site plan, proper lighting of the routes and providing heavy machinery for the site are the most important points to prevent the occurrence of the fourth critical path.

As described in the case study section, the fault tree in the study contains 176 MCSs. Importance analysis of MCSs are applied using Eq. (10) and the ranking of the top 32 MCSs with an importance degree greater than 0.01 is shown in Table B3 of Appendix B. Figure 9 also shows a pie chart for a schematic representation of the top 19 MCSs accounted for 50% of the total importance degree and other 157 MCSs accounted for the other half of the importance degree. This indicates that eliminating the probability of occurrence for only these 19 critical MCSs can significantly reduce the occurrence probability of major fire in the landfill. Furthermore, the combination of BE23 "Uncontrolled dumping of reactive and flammable hazardous waste" and BE24 "Uncontrolled dumping of incompatible chemicals next to each other, which can ignite when mixed" with other events as shown in the figure have a significant contribution to the critical MCSs. This result indicates a large part of the critical MCSs can be eliminated by only preventing these two events. The prevention plan for this purpose can be included some mitigation measures such as classifying, stabilising, labelling, and packaging the incoming loads of hazardous and reactive waste, storing incompatible reactive waste in a separate cell or sub-cell such a way to avoid mixing with others, mapping cells of waste placement for potential future actions and defining standard instructions for mixing waste if required.



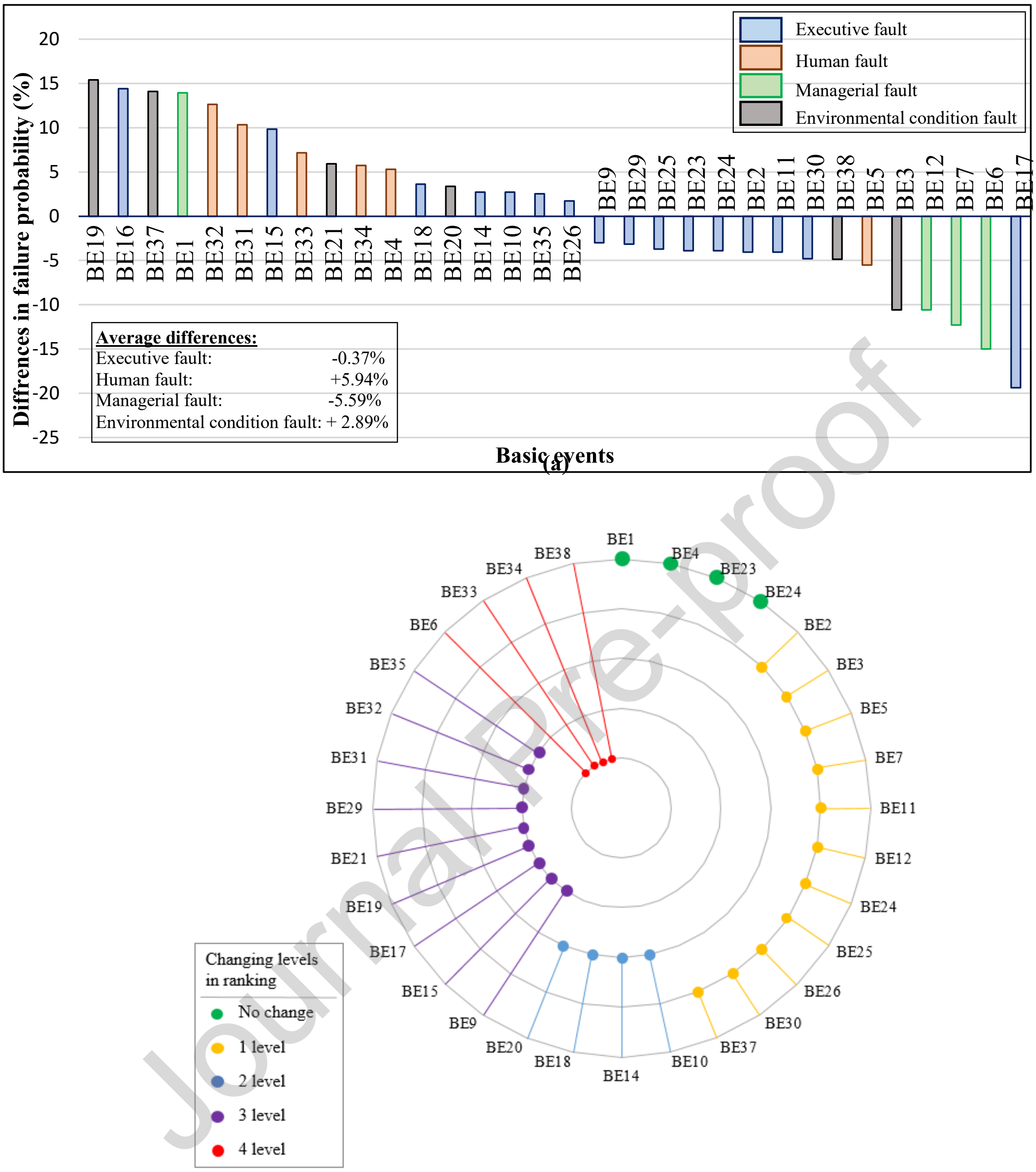
NO.	MCSs	Importance degree	Ranking
1	BE4.BE23	0.04907	1
2	BE5.BE23	0.04404	2
3	BE2.BE23	0.03334	3
4	BE11.BE23	0.03334	3
5	BE4.BE24	0.03322	4
6	BE5.BE24	0.02982	5
7	BE3.BE23	0.02656	6
8	BE12.BE23	0.02656	6
9	BE4.BE26	0.02623	7
10	BE5.BE26	0.02354	8
11	BE2.BE24	0.02258	9
12	BE11.BE24	0.02258	9
13	BE3.BE24	0.01798	10
14	BE4.BE23	0.01798	10
15	BE5.BE23	0.01796	11
16	BE2.BE23	0.01782	12
17	BE11.BE26	0.01782	12
18	BE4.BE30	0.01768	13
19	BE5.BE30	0.01587	14

Figure 9. The top 19 MCSs accounting for 50% of the total importance degrees in the landfill fire of the case study

4.3 Impact of experts' relative weight on the FTA results

All the analyses presented above are based on the differences of the experts' relative weight with respect to their specifications. However, a sensitivity analysis can also be conducted for these weights to evaluate the impact of the experts' relative weight and, in fact, the role of expertise in the FTA results. To that end, equal relative weights are considered for experts and relevant BEs' failure probabilities (FP'_i), importance degrees ($(FV-I)'$) and the relative difference of failure probabilities of BEs between the states of equal and real experts' weights (100×($|FP_i - FP_i'|$)/ FP_i) are calculated and presented in Table B4 of Appendix B. Although the failure probabilities in some events change significantly, the failure probability of the TE is relatively similar. Fig 10 also shows a better visual comparison of the relative percentage difference and change in rank between failure probabilities of BEs. The figure also show eliminating the relative weights can cause the failure probabilities for 11 BEs to change over 10%. The highest impacts are for BE17 "Poorly engineered cap especially on the side slope", BE19 "Heat generation because of remaining waste in aerobic degradation phase", and BE6 "Lack of sufficient personal protective equipment for personnel to participate in firefighting operations", respectively. This can demonstrate that experts' judgement for assessing failure possibilities of these events needs to be scrutinised in more details. Moreover, Fig 10a shows the average differences in each type of fault for BEs. The low average difference in the type of EF and ECF fault indicates the fact that experts have the relatively similar view for EF and ECF fault regardless of their different weights. On the other hand, the high average difference in the type of HF and MF indicates that experts with various levels of knowledge and experience have distinct insights into these two types of fault and hence need to coordinate their efforts in order to better understand human and management fault.

Furthermore, Figure 10b shows the change in the rank of BEs according to their importance degree when applying equal relative weights of experts. Among these BEs, the rank for 4 BEs including BE6 "Lack of sufficient personal protective equipment for personnel to participate in firefighting operations", BE33 "Contact of hot parts of opening equipment with waste", BE34 "Using the welding or electrical equipment on-site" and BE38 "Cap problem in windy weather condition" changed up to 4 levels. Generally, it can be concluded that the experts' weighting scores can have impact on the rank of basic events, and this can result in different prioritisation for any amendment of intervention strategies. Therefore, all these comparisons indicate that evaluating experts' weight and considering the impact of their characteristics in their judgements can make a considerable difference in the FTA results and hence can be impactful when analysing the relevant results.



(a)

(b)

Figure 10. Impact of experts' relative weight on the FTA results: (a) relative percentage difference of failure probabilities of BEs between the two states of equal and real relative weight of experts; (b) change in the rank of failure probabilities of BEs when using equal relative weights of experts

5 Conclusions

Landfilling is the most widespread method for solid waste management all over the world and fire is the most frequent problem occurring occasionally in different types of landfills. This study presented a new framework for assessment of the critical causes for the LFI by using FFTA. The framework developed a new fault tree for the LFI with the classification of the relevant type of faults for each event (executive, managerial, environmental conditions, and human). The principal steps of the FFTA entail developing failure possibility of basic events by using experts' judgement and then generating probability failure of events to perform a comprehensive qualitative analysis through sensitivity analysis. The following can be noted from the application of the methodology to a real-world case study:

- Although there is a relatively high direct correlation between the failure probability and importance degree of BEs, some glaring inconsistency between these indicators in some BEs (e.g. BE21 and BE10) shows the impact of these BEs on the probability of a major fire incident can be negligible in spite of their high failure probability.
- The analysis of the IEs' importance degrees identified four main critical paths with relevant events in the fault tree leading to the major landfill fire in the site. The identified IEs and BEs should be considered for planning of any intervention strategies to minimise the risk of the LFI.
- Executive fault is the most critical type of fault in BEs. This reveals high demand for reviewing the execution processes and technical documents in the site to minimise the impact of relevant BEs on the probability of a major fire incident.
- The results reveal that four critical basic events including "Uncontrolled dumping of reactive and flammable hazardous waste", "Negligence and delayed notification to the fire department by operator", "The late arrival of the fire service", and "Uncontrolled dumping of incompatible chemicals next to each other, which can ignite when mixed" have the highest impact on the probability of a major fire incident.

- The sensitivity analysis for the impact of the relative weights of experts on the FFTA results showed the weights can make a considerable difference up to 15% of change in the failure probability or up to a 4-level change in the rank of basic events in sensitivity analysis, especially for those events identified as human or management faults in which the experts' judgements with different levels of knowledge and experience are quite variable.

The failure analyses and subsequent assessment of events presented here are for illustrative purposes only with the purpose of demonstrating the suggested framework. Although the results identify some potential critical events that can lead to a major fire incident, further analyses including risk-based or scenario-based assessment are also recommended to give a more comprehensive solution for practical decision-making. This work can be further developed based on the risk management cycle to include risk evaluation, risk treatment, and risk monitoring for the LFI that can be recommended for future research works. The suggested framework should also be applied for other case studies to evaluate and verify the performance of the methodology. Finally, the sensitivity analysis can also be extended for other uncertain parameters of the LFI in the future works to provide robust solutions for failure probability and importance degrees of the analysed events.

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Appendix A: Raw data

Table A1. Profile of experts and their scores used in the case study

Experts job title	Professional position	Score	Professional experience (Years)	Score	Educational level	Score	Total weight	Relative weight
Firefighter	Fire chief[1]	5	25	5	MSc	4	14	0.1972
	Assistant fire chief[2]	4	17	4	BSc	3	11	0.1549
Management	Director[3]	5	20	4	PhD	5	14	0.1972
	Manager[4]	4	16	4	MSc	4	12	0.1690
Operation	Chief engineer[5]	5	14	3	MSc	4	12	0.1690
	Engineer[6]	3	9	2	BSc	3	8	0.1127

1: Responsible for directing the plan of firefighting operation in the local fire station.
2: Responsible for holding the firefighting operation on-site.
3: Responsible for providing scientific guidance or recommendations in operations.
4: Responsible for providing the financial budget and required executive decisions.
5: Responsible for planning and supervising the execution of operations on-site.
6: Hired by the board of trustees for operating the system.

Table A2. The results of FFTA stages for the landfill fire of case study

Code	Experts' relative weight and opinion						Aggregation fuzzy number (AFN_i)	Crisp Failure Possibility (CFP_i)	Failure probability (FP_i)
	0.1972	0.1549	0.1972	0.1690	0.1690	0.1127			
BE1	VH	H	M	L	M	L	(0.3887, 0.5472, 0.7056)	0.5472	0.0069
BE2	VH	VH	H	M	H	VH	(0.6422, 0.7775, 0.9127)	0.7775	0.0304
BE3	M	H	H	VH	H	VH	(0.5972, 0.7429, 0.8887)	0.7429	0.0242
BE4	VH	VH	VH	H	H	H	(0.7098, 0.8324, 0.9549)	0.8324	0.0448
BE5	H	H	H	VH	VH	VH	(0.6901, 0.8176, 0.9451)	0.8176	0.0402
BE6	M	M	L	M	H	H	(0.3451, 0.5211, 0.6972)	0.5211	0.0058
BE7	H	VH	M	L	VH	VH	(0.5437, 0.6817, 0.8197)	0.6817	0.0164
BE9	H	M	M	H	H	H	(0.4944, 0.6620, 0.8296)	0.6620	0.0145
BE10	VH	VH	H	VH	VH	H	(0.7380, 0.8535, 0.9690)	0.8535	0.0526

Code	**Experts' relative weight and opinion**						**Aggregation fuzzy number (AFN_i)**	**Crisp Failure Possibility (CFP_i)**	**Failure probability (FP_i)**
	0.1972	0.1549	0.1972	0.1690	0.1690	0.1127			
BE11	VH	VH	H	M	H	VH	(0.6422, 0.7775, 0.9127)	0.7775	0.0304
BE12	H	H	M	H	VH	VH	(0.5972, 0.7429, 0.8887)	0.7429	0.0242
BE14	M	L	M	H	H	M	(0.3704, 0.5458, 0.7211)	0.5458	0.0068
BE15	H	M	L	M	L	L	(0.2634, 0.4296, 0.5958)	0.4296	0.0030
BE16	H	VH	H	M	H	L	(0.5239, 0.6746, 0.8253)	0.6746	0.0157
BE17	M	H	L	M	L	H	(0.3070, 0.4753, 0.6437)	0.4753	0.0042
BE18	H	H	M	H	H	M	(0.5070, 0.6725, 0.8380)	0.6725	0.0155
BE19	H	H	H	M	H	L	(0.4929, 0.6514, 0.8098)	0.6514	0.0135
BE20	VH	H	H	H	VH	H	(0.6732, 0.8049, 0.9366)	0.8049	0.0368
BE21	VH	VH	VH	H	VH	H	(0.7436, 0.8577, 0.9718)	0.8577	0.0544
BE23	VH	VH	H	VH	VH	VH	(0.7606, 0.8704, 0.9803)	0.8704	0.0603
BE24	VH	VH	H	H	H	VH	(0.6929, 0.8197, 0.9465)	0.8197	0.0408
BE25	H	VH	H	H	M	M	(0.4958, 0.7028, 0.8591)	0.6859	0.0168
BE26	VH	VH	H	VH	M	H	(0.6535, 0.7859, 0.9183)	0.7859	0.0322

Code	Experts' relative weight and opinion						Aggregation fuzzy number (AFN_i)	Crisp Failure Possibility (CFP_i)	Failure probability (FP_i)
	0.1972	0.1549	0.1972	0.1690	0.1690	0.1127			
BE29	M	H	M	L	L	M	(0.2789, 0.4542, 0.6296)	0.4542	0.0036
BE30	H	H	M	H	VH	H	(0.5746, 0.7260, 0.8775)	0.7260	0.0217
BE31	H	VH	M	L	L	L	(0.3465, 0.4986, 0.6507)	0.4986	0.0049
BE32	VH	VH	M	H	L	L	(0.4704, 0.6127, 0.7549)	0.6127	0.0106
BE33	H	H	L	M	L	L	(0.3098, 0.4683, 0.6268)	0.4683	0.0040
BE34	H	VH	L	L	M	L	(0.3408, 0.4915, 0.6422)	0.4915	0.0047
BE35	VH	H	H	M	H	H	(0.5887, 0.7373, 0.8859)	0.7373	0.0234
BE37	M	M	H	M	L	L	(0.3028, 0.4789, 0.6549)	0.4789	0.0043
BE38	M	L	L	M	L	M	(0.1958, 0.3697, 0.5436)	0.3697	0.0018

Appendix B: Results details

Table B1. The importance degree of BEs ranked in descending order for the LFI of the case study

BEs	Type of fault	Importance degree	Rank	BEs	Type of fault	Importance degree	Rank
BE23	EF	0.23722	1	BE14	EF	0.02694	15
BE4	HF	0.20686	2	BE6	MF	0.02673	16
BE5	HF	0.18567	3	BE10	EF	0.02168	17
BE24	EF	0.16061	4	BE37	ECF	0.01691	18
BE2	EF	0.14057	5	BE17	EF	0.01648	19
BE11	MF	0.14057	5	BE29	ECF	0.01408	20
BE26	EF	0.12679	6	BE15	EF	0.01164	21
BE3	ECF	0.11195	7	BE21	ECF	0.01126	22
BE12	MF	0.11195	7	BE20	ECF	0.00761	23
BE30	EF	0.08550	8	BE38	ECF	0.00700	24
BE7	MF	0.07571	9	BE19	ECF	0.00280	25
BE25	EF	0.06623	10	BE35	EF	0.00223	26

BE16	EF	0.06170	11	BE32	HF	0.00097	27
BE18	EF	0.06088	12	BE31	HF	0.00045	28
BE9	EF	0.05695	13	BE34	HF	0.00043	29
BE1	MF	0.02717	14	BE33	HF	0.00037	30

Table B2. Ranking of the importance degrees of IEs for the LFI of the case study

IEs	Description	Type of fault	Importance degree	Ranking
IE1	Fire occurrence	MX	1	1
IE2	Lack of preparation for controlling fire	MX	1	1
IE5	Problem with firefighting operation	MX	0.64505	2
IE4	Surface fire	MX	0.51514	3
IE3	Subsurface fire	MX	0.48486	4
IE10	Accidental fire	MX	0.46628	5
IE17	Operational errors	EF	0.46406	6
IE8	The air intrusion into the landfill mass	MX	0.42792	7
IE6	Problem with fire suppression equipment	MF	0.35496	8
IE11	Problems with heavy equipment	MF	0.25252	9
IE14	Problems with cap	MX	0.20084	10
IE13	Existence of voids within the waste mass	EF	0.18849	11
IE19	Existence of fissures and cracks in the soil cover	MX	0.12349	12
IE12	Problems with the gas collection system	EF	0.03858	13
IE22	Poorly maintenance of the cap in all weather conditions	EF	0.02391	14
IE9	Spontaneous fire	MX	0.02168	15
IE15	Formation of shallow hot spots	ECF	0.02168	15
IE16	Surface catching fire	MX	0.00223	16
IE20	Existence of pilot ignition source	HF	0.00223	16

Table B3. The importance and ranking of top 32 MCSs for the landfill fire of case study

MCSs	Probability	Importance degree	Ranking
BE4.BE23	0.00270	0.04907	1
BE5.BE23	0.00243	0.04404	2
BE2.BE23	0.00184	0.03334	3
BE11.BE23	0.00184	0.03334	3
BE4.BE24	0.00183	0.03322	4
BE5.BE24	0.00164	0.02982	5
BE3.BE23	0.00146	0.02656	6
BE12.BE23	0.00146	0.02656	6
BE4.BE26	0.00144	0.02623	7
BE5.BE26	0.00130	0.02354	8
BE2.BE24	0.00124	0.02258	9
BE11.BE24	0.00124	0.02258	9
BE3.BE24	0.00099	0.01798	10
BE12.BE24	0.00099	0.01798	10
BE7.BE23	0.00099	0.01796	11
BE2.BE26	0.00098	0.01782	12
BE11.BE26	0.00098	0.01782	12
BE4.BE30	0.00097	0.01768	13
BE5.BE30	0.00087	0.01587	14
BE3.BE26	0.00078	0.01419	15
BE12.BE26	0.00078	0.01419	16
BE4.BE25	0.00075	0.01370	17
BE4.BE16	0.00070	0.01276	18
BE4.BE18	0.00069	0.01259	19
BE5.BE25	0.00068	0.01230	20
BE7.BE24	0.00067	0.01216	21
BE2.BE30	0.00066	0.01202	22
BE11.BE30	0.00066	0.01202	22
BE4.BE9	0.00065	0.01178	23
BE5.BE16	0.00063	0.01146	24
BE5.BE18	0.00062	0.01130	25
BE5.BE9	0.00058	0.01057	26

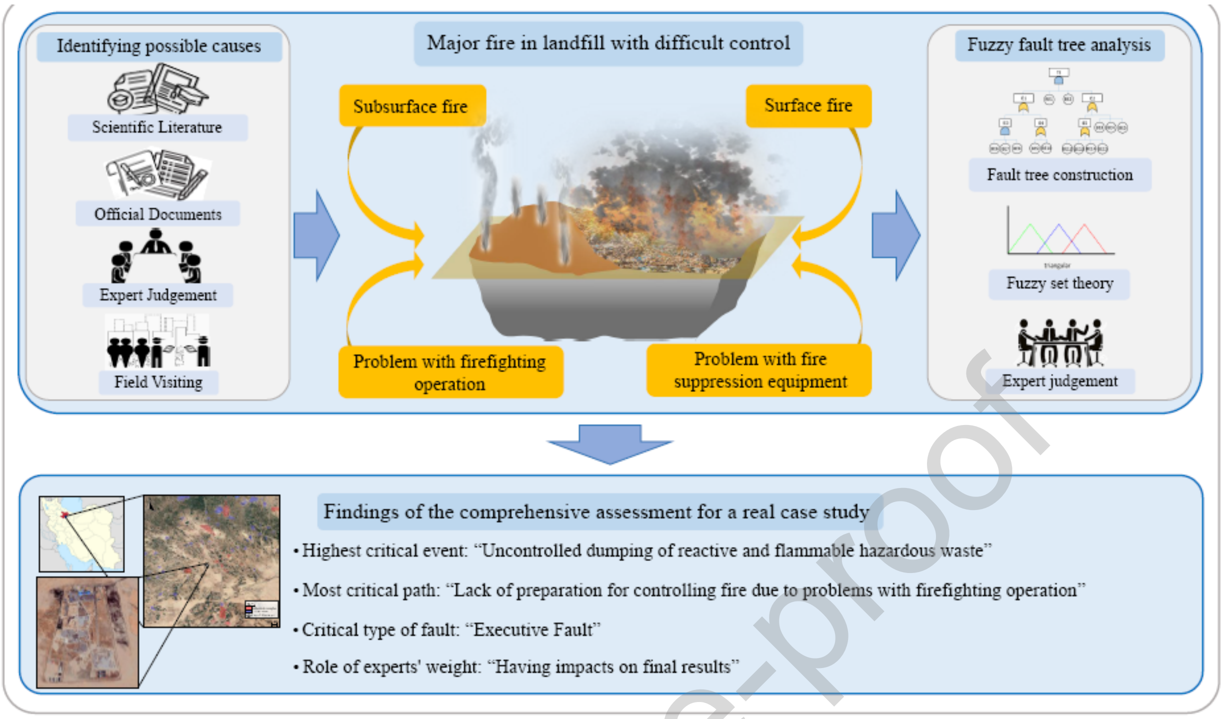
Table B4. Role of expert's weight on FFTA results

Code	Failure probability (FP'_i) (%)[1]	Relative difference (%)[2]	Sensitivity analysis of BEs	
			Importance degree $(\mathbf{FV-I})'$	Ranking
TE	5.51	5.20	-	-
BE1	0.59	13.94	0.0233	14
BE2	3.17	-4.04	0.1396	5
BE3	2.68	-10.57	0.1181	7
BE4	4.24	5.29	0.1869	2
BE5	4.24	-5.50	0.1869	3
BE6	0.67	-15.00	0.0293	16
BE7	1.84	-12.28	0.0811	9
BE9	1.49	-3.01	0.0584	13
BE10	5.12	2.71	0.0197	17
BE11	3.17	-4.04	0.1396	5
BE12	2.68	-10.57	0.1181	7
BE14	0.67	2.72	0.0261	15
BE15	0.27	9.84	0.0104	21
BE16	1.34	14.40	0.0526	11
BE17	0.50	-19.38	0.0196	19
BE18	1.49	3.63	0.0584	12
BE19	1.15	15.40	0.0023	25
BE20	3.55	3.38	0.0071	23
BE21	5.12	5.91	0.0103	22
BE23	6.27	-3.90	0.2454	1
BE24	4.25	-3.91	0.1662	4
BE25	1.75	-3.70	0.0684	10
BE26	3.17	1.74	0.1241	6
BE29	0.37	-3.15	0.0144	20
BE30	2.28	-4.79	0.0892	8
BE31	0.44	10.34	0.0004	28
BE32	0.93	12.62	0.0008	27
BE33	0.37	7.17	0.0003	30
BE34	0.44	5.73	0.0004	29
BE35	2.28	2.54	0.0019	26
BE37	0.37	14.10	0.0144	18
BE38	0.19	-4.86	0.0073	24

1: Calculated based on equal relative weights for experts

2: $100\times(|FP_i - FP'_i|)/\ FP_i$

Graphical abstract



Findings of the comprehensive assessment for a real case study

- Highest critical event: “Uncontrolled dumping of reactive and flammable hazardous waste”
- Most critical path: “Lack of preparation for controlling fire due to problems with firefighting operation”
- Critical type of fault: “Executive Fault”
- Role of experts' weight: “Having impacts on final results”

Declaration of interests

☒ 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.