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Research article

Reliability evaluation of a medical oxygen supply system by FTA based on intuitionistic fuzzy sets

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ABSTRACT

The main objective of healthcare centers is to ensure a consistent and high-purity oxygen supply for the safety of patients. Pressure Swing Adsorption (PSA) is a commonly used technique for supplying medical oxygen by eliminating nitrogen from the ambient air. Due to the increased fire risk associated with oxygen, any malfunctions in the oxygen supply system can lead to serious hospital fires. This study aimed to assess the reliability of the oxygen supply system using Fault Tree Analysis (FTA) based on both the traditional method and Intuitionistic Fuzzy Analysis. FTA is a logical analysis method used to identify events that could result in an undesirable top event and calculate the probability of its occurrence. The FTA of the PSA system outlined the logical sequence of events that could lead to the release of oxygen as a top event. The study revealed that the failure of the pressure switch in the concentrator, inadequate sealing, and the use of inappropriate materials for the seals were the primary basic events that led to the release of oxygen. Additionally, this study utilized the Intuitionistic Fuzzy System to quantify experts' opinions, providing more flexibility in handling ambiguous situations and considering both membership and non-membership functions simultaneously.

1. Introduction

One of the most significant demands in hospitals and medical care centers is the provision of stable, high-purity oxygen for patients. Since the popularization of oxygen therapy at the beginning of the twentieth century, different technologies have been used for oxygen supply in health centers [1]. These technologies range from small ventilation and medical oxygen gas cylinders to large-scale oxygen supply systems [2]. One of the most common methods of oxygen supply, especially in developing countries, is Pressure Swing Adsorption (PSA), which concentrates oxygen by removing nitrogen from ambient air with a purity of more than 90 % [3]. Due to oxygen's inherent properties, such as reducing material flammability, it is important to pay attention to the safe operation aspects of oxygen gas supply systems in hospitals [4].

A study by [5] during the COVID-19 pandemic (2020–2021) revealed that the failure of oxygen supply equipment was the second most common cause of hospital fires, due to the increased use of oxygen. Examples of accidents that have occurred include a fire in the oxygen gas storage tank in Kazakhstan (2020) with one death and a fire in the central oxygen supply unit in Russia (2020) due to

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Abbreviations: FTA, Fault Tree Analysis; PSA, Pressure Swing Absorbance; TIFN, Triangular Intuitionistic Fuzzy Numbers; IFS, Intuitionistic Fuzzy Set; TE, Top Event; IM, Intermediate Event; BE, Basic Events.

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equipment failure. Despite its importance, few studies have assessed the safety of medical oxygen supply systems.

It is worth mentioning the survey by [6] which quantitatively assessed the failure of the liquid medical oxygen supply system and concluded that the failure of the oxygen pipelines could have resulted in critical patient events. Therefore, healthcare providers should assess the hospital's oxygen supply system to ensure high patient safety. In addition, in a case study in Iran [7], conducted a risk assessment of the PSA system to determine the significant events caused by oxygen gas leakage.

1.1. Fault Tree Analysis (FTA)

The Fault Tree Analysis (FTA) can be used as a risk assessment tool to ensure the reliability and precise operation of equipment [8]. Researchers have employed FTA for a variety of applications, including oil storage explosion and fire [9], cyber security [10], Airborne wind energy systems [11], and the probability of fire in photovoltaic systems [12].

[13] used FTA to assess the efficiency of hospital infectious waste management systems; while (Tabibzadeh & Muralidharan, Jun. 2019 [1]) employed it to identify the root causes of medication errors [14]. utilized FTA for the reliability analysis of fire notification systems in office buildings. The researchers have concluded that FTA is a suitable inferential tool for measuring and determining the probability of failures [15]. stated that FTA is the most appropriate reliability tool for detecting components' failures and preventing events in medical equipment, such as the oxygen supply system.

According to FTA, all the basic logical events leading to an unwanted event can be described and quantified. Quantitatively calculating the top event requires the estimation of the probabilities of basic events, which in turn requires the failure rate of parts. However, accurately determining the actual rates of component failures in the real world is important due to the lack of access to initial observations and statistical data. Therefore, techniques such as the Bayesian theorem, fuzzy set theory, and evidence theory have been used to deal with uncertain situations [16,17].

1.2. Fault Tree Analysis and Intuitionistic Fuzzy Approach

One of the valid methods for overcoming uncertainty in the FTA method is the Intuitionistic Fuzzy Approach, which provides a flexible solution through mathematical language in dynamic systems [18,19] used the FTA with fuzzy theory to estimate the probability of basic events, make more accurate decisions regarding equipment risk management, and achieve more logical results [20]. investigated the safety of automatic firearms, using the FTA and Intuitionistic Fuzzy Approaches, to estimate the probability of the occurrence of a top event with uncertain data [21]. also used the Intuitionistic Fuzzy Approach to calculate the probability of the failure of components and the occurrence of the top event due to the lack of efficient data. Furthermore [22], evaluated the probability of basic events using the Intuitionistic Fuzzy Approach through experts' opinions, requiring more data on the failure rate of parts to provide more accurate results for dynamic risk assessment.

However, previous studies have not adequately addressed environmental safety issues associated with the presence of high-purity oxygen, which has inherent flammability risks. Therefore, it is essential to investigate the safety of oxygen supply systems regarding potential incidents such as fires and explosions. Additionally, the maintenance and repair challenges of oxygen supply equipment have not been comprehensively examined in previous studies. Consequently, it is important to assess factors affecting equipment performance and service life, develop appropriate maintenance and repair protocols, and evaluate the risks associated with equipment malfunctions. Keeping this in mind, the current study was conducted as a case study in a hospital combining the FTA with the Intuitionistic Fuzzy Approach to determine the probability of failure occurring in medical oxygen supply equipment.

2. Material and methods

In 2021, a reliability analysis of an oxygen supply system with PSA technology was conducted in a hospital in Kerman, Iran, using the FTA and Intuitionistic Fuzzy approaches. Fig. 1 shows the central oxygen concentrator unit in the hospital.

2.1. Pressure Swing Adsorption

The oxygen supply system produces oxygen with a purity of over 90 % and a pressure of 4–8 bars for patient consumption. The PSA technology involves suctioning ambient air by a compressor, followed by dehydration through a dryer and condensation in an oxygen generator. Zeolites are then used to remove nitrogen, resulting in oxygen-rich air (more than 90 %) which is sent to surge tanks to

Fig. 1. Picture of the central oxygen concentrator unit in the hospital.

maintain a stable flow and prevent any pulses caused by system interruptions [23,24]. Fig. 2 shows the PSA system, which consists of an oil-injected rotary screw air compressor, a refrigerated compressed-air dryer, an air receiver, oxygen generators, an oxygen storage tank, various valves, filters (moisture, particles, and dust), and copper pipelines with multiple connections.

2.2. Intuitionistic fuzzy theories

2.2.1. Fuzzy and intuitionistic fuzzy theories

[25] developed the fuzzy set theory to reduce ambiguity in the nature of sciences, proposing a framework for accepting uncertainty in the real world by expressing the membership functions of verbal variables through fuzzy sets. A fuzzy set is represented as $\widetilde{A} = \{x.\mu_{\widetilde{A}}(x)|x \in X\}$ where $\mu_{\widetilde{A}}(x)$ is the membership function of x to X with condition $0 \leq x \leq 1$. Despite its capabilities, this method could not consider uncertainty for the functions distribution of linguistic variables. As a result [26], introduced the Intuitionistic Fuzzy Approach to address the limitations of fuzzy theory. This approach considers uncertainties in the membership and non-membership functions, providing a more suitable platform for modeling and analyzing data in a dynamic situation.

2.2.2. Intuitionistic fuzzy set

Assuming that X is constant, Xon the IFS can be defined as a triple set of membership, non-membership, and hesitation (indeterminacy) degrees. As $\widetilde{A} = \{x.\mu_{\widetilde{A}}(x), \upsilon_{\widetilde{A}}(x)|x \in X\}$, where $\mu_A(x)$ and $\upsilon_A(x)$ are the membership and non-membership functions of X to A, respectively. In other words, there is $x \in X \text{ to } A \subseteq X$ that the value of the membership and non-membership functions is in the range of [0,1] with a relationship between them as $0 < \mu_A(x) + \upsilon_A(x) < 1$.In addition, the hesitation or indeterminacy degree can be calculated via $\pi_A(x) = 1\text{-}\mu_A(x)\text{-}\upsilon_A(x)$ [26].

2.2.3. Triangular intuitionistic fuzzy number (TIFN)

The *TIFN* is a specific form of IFS defined as $TIFN = \{(a', b', c'); (a, b, c)$ under the condition $a' < a < b < c < c'$. The membership and non-membership functions of a *TIFN* are determined as follows by Equation 1 [27]:

$$\mu_A(x) = \begin{cases} \dfrac{x - a'}{b - a'}; & a' \leq x \leq b \\ \dfrac{c' - x}{c' - b}; & b \leq x \leq c' \\ 0; & otherwise \end{cases} \quad \upsilon_A(x) \begin{cases} \dfrac{b - x}{b - a}; & a \leq x \leq b \\ \dfrac{x - b}{c - b}; & b \leq x \leq c \\ 1; & otherwise \end{cases} \tag{1}$$

2.2.4. Linguistic variables

Uncertainty due to complexity, ambiguity, and uncertain situations can disrupt evaluation and judgment. To aid subjective judgments, linguistic variables such as very low, very high and moderate can be qualitatively useful for describing ambiguity conditions. Intuitionistic Fuzzy Logic can be used to define the membership and non-membership functions of these linguistic variables [28].

2.2.5. Defuzzification

The last part of the Intuitionistic Fuzzy Approach is defuzzification, which converts the fuzzy outputs into crisp values. In this study, the center of mass for the *TIFN* by [29] was used as follows (Equation (2)):

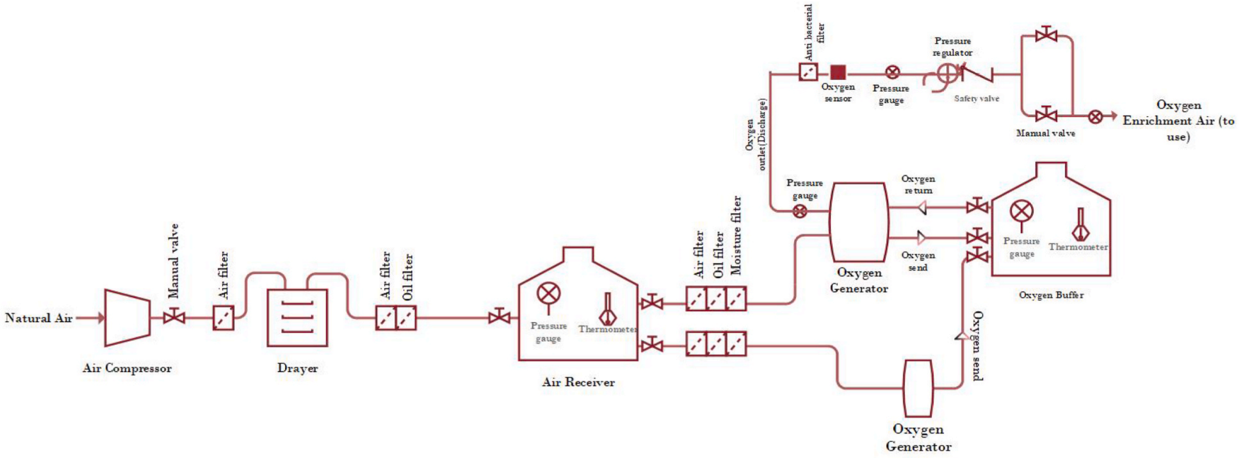

Fig. 2. Diagram of the medical oxygen supply system.

$$S = \frac{1}{3}\left[\frac{(c-a)(b-2c-2a)+(c'-a')(a'+b+c')+3(c^2-a^2)}{(c-a)+(c'-a')}\right] \quad (2)$$

2.3. Fault Tree Analysis

As a method of reliability analysis, FTA quantitatively determines the relationship between initiating events and the probability of an undesired event occurring. The structure of FTA consists of a Top Event (TE), Intermediate Events (IMEs), Basic Events (BEs), AND & OR logic gates. In the tree structure, all logical events leading to the TE can be identified, and IMEs can be further broken down to reach BEs with sufficient levels of detail. FTA follows a top-to-bottom structure with events connected by AND & OR gates. The AND gate is used when all downstream events are necessary for the upstream event, while the OR gate is used when only one downstream event is sufficient for the upstream event. Therefore, the probability of the TE can be calculated by estimating the occurrence of the BE, which can be obtained experimentally or from valid databases [8,30]. A simple chart of the FTA is shown in Fig. 3, consisting of the TE, three IMEs, four BEs, and two AND & OR gates.

In this study, the FTA was developed for the oxygen leak scenario as the top event through brainstorming sessions and input from experts, including the medical equipment manager, operator, maintenance supervisor, and the representative of the oxygen installation company.

The probability of the event $I(P_{AND})$ connected to AND gate (Pi) is calculated by Equation (3). In addition, the probability of the event $I(P_{OR})$ connected to OR gate (Pi) was obtained through Equation (4) [30].

$$P_{AND} = \prod_{i=1}^{n} P_i \quad (3)$$

$$P_{OR} = \prod_{i=1}^{n} (1-P_i) \quad (4)$$

2.4. Fault Tree Analysis based on the intuitionistic fuzzy

In the present study, it is important to note that the probability of failure in a PSA system was estimated using the Intuitionistic Fuzzy (IF) approach, as per the methods employed by [21], as well as conventional and fuzzy methods based on studies conducted by [31,32]. Fig. 4 illustrates the general steps of the proposed method.

2.4.1. Probability of basic events

The probability of the top event's occurrence can be determined by referencing databases such as CPSS, OREDA, or experimental methods [33]. However, in many cases, failure-rate data is not available due to a lack of maintenance-related information, which is often unreliable and uncertain. This issue becomes practically critical for new systems with a short life-span, where failure-rate data is not present in reliable databases and laboratory testing is not available. Thus, the most appropriate approach is to consult with experts and quantify their opinions using techniques like fuzzy logic, to assess the likelihood of the top event occurring [30]. However, the

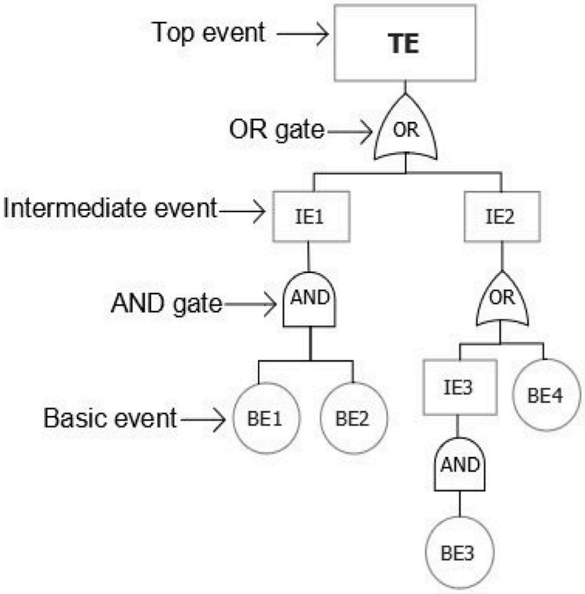

Fig. 3. An example of the FTA structure.

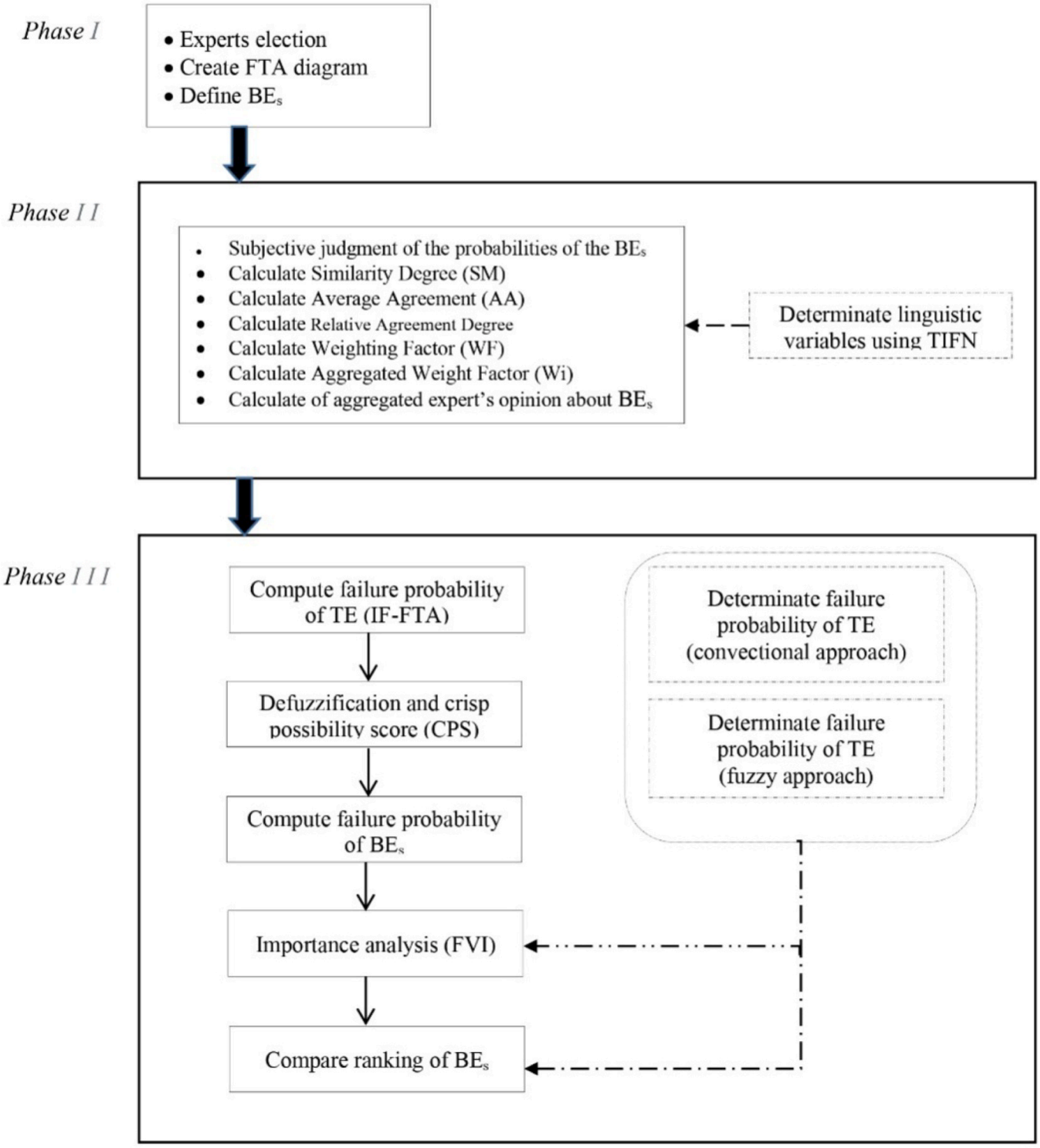

Fig. 4. The framework of the study in three separate phases.

fuzzy logic approach may not adequately account for the uncertainty and unreliability of the data. To address this limitation, this study utilized Intuitionistic Fuzzy Logic to quantify the opinions of experts, offering a more robust method compared to traditional fuzzy logic. Intuitionistic Fuzzy considers not only the membership function, which indicates the degree of an element belonging to a set, but also the non-membership function, which represents the degree of non-belongingness. This comprehensive approach allows for a better representation of uncertainty and ambiguity in the data. In contrast to classical fuzzy logic, Intuitionistic Fuzzy Logic has several advantages in handling ambiguous and imprecise information [28].

- Intuitionistic Fuzzy can capture both the degree of belongingness and non-belongingness, providing a more thorough description of the uncertainty associated with the data.
- Intuitionistic Fuzzy can accommodate situations where the membership and non-membership functions do not necessarily add up to 1, addressing the hesitancy in expert judgments.

By utilizing Intuitionistic Fuzzy, this study was able to effectively capture the ambiguity and unreliability related to the lack of detailed maintenance records and incident reports. This approach allowed for a more nuanced and accurate quantification of the experts' opinions, which is essential for assessing the likelihood of the top event occurring in the absence of reliable failure-rate data.

2.4.1.1. Expert group for the study. As mentioned previously, a group of five experts with diverse occupational and educational backgrounds participated in accessing technical data. The composition of the expert group for this study was carefully chosen to include a wide range of perspectives. Experts were selected based on their extensive experience, geographical locations, degrees, and fields of specialty. This meticulous selection process ensured that the chosen experts had deep subject matter knowledge, practical insights, and a broad understanding of real-world challenges. By including professionals from different geographical regions and diverse fields of expertise, the study benefits from a variety of perspectives, enabling a thorough examination of the subject matter across various contexts.

The experts included.

- The manager of the medical equipment.
- The supervisor of the central system maintenance department.
- Two technicians.
- The evaluator of the oxygen system installation company.

2.4.1.2. Subjective judgment of the probabilities of the basic events by experts. Table 1 displays the linguistic variable according to TIFN, ranging from very low to very high and divided into seven classes, indicating possible failure intervals for membership and non-membership functions.

The experts were asked to subjectively assess the failure probability of basic events using verbal variables. For instance, if the probability of the event failure is very unlikely or rare, few words are used, and if the probability is high, many words are used.

2.4.1.3. Probability of intuitionistic fuzzy failure possibility (IFFP) of basic events. This study utilized a consensus algorithm based on the method of [21] to integrate the opinions of experts and determine the probability of each basic event. The method involves calculating the similarity degree, average agreement degree, relative agreement degree, weighting factor of experts, aggregated weight of experts, and aggregation of expert opinions.

I. Similarity Degree (SM)

The similarity degree or $S_{(Ai,Aj)}$for each expert E_i $(I = 1,2,3,4,5)$ and their opinion on a specific event, which is explained by linguistic variables, can be obtained via Equation (5):

$$S_{(A_i,A_J)} = \begin{cases} \dfrac{EV_{(Aj)}}{EV_{(Ai)}} & If\ EV_{(Ai)} \le EV_{(Aj)} \\ \dfrac{EV_{(Aj)}}{EV_{(Ai)}} & If\ EV_{(Ai)} \ge EV_{(Aj)} \end{cases} \tag{5}$$

which $EV(A_i)$ and $EV(A_j)$ are expectancy evaluation for A_i *and* A_j respectively, Considering the TIFN in this study, the EV for experts' opinions i and j was calculated according to Equation (6).

$$EV_{(Ai)} = \frac{a_i + a'_i + 4b_i + c'_i}{8} \tag{6}$$

This study had more than one expert, about five experts, so the similarity matrix was obtained as follows (Equation (7)):

$$M = \begin{bmatrix} 1 & S_{22} & \dots & S_{m1} \\ S_{21} & 1 & \dots & S_{m2} \\ \vdots & S_{m2} & \dots & 1 \\ S_{m1} & S_{m2} & \dots & 1 \end{bmatrix} \tag{7}$$

Table 1
Linguistic variables in the study.

Linguistic variables	TIFN	
	Non-membership functions	Membership functions
Very Low (VL)	(0,0.05,0.10)	(0,0.05,0.10)
Low (L)	(0.08,0.14,0.21)	(0.07,0.14,0.22)
Reasonably low (RL)	(0.19,0.28,0.38)	(0.17,0.28,0.40)
Moderate (M)	(0.35,0.54,0.66)	(0.32,0.54,0.68)
Reasonably high (RH)	(0.64,0.75,0.80)	(0.61,0.75,0.83)
High (H)	(0.84,0.89,0.93)	(0.82,0.89,0.95)
Very High (VH)	(0.90,1,1)	(0.90,1,1)

II. Average Agreement (AA)

The average agreement for each expert E_i is determined using Equation (8):

$$AA_{(Ei)} = \frac{1}{m-1}\sum_{\substack{i=1\\ i\neq 1}}^{m} S_{ij}, i = (1, 2, \ldots, m) \tag{8}$$

III. Relative Agreement Degree (RAD)

The relative agreement degree for each expert E_i, $i = (1.2 \ldots., m)$, was calculated according to Equation (9):

$$RAD_{(Ei)} = \frac{AA_{(Ei)}}{\sum_{i=1}^{m} AA_{(Ei)}}, i = (1, 2, \ldots, m) \tag{9}$$

IV. Weighting Factor (WF)

The weighting coefficients varied according to the demographic characteristics of the experts who participated in this study. Thus, the values of Table 2 were used for scoring by considering factors such as educational degree, age, professional experience, practice knowledge and professional position. To ensure a more equitable distribution of weight among the experts, their experience working with the PSA system was also taken into account, in addition to their overall professional background. In addition, Equation (10) was employed to calculate the weighting factor, as shown in Table 3.

$$WF_{(Ei)} = \frac{ws_{(Ei)}}{\sum_{i=1}^{m} ws_{(Ei)}}, i = (1, 2, \ldots, m) \tag{10}$$

V. Aggregated Weight Factor (*Wi)*

The aggregated weight of each expert was determined according to Equation (11). In this formula, β, known as the relaxation factor, is located between *0* and *1* $(0 \leq \beta \leq 1)$, which shows the relationship between the aggregated weight *(Ei)* and the relative agreement degree *(Ei)*. When the value of β is close to zero, the weight of an expert has minor importance; if β is close to one, the relative agreement degree has less significance, and vice versa. In this research, the value of β was determined to be 0.5 to establish a balance between the relative agreement degree and the weighting factor.

$$w_i = \beta.WF_{(Ei)} + (1 - \beta).RAD_{(Ei)} \tag{11}$$

VI. Determination of aggregated expert's opinion $\widetilde{(pj)}$.

The last step in this stage was gathering the experts' opinions. Therefore, the views of experts about the basic events are calculated according to Equation (12):

Table 2
Weighting scores.

Status	Classification	Score
Educational degree	PhD	5
	Master of Science (MSc)	4
	Bachelor of Science (BS)	3
	Diploma	2
	Secondary school	1
Professional experience	>30 years	4
	20–29 years	3
	10–19 years	2
	0–9 years	1
Relevance experience	>15 years	4
	10–14 years	3
	5–9 years	2
	0–4 years	1
Professional position	Chief engineer	3
	Supervisors	2
	Technician and operator	1

Table 3
Demographic characteristic of experts and their w_i.

Expert (*Ei*)	Educational degree	Professional position	Professional experience (year)	Relevance experience	Assigned weighting scores	(*WF*)
E1	PhD	Chief Engineer	18	14	12	0.29268
E2	BS	Supervisor Maintenance	15	7	9	0.21951
E3	Diploma	Maintenance Technician	7	7	6	0.14634
E4	Diploma	Maintenance Technician	3	3	5	0.12195
E5	MSc	Supervisors of the Contractors	8	5	9	0.21951

$$\widetilde{(pj)} = \sum_{i=1}^{m} w_i \times p_{ij}, i = (1, 2, \dots, m) \tag{12}$$

2.4.2. *Computing the probability of the top event*

Based on Equations 3 and 4, as well as the FTA diagram presented in Fig. 5, the TE of the study can be generated as follows (Equation (13)):

$$P_{T(A)} = 1 - (1 - P_B)(1 - P_C)(- P_D) \tag{13}$$

$$P_{T(A)} = 1 - (1 - P_{X1} \times P_{X2})(1 - P_{X3})(1 - P_{X4})(1 - P_{X5})(1 - P_{X6})(1 - P_{X7})(1 - P_{X8})(1 - P_{X9})(1 - P_{X10})(1 - P_{X11})(1 - P_{X12})(1 - P_{X1}P_{X2})$$

2.4.3. *Defuzzification and crisp possibility score (CPS)*

In this step, the generated TIFN for the ranges of BE_s and TE are converted into a definite number using Formula 2.

2.4.4. *Converting the crisp probability to failure probability*

In this stage, the actual numbers are converted into probability values through Equation (14), proposed by [34], to determine the event's importance for the next step.

$$\begin{cases} P_{(i)} = \dfrac{1}{10^k}; \quad s \neq 0 \\ 0; \quad s = 0 \end{cases} \quad k = \left(\frac{1 - S}{S}\right)^{\frac{1}{3}} \times 2.301 \tag{14}$$

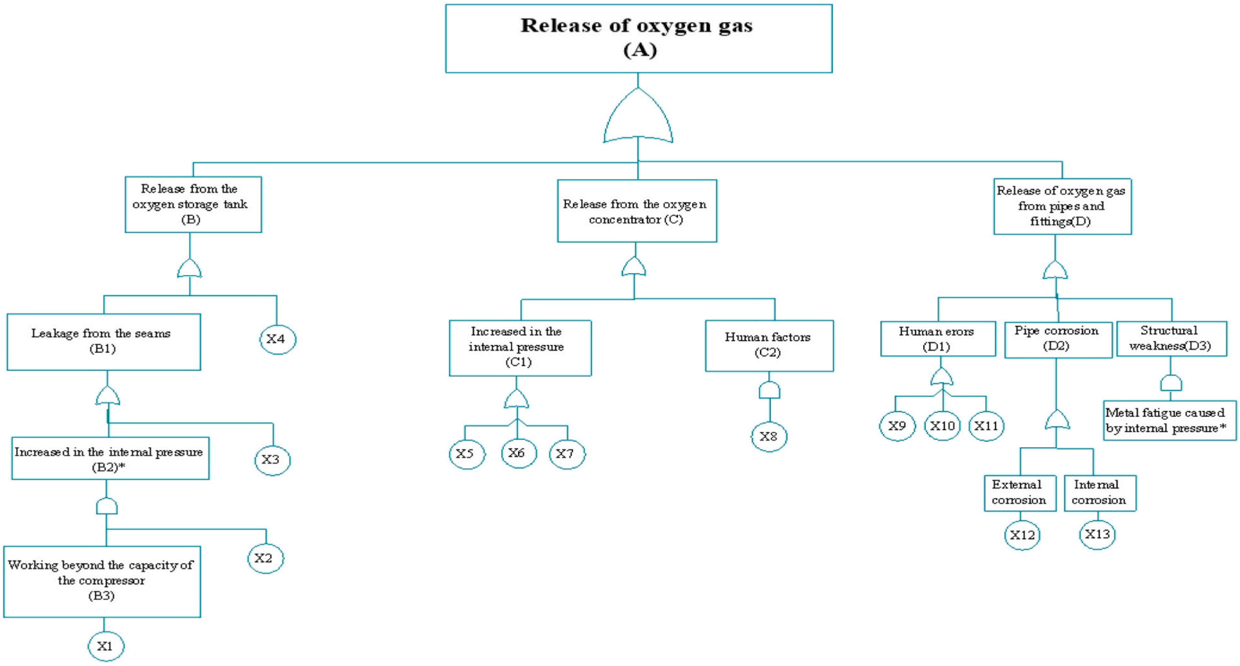

Fig. 5. The FTA diagram for the oxygen release as the top event in the PSA system.

2.4.5. Determining the importance of events

The last stage of the FTA analyses the importance of each basic event for determining the probability of the top event occurrence. This stage helps identify the most important basic events and reduce their effects to prevent the occurrence of the top event. For this purpose, Equation (15) of Fussell-Vesely was used [35]:

$$FVI_{(Xi)} = \frac{P_{Ti}.P_T\ (X_i = 0)}{P_T} \tag{15}$$

In this equal, P_{Ti} is the probability of basic event X_i and P_T refer to the probability of top event. Moreover, when P_{Ti} is related to event X_i, it is equal to 0, P_T assumed to be $P_T\ (X_i = 0)$.

3. Results

Fig. 5 illustrates the oxygen leak scenario outlined in Table 4. Four potential paths- the tank, concentrator, pipes, and connections; -are identified as the top event for the release of oxygen gas. In the tree diagram depicting the oxygen gas release scenario, intermediate event D3 (an increase in internal pressure leading to metal fatigue) results in branch B2, which concludes with two factors, X1 and X2, these factors include an increase in engine torque and a pressure switch failure linked to event B2 by an AND gate. In the calculations concerning the basic events, the probability of event D3 is assumed to be equal to that of event B2.

The opinions of five experts for each of the thirteen basic events are summarized in Table 5.

The results of the experts' opinions aggregation related to the basic events for the oxygen leakage scenario, defined in the TIFN format, can be seen in Table 6.

As an example, all the steps for basic event X9 are summarized in Table 7.

In this regard, the parameters of the crisp probability score and their related failure probability are presented in Table 8.

The results of the top event occurrence probability through the three adopted approaches (conventional, fuzzy, and Intuitionistic fuzzy methods) and the probability interval sets related to the IFs are shown in Table 9. According to the findings, the highest possible score of the top event was associated with the traditional approach, and the lowest score was related to the fuzzy approach.

In this study, thirteen basic events were identified, with X6 and X9 determined as the most critical basic events in the occurrence of the top event. Conversely, X4 and X10, with the same probability, were identified as the least important events in the oxygen leakage scenario. The three approaches reported different FVIs, and, on average, the Intuitionistic Fuzzy approach considered the probability of each basic event more than the other two approaches. The findings indicated that all three approaches yielded similar results for determining the contribution of basic events. The difference between the three approaches was related to events X2, X3, X5, X7, and X13; more details about this can be found in Table 10.

The FVI values in three approaches, including conventional, intuitive, and fuzzy methods are presented in Fig. 6. According to the findings, significant differences were observed in the probability of some basic events. This difference was higher in the conventional approach, and far less in the intuitive fuzzy set. This higher contrast in the conventional method was due to the difference between experts' opinions about the probability of occurrence of basic events, whereas, the low difference in the intuitive fuzzy set was due to the simultaneous consideration of membership and non-membership functions.

Fig. 7 illustrates the five most important basic events that are common among the three adopted approach and play a critical role in realizing oxygen gas from the PSA system.

4. Discussion

In the present research, a risk assessment of the PSA system was conducted using FTA, providing a visual representation of the logical sequence of events that could lead to the release of oxygen as the top event. The findings of this study indicated that the failure of the pressure switch in the concentrator, inadequate sealing, and the use of inappropriate materials for the seals were the main basic

Table 4
Description of events taken from Fig. 5.

Code	Description
X1	Reaching maximum pressure by increasing the motor torque of the compressor.
X2	Failure of the compressor's pressure switch due to sediment and moisture infiltration or lack of replacement at the end of its lifespan.
X3	Mechanical damage to the oxygen storage tank
X4	Opening the valve of the oxygen storage tank
X5	Safety valve failure due to internal damage and reaching the end of its useful life
X6	Failure of the concentrator's pressure switch due to sediment and moisture infiltration or lack of replacement at the end of its useful life.
X7	Defect in the solenoid valve caused by increased entry voltage, bobbin defect, or electrical board malfunction
X8	Mechanical damage to the oxygen supply system
X9	Seal and installation defects in the bead and bobbin resulting in oxygen leakage or use of inappropriate seal materials
X10	Increased internal pressure due to manual valve closure
X11	Failure to use Teflon tape with the appropriate grade (compatible with oxygen)
X12	Damage to the external layer of the oxygen pipeline from physical or mechanical impact
X13	Damage to the internal layer due to corrosive substances or failure to replace the filter as schedule

Table 5
Scoring of the basic events by experts.

BE	E1	E2	E3	E4	E5
X1	M	L	VL	L	L
X2	M	RL	RL	M	L
X3	VL	L	RL	RL	L
X4	VL	VL	VL	VL	VL
X5	L	RL	L	VL	L
X6	RL	M	L	M	M
X7	RL	VL	L	L	L
X8	L	VL	L	L	L
X9	M	RL	RL	RL	L
X10	VL	VL	VL	VL	VL
X11	RL	RL	L	L	VL
X12	RL	L	L	VL	VL
X13	RL	RL	L	L	M

Table 6
The results of the experts' opinions aggregation.

Bottom events	\`a	b	\`c	a	b	c
X1	0.1312	0.2230	0.3040	0.1182	0.2230	0.3150
X2	0.2330	0.3584	0.4602	0.2110	0.3584	0.3190
X3	0.0867	0.1524	0.2248	0.0770	0.1524	0.2345
X4	0.0000	0.0239	0.0649	0.0000	0.0239	0.0650
X5	0.0826	0.1462	0.2487	0.0730	0.1462	0.2270
X6	0.3499	0.5520	0.7208	0.3149	0.5520	0.7481
X7	0.0827	0.1469	0.2101	0.7320	0.1469	0.2276
X8	0.0580	0.1257	0.2170	0.0562	0.1257	0.2250
X9	0.2950	0.4363	0.5798	0.2671	0.4363	0.6026
X10	0.0000	0.0239	0.0649	0.0000	0.0239	0.0650
X11	0.1008	0.1700	0.2462	0.0897	0.1700	0.2573
X12	0.0752	0.1387	0.2081	0.0668	0.1387	0.2166
X13	0.2094	0.3184	0.4180	0.1887	0.3184	0.4362

Table 7
Calculation for the interval probabilistic occurrence for basic event X9.

Expert Elications	E1	M	[(0.35,0.54,0.66); (0.32,0.54,0.68)]	$EV(A_1) = 0.52$
	E2	RL	[(0.19,0.28,0.38); (0.17,0.28,0.40)]	$EV(A_2) = 0.28$
	E3	RL	[(0.19,0.28,0.38); (0.17,0.28,0.40)]	$EV(A_3) = 0.28$
	E4	RL	[(0.19,0.28,0.38); (0.17,0.28,0.40)]	$EV(A_4) = 0.28$
	E5	L	[(0.08,0.14,0.21); (0.07,0.14,0.22)]	$EV(A_5) = 0.22$
Similarity degree			$S_{12} = 1.85$ $S_{13} = 1.85$ $S_{14} = 1.85$ $S_{15} = 2.36$	
			$S_{21} = 1.85$ $S_{23} = 1.00$ $S_{24} = 1.00$ $S_{25} = 1.27$	
			$S_{31} = 1.85$ $S_{32} = 1.00$ $S_{34} = 1.00$ $S_{35} = 1.27$	
			$S_{41} = 1.85$ $S_{42} = 1.00$ $S_{43} = 1.00$ $S_{45} = 1.27$	
			$S_{51} = 2.36$ $S_{52} = 1.27$ $S_{53} = 1.27$ $S_{54} = 1.27$	
Average agreement degree			$AA(E_1) = 1.977$ $AA(E_2) = 1.53$ $AA(E_3) = 1.53$ $AA(E_4) = 1.53$ $AA(E_5) = 1.54$	
Relative agreement degree			$RAD_1 = 0.4380$ $RAD_2 = 0.1886$ $RAD_3 = 0.1886$ $RAD_4 = 0.1886$ $RAD_5 = 0.1901$	
Weight calculation			W1 = 0.51168 W2 = 0.20405 W3 = 0.16470 W4 = 0.15527 W5 = 0.20480	
Aggregation IFN			[(0.2950,0.4363,0.5798); (0.2671,0.4363,0.6026)]	

events leading to the release of oxygen. Consistent with these results, a study by [7] assessed a central oxygen system using FTA and Layer of Protection Analysis (LOPA) methods in combination with fuzzy logic, revealing that the release of oxygen could potentially result in fire and explosion events.

This study focuses on the fire and explosion hazards associated with potential oxygen leaks from the PSA system. While some previous studies have applied FTA to industrial equipment such as [31,36], they did not consider the distinct challenges of operating high-purity oxygen systems in healthcare settings. The flammable nature of oxygen underscores the need for thorough safety assessments to prevent catastrophic incidents that could endanger patient lives [3,4]. Furthermore, this research explores the often-overlooked aspect of maintenance and repair practices for medical oxygen infrastructure. Through extensive consultations with equipment experts, technicians, and maintenance staff, we identified critical factors that impact component degradation, useful lifespan, and the importance of timely replacements and overhauls. This comprehensive evaluation of operational stressors and maintenance practices is an area that has been largely neglected in previous reliability studies focusing on medical oxygen supply chains [7].

Table 8
Scores of CPS$_s$ and FP$_s$.

Basic events	crisp possibility score: CPS	failure probability: FP
X1	3.030E-01	9.1693E-04
X2	4.237E-01	2.8208E-03
X3	2.093E-01	2.6095E-04
X4	2.962E-02	4.3355E-08
X5	2.010E-01	2.2635E-04
X6	7.657E-01	2.8151E-02
X7	2.015E-01	2.2844E-04
X8	1.732E-01	1.3360E-04
X9	6.287E-01	1.1737E-02
X10	2.962E-02	4.3355E-08
X11	2.364E-01	3.9669E-04
X12	1.879E-01	1.7854E-04
X13	4.513E-01	3.5016E-03

Table 9
Probability of TE in C-FTA, F-FTA, IF-FTA

IF-FTA	Failure interval	[(0.7950,0.9464,0.9905); (0.7543,0.9464,0.9919)]
	CRISP	1.455
	P(T)	2.741E-02
F-FTA	P(T)	1.228E-04
C-FTA	P(T)	3.839E-01

Table 10
Final ranking of BE$_s$ in conventional, fuzzy and Intuitionistic fuzzy approaches.

Basic events	FVI (C-FTA)	RANK (C-FTA)	FVI (F-FTA)	RANK (F-FTA)	FVI (IF-FTA)	RANK (IF-FTA)
X1	3.3443E-02	5	1.2555E-02	5	8.4597E-04	5
X2	1.0288E-01	4	1.1882E-01	3	4.1859E-03	3
X3	9.5178E-03	7	1.9328E-03	8	2.1824E-04	7
X4	1.5813E-06	12	2.6077E-10	12	3.1020E-08	12
X5	8.2557E-03	9	1.9513E-03	7	1.8708E-04	9
X6	1.0267E+00	1	6.1921E-01	1	1.8595E-02	1
X7	8.3321E-03	8	1.4698E-03	9	1.9044E-04	8
X8	4.8726E-03	11	5.4393E-04	11	1.0554E-04	11
X9	4.2809E-01	2	2.9393E-01	2	8.1205E-03	2
X10	1.5813E-06	12	2.6077E-10	12	3.1020E-08	12
X11	1.4469E-02	6	3.6786E-03	6	3.2521E-04	6
X12	6.5119E-03	10	1.0597E-03	10	1.5358E-04	10
X13	1.2771E-01	3	7.6264E-02	4	2.8196E-03	4

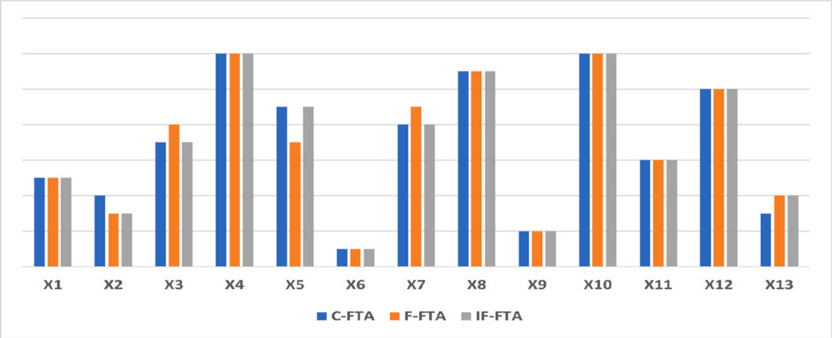

Fig. 6. Comparison of ranking BEs in three adopted approaches.

One of the essential steps in the FTA method is to determine the probability of occurrence of the top event by assessing the likelihood of each of the basic events. Therefore, it is an important part of the quantitative analysis of the FTA, and any errors in determining these probabilities can adversely affect the results [30]. However, most of this data is either incomplete or not available in practice. As a result, the rate of component loss depends on operators' experience and maintenance records, which are primarily

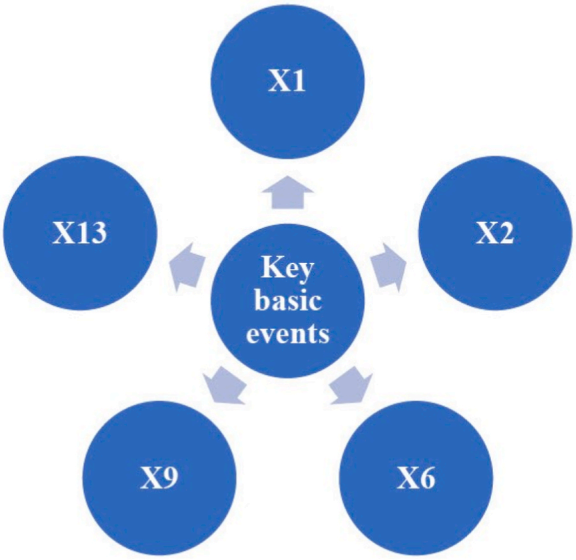

Fig. 7. Key basic events for oxygen gas extraction from the PSA system.

imprecise and subjective. In this regard [36,37], have stated that the risk assessment analysis process using the FTA method is a static method. In addition, there are some limitations in the FTA, including the inherent complexity of the system, insufficiency of input data, and dependency of the probability or failure rate of basic events on the opinion of experts. Therefore, integrating the FTA with approaches such as Bayesian networks, interval calculations, factor analysis, and fuzzy set theory, not only enables the inclusion of a broad range of input variables but also enhances the understanding of uncertainty and facilitates more accurate prioritization in risk analysis. Moreover, in the FTA, it is almost impossible to effectively reduce the ambiguities and uncertainty of the probability of basic events. The study by [38] "assessing the probability of hydrocarbon leakage scenario using FTA method and fuzzy set theory" showed that the implementation of dynamic risk analysis can effectively increase the accuracy of the final ranking of basic events and determine with more precision the likelihood of the top event [39]. utilized fuzzy theory in TFN to analyze oil and gas transmission pipelines to overcome static and uncertain data to estimate the probability of primary events [30]. used fuzzy numbers based on experts' knowledge for risk assessment due to a lack of access to the failure of the parts in the risk assessment. Additionally [19], obtained the reliability of oil and gas transfer pipes by integrating fuzzy and FTA.

However, the fuzzy theory was unable to accurately determine the number of basic events due to not considering the uncertainty of the functions distribution of the linguistic variables. Therefore, it is recommended to utilize the Intuitionistic Fuzzy Approach, which considers the probabilities of events in the membership and non-membership functions. This approach can analyze and measure the system's condition with higher accuracy and be effective in making decisions related to risk management [22,39]. Furthermore, it presents the possibility of an error in the form of an interval and separates membership and non-membership functions to determine the results [40]. The study by [20] estimated the failure probability range using the Intuitionistic Fuzzy implication based on the experts' experiences, leading to more accurate results. In addition [20], used Intuitionistic Fuzzy number aggregation operators through t-norms on fault tree logic gates to investigate the safety of automatic firearms and showed the estimation of the probability of a top event under an uncertain situation [41]. calculated AND & OR gates based on the IFS approach and TIFN to assess the printed circuit board assembly machine. They finally concluded that the adopted approach could determine errors for the safety of complex systems with more flexibility.

Despite this, it is important to acknowledge the limitations researchers encounter when examining issues related to risk assessment, reliability assessment, ranking, and decision-making in different domains. These limitations include a lack of reliable information, incomplete data relating to the system under investigation, and variations in decision-making and judgment among experts and assessors. As a result, various approaches have been employed in recent times to cope with conditions of uncertainty. For instance [42], employed the T-Spherical Fuzzy Maximizing Deviation method to increase the flexibility of expert opinions in risk assessment, taking into account the unique background of each expert, personalizing their opinions, and utilizing the FMEA technique. This study demonstrated that overcoming existing limitations in risk assessment methods led to more precise and stable rankings of failure modes and risk. Similarly [43], developed a q-rung orthopair fuzzy decision-making model to tackle uncertainty and ambiguity in the selection of custom product manufacturers. This method accounted for inherent limitations in the decision-making process, uncertain and inaccurate real-world information, and ambiguous information from decision-makers, with the aim of improving the final ranking process of manufacturers [44]. then utilized the Z-cloud rough number-based BWM-MABAC model to manage uncertainty in evaluating alternative designs in product development. This model accounted for decision-makers personal preferences and characteristics, their judgment and preference inconsistencies, and their perception of ambiguous thinking. The methodology adopted in the study provided more accurate results while managing individual uncertainty, judgmental reliability, and probabilistic uncertainty.

In the present study, the lack of documented records of maintenance and repairs, as well as the low experience of operators led to the use of a fuzzy approach. Therefore, experts' knowledge defined membership fuzzy functions to determine the failure rate of parts and the probabilities of basic events [31]. analyzed the reliability of an ESD system by defining IFSs in the logic gates of the FTA method and determined the most critical minimum cuts with significant effects on the occurrence of the top event. Another study by [22] compensated for incomplete data and experts' qualitative opinions about equipment failures by defining logical gate values using intuitionistic fuzzy operators, which facilitated the possibility of base events.

Identifying key factors influencing the reliability of the oxygen supply system provides valuable insights for healthcare policy-makers to efficiently allocate resources and adopt practical practices. It can also determine areas that require more attention, particularly in terms of the reliability and safety of oxygen supply systems in healthcare settings. Furthermore, the findings can be helpful in developing guidelines and regulations to improve the reliability of oxygen supply systems and preventive maintenance in healthcare facilities.

The findings of this study provide valuable insights for healthcare facilities looking to enhance the reliability and safety of their oxygen supply systems. By identifying critical failure points, such as malfunctioning pressure switches and inadequate sealing, hospitals can prioritize preventive maintenance efforts on these vulnerable components. Taking proactive measures in these areas can reduce the risk of system failures, ensuring a continuous oxygen supply for patients. Additionally, the results of the FTA can assist in developing comprehensive staff training programs. Equipping healthcare personnel with the necessary knowledge and skills to recognize early warning signs follow proper maintenance procedures, and respond effectively to emergencies can significantly enhance patient safety. However, implementing these findings in a hospital setting may present challenges. Establishing robust data management systems for comprehensive data collection, monitoring system malfunctions, maintenance records, and incident reports is crucial to continuously refine the FTA model. Additionally, securing administrative support and allocating resources for the recommended preventive maintenance strategies, staff training initiatives, and system redundancy measures may pose logistical and financial challenges.

Nevertheless, the practical applications of this FTA study have the potential for significant improvements in the safety and reliability of oxygen supply systems within healthcare facilities. Proactive maintenance of critical components can decrease the likelihood of system failures and oxygen-related incidents, such as fires and disruptions in oxygen delivery. Furthermore, enhanced staff training and emergency response protocols can better prepare healthcare personnel to identify and address potential issues, ultimately safeguarding patient well-being and promoting a culture of safety ([45]; Feiz Arefi et al., 2020 [7]).

5. Conclusion

This study highlights the critical importance of ensuring the reliability of oxygen supply systems in healthcare centers for the safety of patients. The research addressed data limitations and demonstrated the effectiveness of the Intuitionistic Fuzzy Approach in estimating events, demonstrating flexibility, and providing realistic estimates. The study also recognized limitations in expert-derived probabilities. Thus, it is recommended to utilize models such as Machine Learning Algorithms, evidence theory, and Bayesian networks to validate the reliability model through real-world testing. These approaches can be useful to improve understanding of oxygen supply system reliability and healthcare critical infrastructure.

CRediT authorship contribution statement

Yeganeh Yousofnejad: Writing – original draft, Methodology, Investigation, Formal analysis. **Mahboubeh Es'haghi:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

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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