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Design for Safety: Safety Consideration in Planning and Design of Airport Airsides

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***Abstract*—During airport planning and design stages, the major issues of capacity and safety in construction and operation of an airport need to be taken into consideration. The airside of an airport is a major and critical infrastructure that usually consists of runway(s), taxiway system, and apron(s) etc., which have to be designed according to the international standards and recommendations, and local limitations to accommodate the forecasted demands. However, in many cases, airport airsides are suffering from unexpected risks that occurred during airport operations. Therefore, safety risk assessment should be applied in the planning and design of airsides to cope with the probability of risks and their consequences, and to make decisions to reduce the risks to as low as reasonably practicable (ALARP) based on safety risk assessment. This paper presents a combination approach of Failure Modes, Effect, and Criticality Analysis (FMECA), Fuzzy Reasoning Approach (FRA), and Fuzzy Analytic Hierarchy Process (FAHP) to develop a risk analysis model for safety risk assessment. An illustrated example is used to the demonstrate risk assessment process on how the design of an airside in an airport can be analysed by using the proposed safety design risk assessment model.

***Keywords*—**Airport airside planning and design, design for safety, fuzzy reasoning approach, fuzzy AHP, risk assessment.

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I. INTRODUCTION

ARESIDE safety is important, particularly for airport operators, which has been affected by aircraft maneuverings from runway(s) to apron(s) through the taxiway system and vice versa. Accidents and incidents are clearly observed in this area, which is more susceptible in airports [1]. Airside operations are dealt with by several service providers and operators such as air traffic controllers, airways, airfield operations, safety auditors, and civil aviation authority [2]. The safety of airside operations is managed by the Safety Management System (SMS), which is organized and published by the International Civil Aviation Organization (ICAO) as regulative procedure to support airport operators in regard to risk management and mitigation. This is required by International Civil Aviation Organization (ICAO) to certify the airports by the national civil aviation authority and to maintain the minimum safety requirements [3]. Risk management is a core of safety management system in the process, which requires identifying the possible hazards and assess the risks during airside operations in order to mitigate the risk opportunities and prevent incidents and accidents [2], [16]. Additionally, the design and operation standards should be regularly reviewed by several kinds of inspections to ensure that all operation requirements comply with international regulations [4]. Airport planning and design should accommodate the required capacity, efficiency and design standards, and maintain the safety requirements that are linked with this process [5]. Reference [1] investigates the effect of airport factors on the operational safety, and develops a model to assess the risks that are related to these factors, which are classified into five main items, i.e., aircraft operations, air traffic control, airport operations, environment, and regulations. However, airport design is ordered as part of airport operations within the third level in the hierarchal framework of factors [1]. Furthermore, most aircraft accidents and incidents are likely to happen in the aerodromes, and the risk of aircraft accidents and incidents are normally mitigated by traditional safety management procedure that consists of two risk parameters, i.e., severity and likelihood. The occurrence of aircraft accidents seems to be limited and numerically complicated. In addition, the shortage of data availability and uncertainty tend to be the other challenges for dealing with risk numerically, and airport facilities are operationally connected with each other as complicated network. Therefore, the whole of airport system could be affected by the fault of any individual facility [10]. This paper presents safety design assessment process model that consists of a combination approach FMECA, FRA, and FAHP, to assess the risks at the planning and design stages. The FMECA is used to investigate all the possible failure modes and their consequences of airsides, particularly at the planning and design stages of the ground maneuvering areas, which could be contributed to airside risks. Three main parameters including probability Occurrence (O), Detection factor (D), and Multiple Criteria Severity (MCS) will be taken into account in safety risk assessment. The MCS is evaluated by four factors, i.e., effects on Aircraft Operations (AO), People (P), Airport Reputation (AR), and Financial Loss (FL). By introducing these four factors, the MCS can be estimated more reliable for all possible failure consequences, and to obtain the creditable risk level. Also in the proposed risk analysis model the FRA is employed to deal with uncertainties and unavailability of data, and cope with failure mode and effect analysis shortages to quantify the expert's knowledge and engineering judgments in order to obtain Risk Priority Number (RPN). The FAHP is then utilized to deal with hierarchical structure of planning and design system and assign weight for each component and make a decision for design for safety system.

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II. DESIGN FOR SAFETY

The term of "design for safety" is a systematic process that deals with risk management. It is a process to identify and assess all distinguishable hazards that are conducted in the design phase. It analyses, the effect and the likelihood of each identified hazard that could occur. Risks should be reduced into the tolerable level before the operation phase. The aim of safety design is to investigate the risks, which are produced by design errors and mistakes, from preliminary to detailed design stages. Risk investigation and analysis of every design stage should be reported for the purpose of building a design database backup during the design improvements phase to enhance the functional and standard process of the design [6]. Design improvement is the way of assessing the concepts and design options to produce the required design alternative based on risk analysis [7].

III. FAILURE MODE, EFFECT, AND CRITICALITY ANALYSIS

The FMECA is one of the methodologies that is critically utilized to identify the hazards and manage the risks for design of a system. This approach can be applied either from the upper to lower levels or the lower to upper levels for safety risk management of design for a system. The upper to lower procedure are employed to assign the main risks. The continuous analysis of risks can be then investigated with regard to causes and consequences of these risks to obtain the final results that are necessary for design improvement. As a system can be decomposed into detailed units, the lower to upper level procedure can be applied to investigate the hazards more precisely from the lower unit level to the upper unit level, and finally to a system. The main difference between the two procedures refers that upper to lower deals with certain risks or problems, and lower to upper level investigates a whole system [7]. The airport infrastructure is similar to a system, which can be safely operated by dealing with initial targets of airport functionality operations and improvements that are manipulated in the planning and design process [8]. The process consists of several steps that start from decomposing the system components and assigning all the possible risks within a system. The risks should be investigated by three parameters that are Occurrence (O), Severity (S), and Detection (D), which can be analysed by (1) to calculate Risk Priority Number (RPN) [11].

$$RPN = O \times S \times D \tag{1}$$

Then, the risks can be criticality investigated qualitatively or quantitatively by using FMECA that is suitable for design enhancement [9]. However, the RPN has been affected by some limitations [8]. The RPN is not represented the actual situation of underlying estimated risks, because sometimes it may be calculated as a same result for different values of the three parameters of O, S, and D. Also, it may have the same degree of risk impact, but the actual situation might be different. Furthermore, these parameters cannot be quantified accurately in some cases. In order to cope with challenges of these limitations of unavailability of data and uncertainty involved, the FRA may be suitable to combine with FMECA for safety risk assessment [12].

IV. FUZZY REASONING APPROACH (FRA)

The FRA has the ability to simulate the human experiences, and deals with reasoning as approximately and accurately. The FRA is represented by fuzzy set [14].

$$A = \{(x, u_A(x))x \in U\} \tag{2}$$

where u_A (x) represents the membership function in a range of [0, 1], x is derived from linguistic terms, and *U* is universe of discourse. Membership function can be graphically represented by several types of triangular, trapezoidal, bell shape, and Gaussian functions. Trapezoidal and triangular functions are the most common utilized for risk management. The triangular function can be determined as follows [14].

$$f(x;a,b,c) = \begin{cases} 0 & x \le a \\ \dfrac{x-a}{b-a} & a \le x \le b \\ 1-\dfrac{x-b}{c-b} & b \le x \le c \\ 0 & x \ge c \end{cases} \tag{3}$$

where *a, b,* and *c* represent the range values of triangular function that determine *x* relationship. The most important fuzzy operations, which are utilized for risk management, are intersection and union. They can be represented by minimum and maximum functions. Approximate reasoning is also depended on if – then rules that are derived from human experiences, which consist of more than one input and one output [14], [15].

$$R_i : IFx_1\, isA_1\, ANDx_2\, isA_2 THENyisB \tag{4}$$

where x_1 , x_2 , A_1 ,and A_2 are linguistic input terms, and *y*, and *B* are linguistic output terms.

The fuzzy inference system can be divided into four items that are started from rule base establishment towards fuzzification, fuzzy inference engine, and lastly defuzzification. Fuzzification is the process of the transfer of expert knowledge as a linguistic term, number, or range of numbers into corresponding member functions that have intervals of [0, 1]. The fuzzy rules are then assessed by fuzzified numbers to recognize which rules can be fired. The fired rules have values in the first part that is denoted IF statement. The firing strength (α_i) should be calculated by applying minimum operation for the fired rules to obtain truncated fuzzy sets, and can be represented by (5) [14], [15].

$$\alpha_i = \min\{u_{A1}(x_1), u_{A2}(x_2)\} \tag{5}$$

where $u_{A1}\left(x_1\right)$ and $u_{A2}\left(x_2\right)$ are membership functions of fuzzy sets A_1 ,and A_2 .

The implication process is implemented by using (6) that is represented by minimum operation for membership functions of firing strength, and the rules consequences that are represented by linguistic terms such as low risk, medium risk, or high risk [14], [15].

$$u_{imp} = \min\{\alpha_i , u_{\beta}(y)\} \tag{6}$$

Maximum operation should be then utilized to aggregate firing strength results into one fuzzy set by using (7).

$$u_{agg}(y) = \max\{u_{imp\,1}(y), u_{imp\,2}(y), u_{impi}(y)\} \tag{7}$$

where $u_{agg}(y)$ is membership function of fuzzy set after aggregation and $u_{impi}(y)$ is membership function of the truncated fuzzy set (i) after implication.

The last step of the process is to defuzzify the output of aggregation into crisp number by using centre of area method that can be determined as:

$$Y_{def} = \frac{\sum_{i=1}^{n} y_i u_{agg}(y_i)}{\sum_{i=1}^{n} u_{agg}(y_i)} \tag{8}$$

where Y_{def} is the weighted mean value of maximum conclusion. y_i represents the support value at which *i-th* membership function reach its mean value, and n is the number of aggregated risk level conclusions [14], [15].

V. Fuzzy Analytic Hierarchy Process (FAHP)

The FAHP methodology is a useful approach to maintain the relative weights and data of partial sub-components to component, and then to a system. It is also a flexible approach that can be simply combined with other theories. This methodology compares criteria and sub-criteria levels by fuzzy numbers that are determined from nine fuzzy scales as shown in Fig. 1 [13].

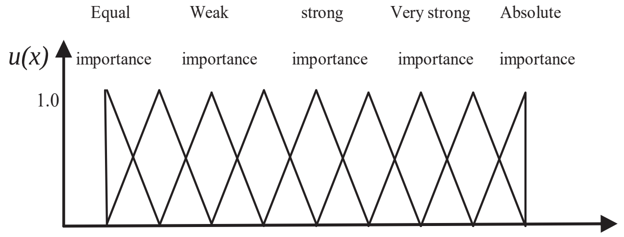

Fig. 1 MFs of qualitative descriptors

The geometric mean method is suitable to cope with the shortcomings of traditional AHP. The weights are calculated by geometric mean method according to (9)-(11) [18].

$$\begin{pmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \tilde{a}_{13} \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \tilde{a}_{23} \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots \; \tilde{a}_{ij} & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \tilde{a}_{n3} \cdots & \tilde{a}_{nn} \end{pmatrix} \begin{matrix} (i = 1,2,3,\ldots\ldots,\ n) \\ (j = 1,2,3,\ldots\ldots,\ n) \end{matrix} \tag{9}$$

$$\tilde{r}_i = \left(\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \tilde{a}_{i3} \otimes \tilde{a}_{i4} \otimes \cdots \otimes \tilde{a}_{in}\right)^{\frac{1}{n}} \tag{10}$$

$$\tilde{w}_i = \tilde{r}_i \otimes \left(\tilde{r}_1 \oplus \tilde{r}_2 \oplus \tilde{r}_3 \oplus \tilde{r}_4 \oplus \cdots \oplus \tilde{r}_n\right)^{-1} \tag{11}$$

where $\tilde{a}_{ij}$ is fuzzy triangular number, n is matrix dimension, $\tilde{r}_i$ is the geometric mean of the *i-th* row, and $\tilde{w}_i$ is the weight of the *i-th* factor in the system.

The weight factors can be determined by the defuzzification of the weights according to (12) [18].

$$NFW = \frac{[(U_w - L_w) + (M_w - L_w)]}{3} + L_w \tag{12}$$

where *NFW* is the non-fuzzy weight value, Uw, Mw, and Lw are upper, medium and lower weights, respectively.

Finally, the normalized weights can be obtained by (13) [13].

$$w_i = \frac{NFW_i}{\sum_{i=1}^{n} NFW_i} \tag{13}$$

where w_i is normalized weight of *i-th* factor, NFW_i is crisp weight of *i-th* factor, and n is number of weight factors.

The weighted risk level for components, sub-components, and a system can be calculated by (14) [13].

$$RL_{system} = \sum_{i=1}^{n} RL_{component\ i}\, w_{component\ i} \tag{14}$$

where $RL_{component\ i}$ is risk level for factor of *i-th* component.

VI. Safety Design Assessment Process Model

In this paper, a combination approach has been employed for the safety risk assessment in the planning development and design stages for the ground maneuvering areas in airport airsides. The stages consist of site selection, master plan, conceptual design, and detailed design. A combination methodology includes FMECA, FRA, and FAHP. The FMECA has been employed to investigate and assess the risks for design of the ground maneuvering area within airport airsides, and prioritize the risks according to three main parameters, which are probability occurrence, multiple criteria severity, and detection, to obtain the required actions for risk mitigation. FRA has been combined with FMECA to cope with the uncertainties and the lack of data by dealing with human experiences. The FAHP approach has been also combined to obtain the relative preference for risk factors and avoid the missing data in hierarchical levels that are started from sub-components to components and to a system.

Most researches of safety risk assessment for the airport's industry have considered operational causes and effects of risks, and shortcomings seem to be clear in the modeling development of safety considerations in the planning and design of airport airsides.

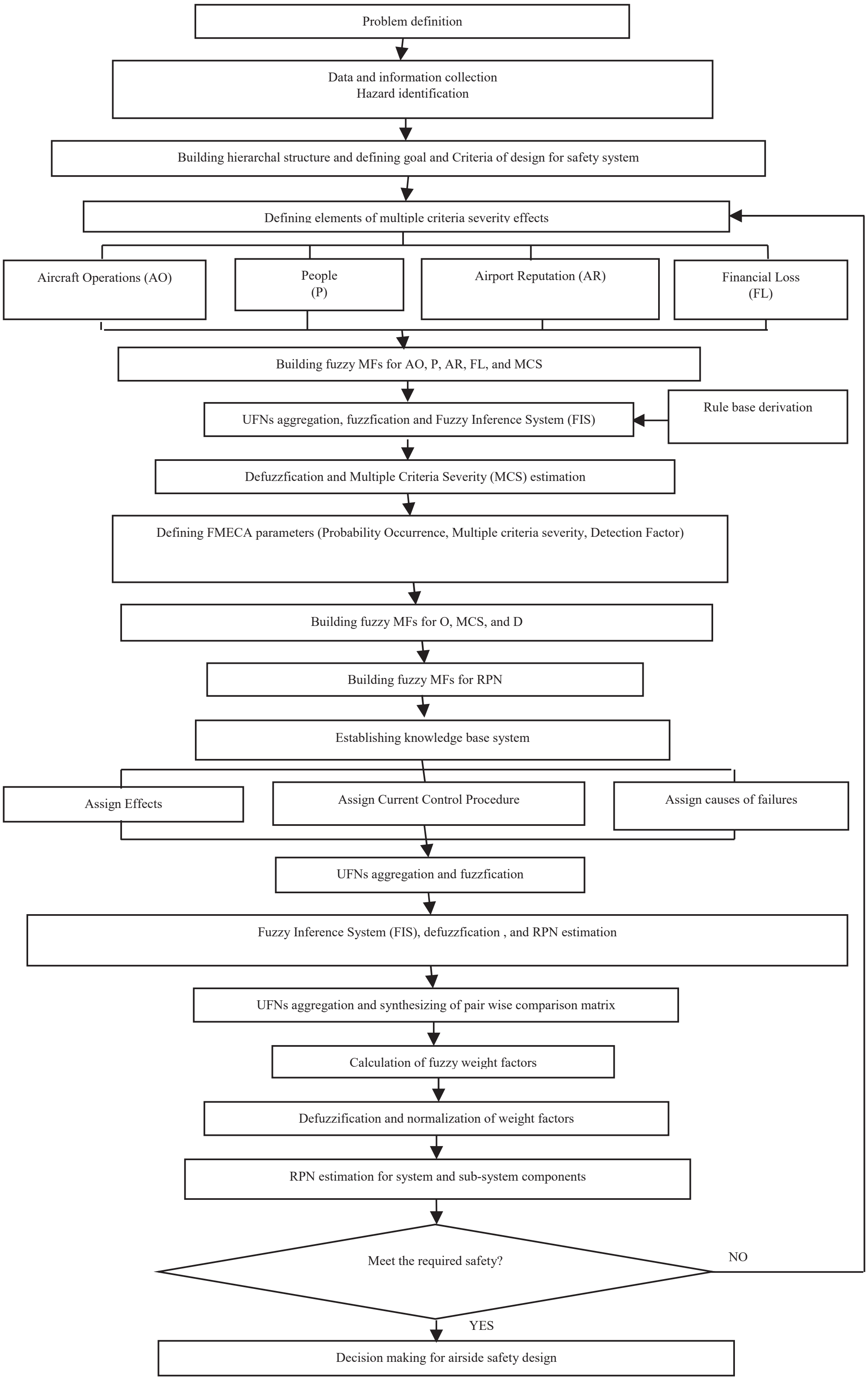

Fig. 2 Safety design assessment process model

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The safety design assessment process model has been proposed to incorporate risk assessment with the planning development and design stages, as shown in Fig. 2. Because airport planning and design is strategic process, the model developing includes investigation of risk effects in details that could affect risk priority and decision making for design reviewing. The proposed model is explained in more details by the following steps.

A. A Hierarchal Framework of Planning and Design System

The hazard identification is to consider any possible fault within components of a system. The hazard could not produce dangerous events without appearing certain condition that affect the airport environment. Hazards could be directly or indirectly appeared in airport environment [17]. Based on the procedure of bottom up risk assessment, planning development and design system of airport airsides in particular areas of ground maneuverings is decomposed into three main levels. The design for safety represents the first level of a system, which is followed by airport planning and design stages that consist of site selection, master plan, conceptual design, and detailed design. The all possible failure modes for each stage are identified from literatures in the third level, and they can be demonstrated in Table I.

TABLE I
POTENTIAL FAILURE MODES

Stage	FM	Potential failure modes
Site Selection	FM11	Shortage of site expandability.
	FM12	Shortage of feasibility.
	FM13	Difficult site topography.
	FM14	Adverse weather conditions.
	FM15	Unsuitable geotechnical effects
	FM16	Shortage of runway configuration.
Master Plan	FM21	Shortage of expected demand.
	FM22	Shortage of airside capacity.
	FM23	Shortage of efficiency of taxiway layout.
	FM24	Shortage of finance.
	FM25	Shortage of flexibility of taxiway system.
Conceptual Design	FM31	Shortage of criteria of taxiway physical characteristics.
	FM32	Shortage of types of taxiways and geometry.
	FM33	Shortage of segregation concept for vehicle's traffic in airside.
	FM34	Shortage of pavement characteristics.
	FM35	Shortage of characteristics of new large aircraft.
Detailed Design	FM41	Shortage of geometric design of taxiway elements.
	FM42	Shortage of visual aids.
	FM43	Shortage of design of paved and unpaved areas.
	FM44	Shortage of drainage system.
	FM45	Unsuitable service road specifications

FM = Failure Mode

B. Estimation of Multiple Criteria Severity

Step 1: Input Parameters

Multiple criteria severity is estimated by introducing the input criteria, which are impacts on aircraft operations (AO), impacts on people (P), impacts on airport reputation (AR), and impact of financial loss (FL). The aircraft operations criterion is used to examine the impact of faults, incidents or accidents severity on safety of aircraft operations and how it may be significantly reduced. People criterion is used to examine the effects of faults, incidents or accidents physical impact on people, which are passengers, aircraft crew, employees, etc. Airport reputation is the third criterion, which is used to assess the effects of faults, incidents or accidents on reputation impact within community, national, or international level. The last criterion deals with financial impact that are related to amount of losing based on consequences of damages [17]. Every failure mode within design system has four severity input parameters, which are (AO), (P), (AR), and (FL). These parameters are based on subjective classification to assess the seriousness of fault, incident or accident consequences. FRA is employed to estimate the multiple criteria severity, and cope with uncertainty and subjectivity of data that are depended on expert knowledge.

Step 2: Expert Weighted Scores

Because of unavailability of data and uncertainty, five experts within the domain of airport safety design and operation are assumed to obtain the required data that are depended on their experiences and skills. Every expert has different backgrounds in terms of experience years, and job title in a particular field. The experts in airports have different specialist backgrounds and experience years, for example there are experts in airfield operations, safety auditing, air traffic control, and maintenance of airfield infrastructures. The experience years vary from less than five years to more than 30 years, and reflect the expert's knowledge and judgments about risk assessment for an airside system. Experts have a variety of opinions and judgments that affect the results of risk assessment. Weight factor, which should be assigned for every expert, depends on experience years that vary for long time among them. In this paper, expert weight factors are determined based on their experience years in airport airsides by using (15), and the sum of factors must be equal to one.

$$EWF_i = \frac{EY_i}{\sum_{i=1}^{n} EY_i} \tag{15}$$

where EWF_i is the weight factor of the *i-th* expert, EY_i is expert's experience years, *n* is number of experts.

The scores for the risk factors, which reflect the expert's ideas and experiences in their jobs, should be assigned. The scores can be assigned in different forms that could be certain number, range of numbers, fuzzy values, which may be trapezoidal or triangular, or linguistic term in order to help the experts to give their scores with less difficulties of judgment. All these types of feedbacks can be transformed into a typical fuzzy triangular number as illustrated in Table II [13].

TABLE II
EXPERT JUDGMENT AND UFNS

Description	Input values	Input types	UFNs
‘‘. . . is a’’	{a}	A numerical value	{a; a; a}
‘‘. . . is between a and b’’	{a; b}	A range of number	{a; (a+b)/2; b}
‘‘. . . is between a and c and most likely to be b’’	{a; b; c}	Triangular fuzzy numbers	{a; b; c}
‘‘. . . is between a and d and most likely between b and c’’	{a; b; c; d}	Trapezoidal fuzzy numbers	{a; (a+d)/2; d}
‘‘. . . is RARE’	RARE	A linguistic term	RARE MF {a; b; c}

UFNs= Uniform Format Number

The assumed weighted scores are calculated for five experts according to their experience in the airport environment using (16):

$$WS_j = \sum_{i=1}^{n} EWF_i s_{ij} \tag{16}$$

where WS_i is weighted score for *j-th* paramter, EWF_i is the weight factor of *i-th* expert, and s_{ij} is score for *j-th* parameter.

Step 3: Fuzzy Rule Establishment

The fuzzy rule base is established based on the investigation and experience of the experts. They are generated according to membership function mapping. The number of rules depends on the number of linguistic descriptors that refer to input terms in rule statement [13], [14].

The severity can be classified into five linguistic terms which are: ’’No safety effect’’, ’’Minor’’, ’’Major’’, ’’Hazardous’’, and ’’Catastrophic’’ [17]. In this case the number of linguistic descriptors is five, and the number of parameters is four. The number of rules can be calculated as (5 × 5 × 5 × 5 = 625) rules. However, they represent a high number of rules, which require more time and efforts to estimate the multiple criteria severity. They are decomposed into two groups to estimate the severity for every two parameters separately. Multiple criteria severity is then estimated by using the results of two groups of parameters in order to significantly decrease the number of rules. The first group consists of effects on aircraft operations (AO) and effects on people (P), and the second group consists of effects on airport reputation (AR) and financial loss (FL). The rules are built for each group as (5 ×5 = 25) rules, and after the estimation of (AO & P) and (AR & FL) severity, the rules are calculated as (5 × 5 = 25) for multiple criteria severity estimation. The total number of rules is 75 instead of 625 rules, which refer to 88 % of rules are decreased. In this case, the input parameters are reduced into two parameters instead of four for each rule base, for example (If effect on AO is minor and effect on P is No safety effects then AO & P is minor), and the other rules are established in a similar method.

Step 4: Fuzzy Inference System

The linguistic terms are represented by proposed numerical range values. Triangular membership functions are drawlingly employed to represent descriptors of severity parameters as illustrated in Fig. 3.

The uniform weighted scores of severity parameters are fuzzified to obtain the corresponding membership function values within range of [0, 1]. The fuzzified values are applied to obtain the fired rules for every group of parameters. The firing strength is determined by using (5). The minimum operation is applied to membership functions of firing strength to obtain the truncated fuzzy set after implication by utilizing (6). The maximum operation is also applied to determine the fuzzy aggregation by using (7).

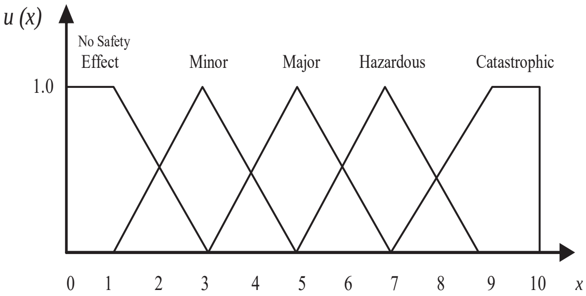

Fig. 3 Triangular MFs of qualitative descriptors

Step 5: Defuzzification

After the fuzzy inference process, the results of (AO&P) and (AR & FL) are defuzzified using (8) in order to obtain the crisp values, which are then used as input parameters in the next step. These parameters are introduced to estimate the multiple criteria severity by a similar process. The final crisp value of the multiple criteria severity is applied in the next step of RPN estimation.

C. *Risk Priority Number Estimation*

Risk parameters are also assigned, which are probability Occurrence (O), Multiple Criteria Severity (MCS), Detection factor (D), and Risk Priority Number (RPN). In this research, multiple criteria severity is considered to develop the reliable seriousness of severity that is contributed in RPN estimation. The risk parameters are graphically represented by fuzzy triangular mapping that includes five linguistic terms for O, MCS, and D. A sample of triangular MFs for risk parameters is shown in Fig. 4. The RPN is represented by the fuzzy triangular mapping of three linguistic terms as shown in Fig. 5.

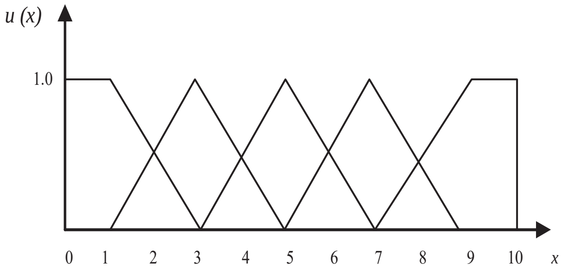

Fig. 4 Triangular MFs of qualitative descriptors of risk parameters

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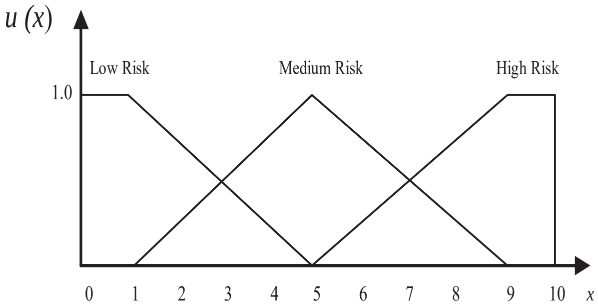

Fig. 5 MFs of qualitative descriptors for RPN

By combining FRA and FMECA, risks can be evaluated through a rule base. The number of fuzzy rules for the three main risk parameters, which are O, MCS, D, is 125 rules. The typical rule for risk estimation in this study is stated as (IF O is Probable and MCS is Minor and D is Very low likelihood THEN RL is Medium Risk). The risks are criticality assessed by evaluation of the fuzzy rule statements.

The uniform format triangular numbers, which are obtained from the knowledge of experts, are fuzzified to obtain their corresponding membership function numbers within the range of [0, 1]. The values of membership functions are applied into the rule base to verify rule statements, which have real values and can be fired. Firing strength is calculated by utilizing (5). The implication process is implemented by minimum operation for membership functions of firing strength, and the rule outputs, which are represented by linguistic terms such as low risk, medium risk, and high risk, by using (6). The aggregation of minimum operation implications, which are contributed for all fired rules, is determined by maximum operation for every failure mode consequence at planning and design system. This aggregation is calculated using (7).

The aggregation results are transformed into crisp numbers to obtain priorities of risks and ranking them. The centre of area method is used for defuzzification fuzzy numbers and determination crisp values of RPN by using (8).

D. Risk Weight Estimation

Every failure mode contributes in risk assessment for the safety design system of airport airsides. It is compared with other failure modes within the same stage. FAHP is employed to assign relative preference among the failure modes in a system. The planning development and design system is decomposed into multiple levels by the concept of component and sub-component levels that could affect the safety requirements for the design developments and operations of ground maneuvering areas in airport airsides. The hieratical framework of the system components is shown in Fig. 6.

FAHP methodology compares components and sub-components by fuzzy numbers that are determined from a nine-point fuzzy scale, which have qualitative descriptors, for instance fuzzy number (four, five, six) is described by ‘’strong importance’’. The fuzzy scale is graphically represented by triangular MFs [13]. Pairwise comparison matrices are formed to estimate the degree of importance among failure modes, for example to compare FM11with FM12, FM13, FM14, FM15, and FM16.The pairwise comparison matrix for the stages is also formed to determine the degree of importance for every stage with respect to others, for example compare the master plan stage with the site selection, conceptual design, and detailed design stages. The pairwise comparison matrices are formed by assumed scores, which are based on the knowledge and opinions of experts. The scores can be assigned by linguistic terms, or values that are transformed into fuzzy triangular numbers. The weights of stages and failure modes are computed by geometric mean method. The several pairwise comparison matrices can be formed and synthesized based on the opinions of experts who are interviewed to give their judgment scores for comparisons. The geometric mean method is employed to compute the weights for stages and failure modes as locally and overall weights by using (10)-(12). The crisp weight numbers are normalized utilizing (13) in order to accurately assess the risks at design for the safety system. The weight factors for failure modes and stages, which are part of a system risk, are used to calculate the more creditable RPN for the failure modes, stages, and design for safety system by utilizing (14).

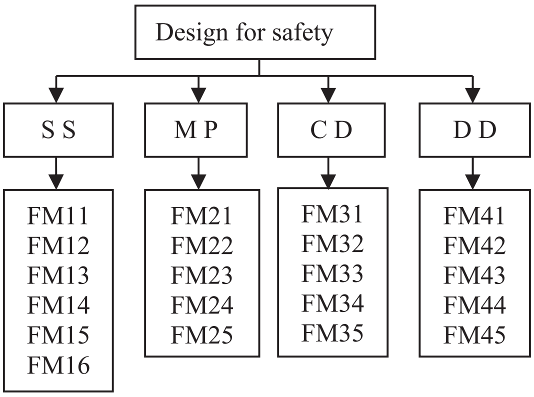

Fig. 6 Hierarchal structure of design for safety system

VII. NUMERICAL ANALYSIS

Failure Mode (FM23), which is shortage of efficiency of the taxiway layout in master plan stage, is utilized as an illustrative example to demonstrate the proposed safety design assessment process model to assess the risks for the ground maneuvering area in the airport airsides.

A. Expert Weight Factors

The expert’s team is established by assumed example. Five experts are assumed with 15, 35, 35, 40, and 25 experience years respectively. The expert’s experience factors are calculated by applying (15) and the *EWFs* for five experts are 0.10, 0.23, 0.23, 0.27, and 0.17, respectively.

B. Multiple Criteria Severity Estimation

Five experts have given their scores of severity parameters for the consequence of FM23, and are transformed into UFNs. Weighted scores are calculated according to (16) as:

$$AO = (8, 8, 8) \times 0.1 + (5, 6, 7) \times 0.23 + (6, 7, 8) \times 0.23 + (5, 7, 9) \times 0.27 + (5, 7, 9) \times 0.17 = (5.53, 6.87, 8.21)$$

TABLE III
EVALUATION AND UFN OF AO AND P

Expert	AO		P	
	Score	UFN	Score	UFN
E1	8	(8,8,8)	4	(4,4,4)
E2	(5,7)	(5,6,7)	(2,4)	(2,3,4)
E3	About 7	(6,7,8)	About 5	(4, 5, 6)
E4	(5, 6, 8, 9)	(5,7,9)	(0, 1, 3, 4)	(0,2,4)
E5	Hazardous	(5, 7, 9)	Minor	(1, 3, 5)
Aggregated UFNs	(5.53, 6.87, 8.21)		(1.95, 3.29, 4.63)	

These scores are used as input numbers in membership functions of AO, P, AL, and FL to obtain the corresponding membership function values within range [0, 1], as shown in Figs. 7-10. The MF values are determined for every severity criterion as illustrated in Table V.

TABLE IV
EVALUATION AND UFN OF AR AND FL

Expert	AR		FL	
	Score	UFN	Score	UFN
E1	2	(2,2,2)	4	(4,4,4)
E2	(3,5)	(3,4,5)	(1,3)	(1,2,3)
E3	About3	(2,3,4)	About 3	(2,3,4)
E4	(0, 1, 3, 4)	(0,2,4)	(3. 4, 6, 7)	(3,5,7)
E5	No effect	(0, 1, 3)	Minor	(1, 3, 5)
Aggregated UFNs	(1.35 ,2.52, 3.86)		(2.07, 3.41, 4.75)	

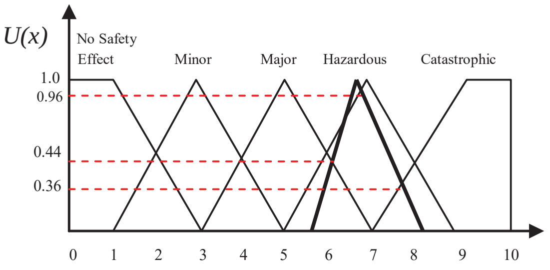

Fig. 7 MFs of AO parameter

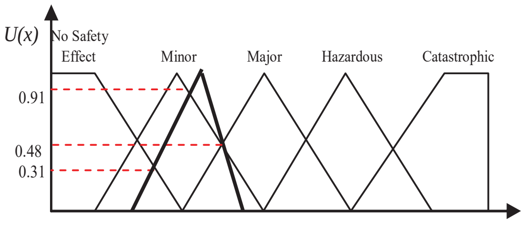

Fig. 8 MFs of P parameter

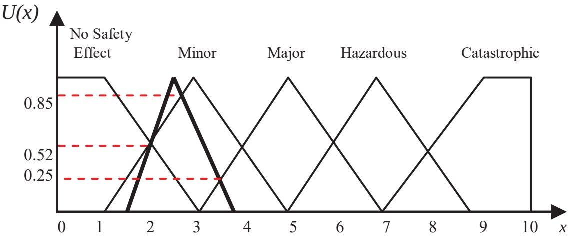

Fig. 9 MFs of AR parameter

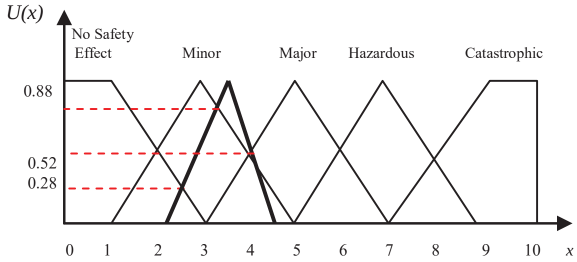

Fig. 10 MFs of FL parameter

TABLE V
FUZZIFICATION RESULTS

FM	Input parameter	Linguistic term	Membership function
FM 23	AO	Major	0.44
		Hazardous	0.96
		Catastrophic	0.36
	P	No effect	0.31
		Minor	0.91
		Major	0.48
	AR	No effect	0.52
		Minor	0.85
		Major	0.25
	FL	No effect	0.28
		Minor	0.88
		Major	0.52

The next step, which is the fuzzy inference system, consists of the evaluation of fuzzy rules, implications, and aggregation. The rules are evaluated by using values of MFs as input values for the rule statement to verify which rules are fired. The fired rules include the real values for all parts of the rule statement as given and result parts.

The fired rules for the FM23 consequence of the first group, which consists of AO & P, include:

- R11 IF Effect on AO is Major and Effect on P is No Effects THEN AO & P is Minor
- R12 IF Effect on AO is Major and Effect on P is Minor THEN AO & P is Major
- R13 IF Effect on AO is Major and Effect on P is Major THEN AO & P is Major
- R16 IF Effect on AO is Hazardous and Effect on P is No Effects THEN AO & P is Major
- R17 IF Effect on AO is Hazardous and Effect on P is Minor THEN AO & P is Major
- R18 IF Effect on AO is Hazardous and Effect on P is Major THEN AO & P is Hazardous
- R21 IF Effect on AO is Catastrophic and Effect on P is No Effects THEN AO & P is Major
- R22 IF Effect on AO is Catastrophic and Effect on P is Minor THEN AO & P is Major
- R23 IF Effect on AO is Catastrophic and Effect on P is Major THEN AO & P is Hazardous

The fired rules for FM 23 consequence of the second group, which consists of AR & FL, are:

- R1 IF Effect on AR is No Effects and FL is No Effects THEN AR & FL is No Effects

- R2 IF Effect on AR is No Effects and FL is Minor THEN AR & FL is No Effects
- R3 IF Effect on AR is No Effects and FL is Major THEN AR & FL is Minor
- R6 IF Effect on AR is Minor and FL is No Effects THEN AR & FL is No Effects
- R7 IF Effect on AR is Minor and FL is Minor THEN AR & FL is Minor
- R8 IF Effect on AR is Minor and FL is Major THEN AR & FL is Major
- R11 IF Effect on AR is Major and FL is No Effects THEN AR & FL is Minor
- R12 IF Effect on AR is Major and FL is Minor THEN AR & FL is Major
- R13 IF Effect on AR is Major and FL is Major THEN AR & FL is Major

The firing strengths are determined using minimum operations for AO & P and AR & FL as:

- α11 = min {Major, No effect} = min {0.44, 0.31} = 0.31
- α12 = min {Major, Minor} = min {0.44, 0.91} = 0.44
- α13 = min {Major, Major} = min {0.44, 0.48} = 0.44
- α16 = min {Hazardous, No effect} = min {0.96, 0.31} = 0.31
- α17 = min {Hazardous, Minor} = min {0.96, 0.91} = 0.91
- α18 = min {Hazardous, Major} = min {0.96, 0.48} = 0.48
- α21= min {Catastrophic, No effect} = min {0.36, 0.31} = 0.31
- α22 = min {Catastrophic, Minor} = min {0.36, 0.91} = 0.36
- α23 = min {Catastrophic, Major} = min {0.36, 0.48} = 0.36
- α1 = min {No effect, No effect} = min {0.52, 0.28} = 0.28
- α2 = min {No effect, Minor} = min {0.52, 0.88} = 0.52
- α3 = min {No effect, Major} = min {0.52, 0.52} = 0.52
- α6 = min {Minor, No effect} = min {0.85, 0.28} = 0.28
- α7 = min {Minor, Minor} = min {0.85, 0.88} = 0.85
- α8 = min {Minor, Major} = min {0.85, 0.52} = 0.52
- α11= min {Major, No effect} = min {0.25, 0.28} = 0.25
- α12 = min {Major, Minor} = min {0.25, 0.88} = 0.25
- α13 = min {Major, Major} = min {0.25, 0.52} = 0.25

The implications are determined by minimum operation for the firing strength. The results consist of firing strength, which graphically represents the turn cut for fuzzy set at the amount of MF, and rule output descriptor as:

- $R11: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.31, \mathit{Minor}$
- $R12: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.44, \mathit{Major}$
- $R13: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.44, \mathit{Major}$
- $R16: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.31, \mathit{Major}$
- $R17: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.91, \mathit{Major}$
- $R18: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.48, \mathit{Hazardous}$
- $R21: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.31, \mathit{Major}$
- $R22: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.36, \mathit{Major}$
- $R23: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.36, \mathit{Hazardous}$
- $R1: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.28, \mathit{No\ safety\ effects}$
- $R2: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.52, \mathit{No\ safety\ effects}$
- $R3: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.52, \mathit{Minor}$
- $R6: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.28, \mathit{No\ safety\ effects}$
- $R7: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.85, \mathit{Minor}$
- $R8: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.52, \mathit{Major}$
- $R11: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.25, \mathit{Minor}$
- $R12: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.25, \mathit{Major}$
- $R13: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.25, \mathit{Major}$

The aggregation is applied to obtain one value from the control outputs by applying the maximum operation. Defuzzification is applied to determine the crisp number for the estimation of the severity criteria by using (8). The results refer to the AO&P severity equals to 5.20 and AR&FL severity equals to 3.00. The severity of effect on aircraft operations and people is higher than the severity of effect on airport reputation and financial loss. This computation results interpret four parameters into two based on a more reliable estimation.

Crisp Number of (AO & P) Severity for (FM 23) = (3×0.31) + (5×0.91) + (7 × 0.48) /0.31 + 0.91 + 0.48= 5.20
Crisp Number of (AR & FL) Severity for (FM 23) = (1×0.52) + (3×0.85) + (5×0.52)/0.52+ 0.85+ 0.52 = 3.00

All steps, which are mentioned above, are repeated to estimate the multiple criteria severity from severity of (AO&P) and (AR&FL) in order to obtain single severity value. MCS represents the actual situation of severity for failure modes. The final result, which is calculated for multiple criteria severity of FM23 in the master plan stage, is 5.00 that belongs to Major descriptor in fuzzy MF. This result is used in the next step to calculate the RPN for FM23.

C. RPN Estimation

The consequence of FM23, which is shortage of efficiency of taxiway layout within the master plan stage, is continuously utilized as an illustrative example to explain the RPN calculation from the three parameters for risk assessment of the design process for airport airsides.

Fuzzification is the process to obtain the corresponding MF numbers from weighted scores that are used as input values. In the FM 23 five experts have given their scores for O and D, and weighted scores are calculated according to (16). The results are O = (1.06, 2.13, 3.2) and D = (2.06, 3.40, 4.74). The scores of three kinds of parameters are used in membership functions of MCS, O, and D, to obtain the corresponding MF values within range [0, 1] as illustrated in Fig. 11.

The rules are evaluated by using the values of the MFs as input values for the rule statement to verify which rules are fired. The fired rules include the real values for all parts of rule statement as given parts and result part. The fired rules for the three risk parameters of FM23are:

- R3 IF O is Extremely Improbable and MCS is Major and D is Extremely likely THEN RL is Medium Risk
- R8 IF O is Extremely Remote and MCS is Major and D is Extremely likely THEN RL is Medium Risk
- R13 IF O is Remote and MCS is Major and D is Extremely likely THEN RL is Medium Risk
- R28 IF O is Extremely Improbable and MCS is Major and D is high likelihood THEN RL is Medium Risk
- R33 IF O is Extremely Remote and MCS is Major and D is high likelihood THEN RL is Medium Risk
- R38 IF O is Remote and MCS is Major and D is high likelihood THEN RL is Medium Risk
- R53 IF O is Extremely Improbable and MCS is Major and D is Medium likelihood THEN RL is Medium Risk
- R58 IF O is Extremely Remote and MCS is Major and D is Medium likelihood THEN RL is Medium Risk
- R63 IF O is Remote and MCS is Major and D is Medium likelihood THEN RL is Medium Risk

The firing strengths are determined by using minimum operations as follows:

- $\alpha 3 = \min\{0.63, 1.00, 0.28\} = 0.28$
- $\alpha 8 = \min\{0.71, 1.00, 0.28\} = 0.28$
- $\alpha 13 = \min\{0.06, 1.00, 0.28\} = 0.06$
- $\alpha 28 = \min\{0.63, 1.00, 0.88\} = 0.63$

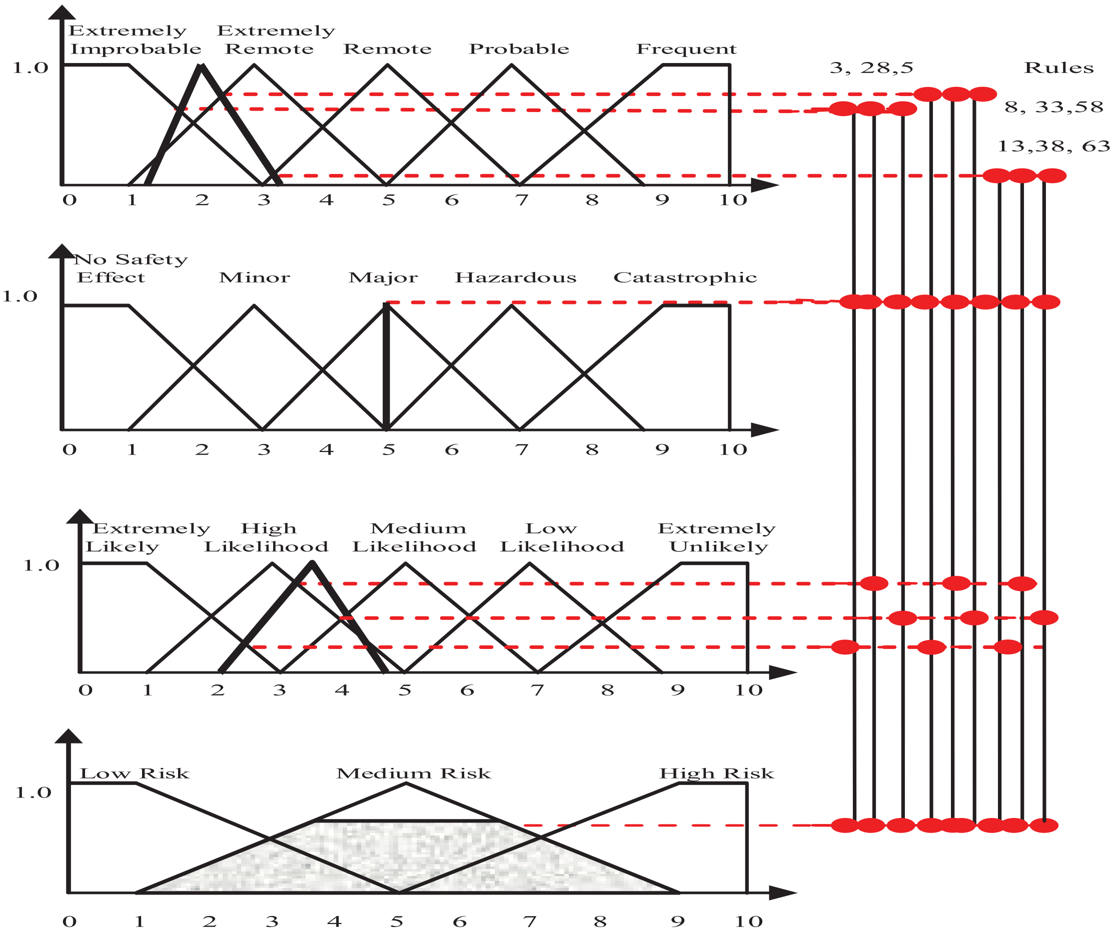

Fig. 11 Rule assessment procedure

- $\alpha 33 = \min\{0.71, 1.00, 0.88\} = 0.71$
- $\alpha 38 = \min\{0.06, 1.00, 0.88\} = 0.06$
- $\alpha 53 = \min\{0.63, 1.00, 0.52\} = 0.52$
- $\alpha 58 = \min\{0.71, 1.00, 0.52\} = 0.52$
- $\alpha 63 = \min\{0.06, 1.00, 0.52\} = 0.06$

The implications are determined by minimum operation for firing strength. The results consist of firing strength, which graphically represents the turn cut for fuzzy sets at the amount of MF value, and descriptors of fuzzy set for risk level, which are low, medium, and high, as:

- $R3: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.28, Medium$
- $R8: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.28, Medium$
- $R13: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.06, Medium$
- $R28: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.63, Medium$
- $R33: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.71, Medium$
- $R38: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.06, Medium$
- $R53: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.52, Medium$
- $R58: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.52, Medium$
- $R63: u_{imp} = \min\{\alpha_i, u_\beta(y)\} = 0.06, Medium$

The aggregation is the process to obtain one value from rule outcomes by applying the maximum operation by using (7). Defuzzification is applied to determine the crisp value for RPN by using (8). The result refers to the RPN equals to 5.00. The risk ranking of the FM23 consequence for shortage of efficiency of taxiway layout is medium.

Crisp Number of RPN for (FM 23) = (5×0.71)/ 0.71 = 5.00

The RPNs are calculated for each FM consequence, which are ordered from FM11 to FM16 in site selection, FM21 to FM25 in master plan, FM31 to FM35 in conceptual design, and FM41 to FM45 in detailed design at the planning development and design system for airport airsides. The results of RPN for all failure modes are shown in Fig. 12.

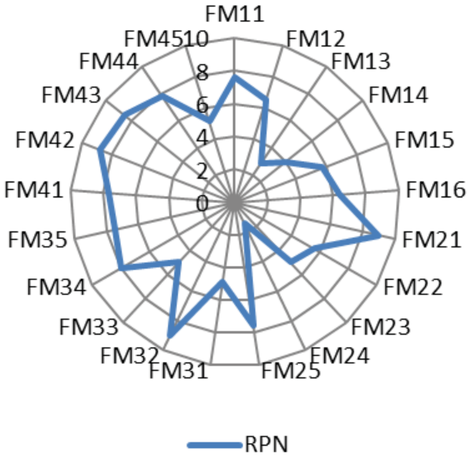

Fig. 12 RPN of failure modes

TABLE VI
PAIR WISE COMPARISON MATRIX

Master plan	FM21	FM22	FM23	FM24	FM25
FM21	(1,1,1)	(0.67, 0.81, 0.99)	(0.58, 0.72, 0.91)	(0.36, 0.50, 0.66)	(0.58, 0.74, 0.93)
FM22	(1.00, 1.23, 1.49)	(1,1,1)	(1.63, 2.63, 3.63)	(2.10, 3.10, 4.10)	(1.53, 2.53, 3.53)
FM23	(1.09, 1.37, 1.72)	(0.27, 0.38, 0.61)	(1,1,1)	(1.36, 2.27, 3.14)	(1.64, 2.50, 3.42)
FM24	(1.50, 1.99, 2.75)	(0.24, 0.32, 0.47)	(0.31, 0.44, 0.73)	(1, 1,1)	(1.45, 2.31, 3.23)
FM25	(1.07, 1.35, 1.70)	(0.28, 0.39, 0.65)	(0.29, 0.39 ,0.60)	(0.30, 0.43, 0.68)	(1,1,1)

FM = Failure Mode

D. Relative Preference Estimation

The pairwise comparison matrix of the master plan stage can be formed and synthesized by experts, and it includes five failure modes, which are expected demand, airside capacity, efficiency of taxiway layout, finance, and flexibility of taxiway system. The scores of importance are obtained by assumed experts' judgments and experience weight factors for matrix of (5 × 5). Every failure mode is compared with others based on degree of importance for example efficiency of taxiway layout has more importance than flexibility of taxiway system, and it has a triangular fuzzy number equal to (1.64, 2.50, 3.42) as demonstrated in Table VI. In this sample calculation, the master plan stage is used as illustrative example in details by using (10)–(11) as:

$$\tilde{r}_1 = \begin{pmatrix} 1\times 0.67\times 0.58\times 0.36\times 0.58, 1\times 0.81\times 0.72\times 0.50\times 0.74, \\ 1\times 0.99\times 0.91\times 0.66\times 0.93 \end{pmatrix}^{\frac{1}{5}}$$

$$\tilde{r}_2 = \begin{pmatrix} 1.00\times 1\times 1.63\times 2.1\times 1.53, 1.22\times 1\times 2.63\times 3.10\times 2.53, \\ 1.48\times 1\times 3.63\times 4.10\times 3.53 \end{pmatrix}^{\frac{1}{5}}$$

$$\tilde{r}_3 = \begin{pmatrix} 1.09\times 0.27\times 1\times 1.36\times 1.64, 1.37\times 0.38\times 1\times 2.27\times 2.50, \\ 1.72\times 0.61\times 1\times 3.14\times 3.42 \end{pmatrix}^{\frac{1}{5}}$$

$$\tilde{r}_4 = \begin{pmatrix} 1.49\times 0.24\times 0.31\times 1\times 1.45, 1.99\times 0.32\times 0.44\times 1\times 2.31, \\ 2.75\times 0.47\times 0.73\times 1\times 3.23 \end{pmatrix}^{\frac{1}{5}}$$

$$\tilde{r}_5 = \begin{pmatrix} 1.07\times 0.28\times 0.29\times 0.30\times 1, 1.35\times 0.39\times 0.39\times 0.43\times 1, \\ 1.70\times 0.65\times 0.60\times 0.68\times 1 \end{pmatrix}^{\frac{1}{5}}$$

$$\tilde{r}_1 = (0.61, 0.74, 0.89), \tilde{r}_2 = (1.39, 1.90, 2.39)$$

$$\tilde{r}_3 = (0.92, 1.24, 1.62), \tilde{r}_4 = (0.70, 0.92, 1.25)$$

$$\tilde{r}_5 = (0.48, 0.62, 0.85)$$

$$\tilde{w}_1 = (0.61, 0.74, 0.89) \otimes (7.02, 5.43, 4.11)^{-1} = (0.09, 0.13, 0.22)$$

$$\tilde{w}_2 = (1.39, 1.90, 2.39) \otimes (7.02, 5.43, 4.11)^{-1} = (0.20, 0.35, 0.58)$$

$$\tilde{w}_3 = (0.92, 1.24, 1.62) \otimes (7.02, 5.43, 4.11)^{-1} = (0.13, 0.23, 0.39)$$

$$\tilde{w}_4 = (0.70, 0.92, 1.25) \otimes (7.02, 5.43, 4.11)^{-1} = (0.10, 0.17, 0.30)$$

$$\tilde{w}_5 = (0.48, 0.62, 0.85) \otimes (7.02, 5.43, 4.11)^{-1} = (0.07, 0.11, 0.21)$$

Non-fuzzy weight factors are calculated by using (12).

$$NFW_1 = \frac{[(0.22 - 0.09) + (0.13 - 0.09)]}{3} + 0.09 = 0.15$$

$$NFW_2 = 0.38, NFW_3 = 0.25, NFW_4 = 0.19, NFW_5 = 0.13$$

The weights are normalized by using (13) in order to obtain the final weights.

$$\sum NFW_i = 0.15 + 0.38 + 0.25 + 0.19 + 0.13 = 1.10$$

$$w_1 = 0.15/1.10 = 0.14, \; w_2 = 0.34, \; w_3 = 0.23, \; w_4 = 0.17, \; w_5 = 0.12$$

The results refer that FM22 has highest importance than the other failure modes, and the FM25 has lowest importance in the master plan stage. The similar calculation procedure is applied for the other stages to compute the weights for all consequences of failure modes. The weights for the stages are also computed in a similar way.

The results of calculations for all design stages are illustrated in the Table VII. They refer to RPN for FM consequences vary from high risk such as (FM21, FM32, etc.), to low risk such as (FM24), these variations are depended on the faults, incidents, or accidents effects, probability, and operational detection.

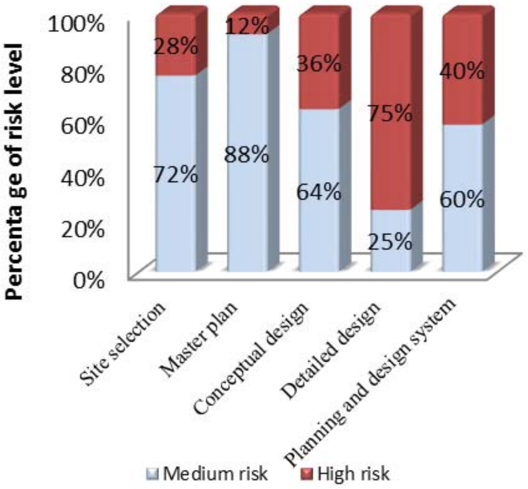

Fig. 13 Percentage of risk level for design system

TABLE VII
RISK PRIORITY NUMBER OF FAILURE MODES AND STAGES

Stage	FM	RPN	Weight factor	Weighted RPN	Stage RPN
Site Selection	FM11	7.58	0.34	2.58	6.11
	FM12	6.54	0.33	2.16	
	FM13	2.86	0.16	0.46	
	FM14	3.98	0.06	0.24	
	FM15	5.76	0.06	0.35	
	FM16	6.40	0.05	0.32	
Master Plan	FM21	9.00	0.14	1.26	5.48
	FM22	5.64	0.34	1.92	
	FM23	5.00	0.23	1.15	
	FM24	1.43	0.17	0.24	
	FM25	7.55	0.12	0.91	
Conceptual Design	FM31	4.90	0.39	1.91	6.45
	FM32	9.00	0.24	2.16	
	FM33	5.00	0.18	0.90	
	FM34	8.00	0.12	0.96	
	FM35	7.48	0.07	0.52	
Detailed Design	FM41	7.71	0.34	2.62	8.02
	FM42	8.83	0.28	2.47	
	FM43	8.57	0.20	1.71	
	FM44	7.82	0.11	0.86	
	FM45	5.20	0.07	0.36	

The RPN for stages are also calculated, and the results vary between medium and high risk levels with variety of percentages, for instance master plan is belonged 88 % medium risk and 12 % high risk. Furthermore, the RPN of planning and design system, which is belonged 40 % high and 60 % medium, is 6.62 as illustrated in Table VIII and Fig. 13

As a result of high risk (RPN = 6.62), which requires for crucial risk mitigation, the planning and design system should be reviewed. The risks of the system components, which vary from medium to high risks with different values of RPN, can be more extensively investigated. The detailed design is the critical stage, and its risks should be mitigated into acceptable level by reducing the risks of FMs, which are included in this stage.

TABLE VIII
RISK PRIORITY NUMBER OF STAGES AND DESIGN PACKAGE

Stage	Stage RPN	Weight factor	System RPN
Site Selection	6.11 72% Medium Risk 28% High Risk	0.16	6.62 60% Medium Risk 40% High Risk
Master Plan	5.48 88% Medium Risk 12% High Risk	0.31	
Conceptual Design	6.45 64% Medium Risk 36% High Risk	0.20	
Detailed Design	8.02 25% Medium Risk 75% High Risk	0.33	

VIII. CONCLUSION

The model is proposed to assess the risks that are related to the planning and design system. It may support airport industries to make decision and priorities for the required mitigations and kinds of action plan. The model can be utilized to assess the unexpected risks, which could occur infrequently in airport airsides. The proposed model will support airport operators and designers to assess the risks periodically and make design reviewing according to more creditable seriousness of risks by introducing the new severity parameters. It is developed to prepare and review the planning and design system for airport airside, in particular those ground the maneuvering areas based on risk assessment. The numerical calculations demonstrate the benefit of risk analysis in details for failure modes, stages and for a whole system. The combination approach of FEMCA, FRA, and FAHP provides useful methodology for airport operators to audit and review the design and operational control for airport airsides. In addition, it seems to be helpful for risk assessment and mitigation and reduction of time and cost according to risk priorities.

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