Journal of Engineering Science and Technology Review 17 (1) (2024) 178 - 186

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Risk Cause Analysis of Runway Excursion Accidents in the Aircraft Landing Stage through Integrated FTA-BN Method

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Received 11 December 2023; Accepted 3 March 2024

Abstract

Runway excursion accidents in the aircraft landing stage are the emphasis in civil aviation safety management. Correctly analyzing and evaluating the influencing factors of runway excursion accidents are the key issues in the current research. In this study, a fault tree model was established to the runway excursion accident risk in the aircraft landing stage based on the fault tree analysis method. Then, the basic events leading to aircraft runway excursions were summarized, and the minimum cut sets and structural importance were calculated. Next, the probability and critical importance of each basic event and the occurrence probability of the top event were analyzed. Subsequently, a Bayesian network (BN) model was constructed through the identified risk factors for runway excursion accidents of aircrafts. The influencing factors of the occurrence probability of each top event and the relative importance of each basic event were investigated, and the critical risks causing runway excursion accidents of aircrafts were revealed. Results show that, 21 basic events in the runway excursion accidents during aircraft landing, among which system fault, ice and snow accumulation on airport runway pavement, and water accumulation on runway pavement are critical events leading to runway excursions. The obtained conclusions provide a decision-making reference for scientifically managing and controlling runway safety events at transport airports.

Keywords: Aircraft landing; Runway excursion; Fault tree analysis; Bayesian network

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1. Introduction

Air transportation is the main mode of modern international transportation and an important embodiment of a country's economic development. According to the statistical main production indicators of the Civil Aviation Administration of China in June 2023, the passenger volume of the entire industry in the first half of 2023 was 284 million, which reflected a year-on-year growth rate of 140.2%. This volume restored to 88.2% of that in the first half of 2019. In addition, the aircraft movements reached 5.583 million, which showed a growth rate of 60.3% and restored to 98.3% of that in the first half of 2019. The data show that China's civil aviation industry is constantly recovering, and the air transport industry will further develop, with safety being an important concern. Once an aviation accident happens, the survival rate is low, which is accompanied by serious economic losses and enormous social impacts. The final approach and landing stage of an aircraft is the most critical stage in flight, and nearly half of civil aviation flight accidents occur in this stage [1]. Boeing's statistical data on commercial civil aviation aircrafts from 2013 to 2022 show that, during this decade, 32 fatal accidents occurred in the approach and landing stage. These accidents resulted in 1140 deaths, and 31% of such fatal accidents occurred in the landing stage, which only accounted for 1% of the average flight time, as shown in Fig. 1. Therefore, exploring the safety risk during aircraft landing is practically important.

Within the civil aviation industry, the existing research of international civil aviation regulatory agencies on runway excursion accidents in the aircraft landing stage has been conducted mainly through information acquisition and early warning systems. Through fusion prediction of relevant data in a flight monitoring analysis system, for instance, the Civil Aviation Authority, UK, pointed out the influencing factors related to runway safety accidents to prevent and control the occurrence of runway excursion accidents by formulating prevention and control measures [2]. Meanwhile, Airbus has developed a runway excursion warning system and a runway excursion protection system to prevent such runway excursion accidents [3]. In the revised advisory circular (ACNo:91-79A) on reducing the runway excursion risk, the US Federal Aviation Administration stated that an unstable approach, increased ground speed due to landing at high airport altitude or high density altitude, flight over the runway entrance at a large airspeed, heavy landing weight, far grounding point, slope under the runway, flight through the runway entrance at an excessive altitude, delayed use of deceleration devices, downwind landing, and landing on a humid or polluted runway will all increase the runway excursion risk [4]. The abovementioned international civil aviation organizations and large aviation enterprises have conducted considerable practical safety research focused on runway excursion accidents during the aircraft landing stage. However, the relevant work is mainly based on the physical parameters and information system of the aircraft and the airport runway. Although runway safety accidents can be avoided to some extent, the related research fails to reveal

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doi:10.25103/jestr.171.21

the underlying mechanisms and the coupling relationship among risk factors that lead to aircraft runway excursions.

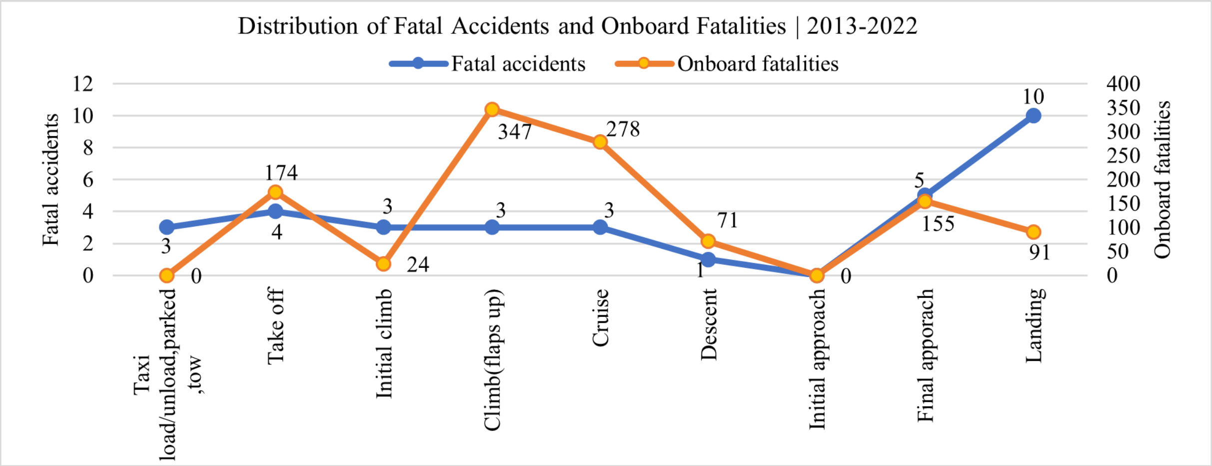


Fig.1. Fatal accidents and deaths in each flight stage

In addition, the existing academic research on accidents in the aircraft landing stage mostly concentrates on the predictive study on the overall possible risks in the landing stage and the direct risk cause analysis [5]. Meanwhile, deep-layer factors, such as crew, mechanical, environmental, and management factors, have been insufficiently concerned and analyzed. Meanwhile, chain analysis and mechanisms often fail to reveal risk problems in the current studies on events such as aircraft runway excursions in the landing stage, which causes difficulties for the practical application of risk management and control strategies. Therefore, the risk factors related to runway excursion events in the aircraft landing stage were screened out in this study from four levels-man, machine, environment, and management-to compensate for the deficiencies of the existing research. Then, the influencing degree of each factor on the accidents was identified, and the critical influencing factors therein were determined to provide scientific references for proposing management and control countermeasures.

The remainder of the study is organized as follows. In Section II, a literature review is given, and the literature documents regarding runway excursions in the aircraft landing stage are sorted out. In Section III, the influencing factors of runway excursions in the aircraft landing stage, the integrated analysis steps of the fault tree analysis (FTA) and the Bayesian network (BN) are introduced. In Section IV, the risk analysis results of runway excursions in the aircraft landing stage are analyzed. In Section V, the entire study is summarized, and relevant conclusions are drawn.

2. State of the Art

At present, many risk factors exist in the aircraft landing stage, and they are coupled with one another, which leads to complex cause mechanisms. Among the studies on aircraft safety in landing process, Wang et al. [6] mainly used multi-source real-time data and integrated qualitative and quantitative information to realize the assessment and early warning of landing dynamic risks. Stolyarov et al. [7] considered landing weight and speed in their proposed method to determine the runway excursion risk during aircraft landing by mathematical risk modeling. Paola et al. [8] created a set of structured methods and models, expressed the risk with the product of occurrence probability and damage severity, and identified and displayed the areas with high accident risks through a risk map. Zhao et al. [9] constructed a BP neural network model to depict runway excursions of aircrafts during takeoff and landing and predicted the frequency of runway excursions and accident symptoms. Sameerañ et al. [10] proposed a method to locate the quick exit of a taxiway based on offset risk, which realized a double improvement in runway operation ability and landing safety. Based on the functional resonance accident model (FRAM), Yan et al. [11] built functional network models for two stages-aircraft glide landing and brake running, simulated the landing process of the pilot by means of virtual trial flight, improved the FRAM analysis process, and established the validation procedures for data acquisition of rolling optimization and effectiveness of safety barriers. Calle-Alonso et al. [12] used a method based on the BN model to provide risk scenario information related to landing procedures after exploratory analysis and hypothesis testing. They also established several scenarios to realize risk assessment of runways. Aniqua et al. [13] introduced a real-time multifunctional system based on SDR to monitor aviation frequency bands. In view of the safety information in flight, two teams respectively led by Chen et al. [14] and Wang et al. [15] analyzed the information mining of risk factors in the near landing stage of flight travel and explored the flight data information of influencing factors inducing long landing and heavy landing. They sought for the relevance between the two aspects through the gray relational analysis method, which provided a reference for risk prevention and control in the landing stage. Gianluca et al. [16] put forward a wheel slip control scheme by using a data-driven method of neural network architecture to solve the problem of wheel slip for the application of wheel slip control strategies during aircraft braking.

In summary, the current runway safety accident analysis in the aircraft landing stage focuses mainly on the prediction and control of runway excursion risk, but less attention has been paid to multi-chain and multi-risk coupling relations leading to such accidents. With regard to the cause of runway excursions in the aircraft landing stage, the existing research method mainly refers to the accident rehearsal based on the accident survey and the simulation analysis of historical cases by civil aviation departments. Accident survey can intuitively reveal the direct and indirect causes of accidents, but it is not sufficiently universal due to the restriction of accident type, environment of accident occurrence, and data availability. Although accident scenarios can be simulated and accident causes can be determined through simulation analysis, the deep-rooted factors leading to accidents cannot be comprehensively considered. Moreover, the analysis results can barely be applied to practical risk prevention and control of civil aviation systems.

First, the importance of basic events affecting aircraft landing and their influencing factors was investigated in this study. Then, the basic events causing runway excursions during aircraft landing were summarized, a fault tree model was established, and the minimum cut sets and structural importance were calculated. Meanwhile, a value was assigned to the occurrence probability of each basic event, and the probability importance, critical importance, and occurrence probability of the top event were solved. Next, a BN model was constructed, and the occurrence probability of the top event and the factor influencing the relative importance of each basic event were calculated. Finally, the evaluation results obtained by the two methods were combined to identify the critical events leading to runway excursions. The conclusion supports the subsequent risk control and provides decision-making references for scientifically managing runway risk events.

3. Methodology

3.1 Risk Identification Framework in the Aircraft Landing Stage

Unsafe events in the process of aircraft landing mainly include controlled flight into terrain, off-site landing, aircraft runway excursion, partial landing outside the landing gear wheel, and aircraft collision with ground obstacles or ground facilities. The factors leading to accidents are usually not unique, but they are coupled or superposed. Based on the theoretical framework of "man-machine-environment-management" for risk factor screening in the engineering theory of safety systems, the influencing factors of unsafe events are summarized into four factors: crew, management, environmental, or mechanical factors [17].

(1) Crew factors

Crew factors mainly include skill failure, illegal operation, loss of situation awareness, and resource management failure [18]. Skill refers to the ability to master and use special techniques, especially the highly automatic response of hands, feet, and mouth when the motion system executes decisions, such as the basic driving skills of pilots and the calibration and correction techniques under special flight conditions. Illegal operation means the violation against general aviation laws, regulations, rules, and operating procedures. Situation awareness refers to the ability to perceive environmental changes and predict future development in public relations of information processing. Crew resource management refers to making full, effective, and reasonable use of all available resources to achieve the purpose of safe and efficient flight operation. The failure of unit resource management lies in the failure of the unit to communicate and cooperate effectively with the team for reasonably allocating tasks and making correct decisions.

(2) Mechanical factors

Mechanical factors mainly include aircraft design defects and aircraft mechanical failures [19]. Aircraft design defects are mainly divided into aircraft flight performance design defects and alarm system and fault-tolerant system defects. Aircraft mechanical failures mainly include landing gear failure, tire failure, thrust reverser failure, and spoiler failure.

(3) Environmental factors

Environmental factors mainly include bad weather, runway design defects, and runway humidity or pollution. The influence of weather factors results from the comprehensive action in the aircraft landing stage. Rain and snow cause the runway to be slippery or polluted, which will influence the landing braking effect and extend the landing distance of the aircraft. Pilots may fail to see the runway clearly or may have visual illusions due to low visibility, which leads to unstable approach or too long landing distance. Sudden gust or flood will seriously affect the control of the crew over the speed and altitude of the aircraft, which results in the too long aircraft floating and landing distance. All these factors will adversely affect the operation of the crew, which further aggravates the risk of unsafe events. In addition, poor runway design, the inclined shape of runway entrance, the difference between runway width and normal runway, and the slope of runway belt tend to cause the visual errors of crew members and too late landing or too long landing distance. The lack of airport approach guidance will also make crew approaches difficult and indirectly contribute to accidents.

(4) Management factors

Management factors are mainly manifested in the defects of airline documents, airline training, air traffic services, and airport runway management. The defects of airline documents are reflected in the lack of guidance documents under special circumstances, the omission of flight documents, unreasonable flight procedures, and imperfect regulations or standards. The defects of air traffic services are reflected in improper air traffic control instructions and failure to provide accurate weather and runway information in time. The defects of airport runway management are mainly embodied in the detection and maintenance of runway pavement.

3.2 Fault Tree Model of Aircraft Runway Excursion

Runway excursion is the primary cause of approach and landing accidents but second only to controlled flight into terrain, where 83% of runway excursion accidents occur in the landing stage. During aircraft landing, the factors leading to runway excursions mainly include crew operation error, controller command error, aircraft power system failure, aircraft landing gear failure, poor meteorological conditions, and slippery runway. Different trigger factors may lead to distinct consequences.

FTA is a probability-based analysis technique, which is used to estimate the risk probability of the top event and is an important method to analyze the security and reliability of systems [20]. The model can take the most unexpected event of the system as the top event of the fault tree. It can refine the tree diagram from top to bottom with the specified logical symbols until the root cause of the system failure is determined. The occurrence probability of the basic event is determined by expert judgment and historical analysis data. This method is also called the logical block diagram analysis method of accidents. This method is usually used to distinguish and evaluate the risks of various systems, which not only can analyze the direct causes of accidents but also can reveal the potential causes of accidents in depth. Describing the causal relationship of accidents using this method is intuitive, clear, and logical. FTA can be divided into qualitative or quantitative analysis. It is generally applied to risk identification and reliability analysis in high-risk industries, such as aerospace, nuclear power, chemical industry, pharmacy, and petrochemical industry [21].

The modeling analysis process for aircraft runway excursion accidents based on a fault tree model is as follows:

(1) The minimum cut sets are solved through the Boolean algebra method:

$$T = M_1 M_2 = \left(M_3 + M_4\right)\left(M_5 + M_6\right) \tag{1}$$

(2) The structural importance of each basic event is analyzed:

The structural importance [22] of the *i*-th basic event is:

$$I(i) = 1 - \prod_{X_i \in K_j} \left(1 - \frac{1}{2^{n_j - 1}}\right) \tag{2}$$

where K_j is the *j*-th minimum cut set, and n_j denotes the total number of basic events in K_j.

(3) Probability importance analysis of basic events:

The probability importance [23] of the *i*-th basic event is:

$$I_g(i) = \frac{\partial P(T)}{\partial q_i} \tag{3}$$

where $P(T)$ is the occurrence probability function of the top event, and q_i is the occurrence probability of the *i*-th basic event.

(4) Critical importance analysis of basic events:

The critical importance [24] of the *i*-th basic event is:

$$\begin{aligned} I_g^c(i) &= \lim_{\Delta q_i \to 0} \frac{\Delta P(T) / P(T)}{\Delta q_i / q_i} \\ &= \frac{q_i}{P(T)} \lim_{\Delta q_i \to 0} \frac{\Delta P(T)}{\Delta q_i} = \frac{q_i}{P(T)} I_g(i) \end{aligned} \tag{4}$$

where $P(T)$ is the occurrence probability function of top event, q_i represents the occurrence probability of the *i*-th basic event, and $I_g(i)$ is the probability importance of the basic event X_i.

(5) Occurrence probability calculation of top event:

The calculation formula for the occurrence probability [22] of top event is:

$$P(T) = \sum \psi(x) \prod_{i=1}^{n} q_i^{X_i} (1 - q_i)^{1 - X_i} \tag{5}$$

where $\psi(x)$ is the function of top event, and X_i stands for the state value of the *i*-th basic event. $X_i = 0$ means that the event does not occur, and $X_i = 1$ means that the event already happens. q_i is the occurrence probability of the *i*-th basic event.

3.3 BN Model of Aircraft Runway Excursion

BN provides a way to express causal information. It can relate the influencing factors of unsafe events with the severity of consequences, which determines the influence relationship between the causes and consequences of events [25-27].

Considering that the logical relationship between basic events cannot be embodied in the fault tree, the fault tree model for aircraft runway excursion was mapped into the BN model via network modeling analysis software Netica [28]. The specific procedures are listed as follows:

(1) Each basic event in the fault tree of aircraft runway excursion is taken as the root node of BN, and the repeated basic events only need to be expressed as a root node.

(2) The occurrence probability of each basic event in the fault tree of aircraft runway excursion is taken as the prior probability of the root node of BN.

(3) The links of the corresponding nodes in BN are established according to the connection relationship in the fault tree of aircraft runway excursion.

(4) The conditional probability of the corresponding node in BN is established according to the logic gate relationship in the fault tree of aircraft runway excursion.

(5) The occurrence probability of the top event is solved as follows [29]:

$$P(T) = \prod_{i=1}^{n} P\left(\frac{X_i}{F(X_i)}\right) \tag{6}$$

where X_i is the state value of a child node, $F(X_i)$ is the state value of the corresponding parent node, and n is the number of nodes.

(6) The influencing factor of relative importance of basic events is calculated. When the basic event i occurs, the ratio of the difference in the occurrence probability of the top event to the occurrence probability of the top event when the event occurs is considered the influencing factor of the relative importance of the basic event *i* [30], as shown in the following formula:

$$n_i = \left[\frac{(P_1 - P_0)}{P_1}\right] \tag{7}$$

where P_1 is the occurrence probability of the top event when the basic event *i* takes place, and P_0 is the occurrence probability of the top event when the basic event *i* does not occur.

4. Results Analysis and Discussion

4.1 Risk Identification Result of Aircraft Runway Excursion Accident

Combining predecessors' method of extracting the factors influencing aircraft runway excursion accidents, a total of 129 aircraft runway excursion accidents on a global scale during the period of 2010-2022 were collected and organized through the information reported by domestic and foreign mainstream media. On this basis, 20 experts dedicated to civil aviation safety management were interviewed through e-mail, phone call, and video conference to further optimally screen out influencing factors. By arranging and analyzing the interview results, 21 simplified basic events leading to aircraft runway excursion events and their occurrence probability and 12 fault types were acquired according to the index division framework of man-machine-environment-management, as shown in Table 1.

Table 1. Code display in fault tree and occurrence probability of basic events

Code	Meaning	Occurrence probability
T	Aircraft runway excursion	-
M_1	Too fast aircraft speed	-
M_2	Pilot control error	-
M_3	Sudden failure of relevant aircraft systems	-
M_4	Small runway friction coefficient	-
M_5	Pilot misoperation	-
M_6	Pilot misjudgment	-
M_7	Slippery runway pavement	-
M_8	Failure of aircraft instrument to effectively display the flight status	-
M_9	Inappropriate air traffic control	-
M_{10}	The instrument fails to establish effective interactive information with external environment	-
M_{11}	Complex weather conditions around the airport	-
M_{12}	Functional instruments are not turned on	-
X_1	System failure	6×10^{-4}
X_2	Influence of surrounding environment of the airport	2×10^{-5}
X_3	Insufficient cleaning of airport runway pavement	1×10^{-4}
X_4	Deficiency in pilot technique	4×10^{-4}
X_5	Violation against standard operating procedures	3×10^{-4}
X_6	Failure in crew resource management	2×10^{-4}
X_7	Ice and snow accumulation on airport runway pavement	2×10^{-4}
X_8	Water accumulation on airport runway pavement	2×10^{-4}
X_9	No grooving on runway pavement	1×10^{-4}
X_{10}	Aircraft instrument fault	2×10^{-4}
X_{11}	No effective functional instruments are installed	3×10^{-5}
X_{12}	Unreasonable flight procedure design	5×10^{-5}
X_{13}	Inappropriate command of air controlmen	1×10^{-4}
X_{14}	Adverse airport lighting conditions	5×10^{-5}
X_{15}	The signal around the airport is interfered	2×10^{-5}
X_{16}	Substantial crosswind or tailwind	2.5×10^{-4}
X_{17}	Wind shear	2.5×10^{-4}
X_{18}	Too low visibility	3×10^{-4}
X_{19}	The airborne meteorological radar function is not opened	3×10^{-5}
X_{20}	The airborne wind shear detection function is not opened	3×10^{-5}
X_{21}	Other important functional instruments are not turned on	3×10^{-5}

4.2 FTA Results of Aircraft Runway Excursion Accidents

The FTA method was introduced to establish the FTA diagram for runway excursions in the aircraft landing stage, as shown in Fig. 2. In this way, the mechanism of each trigger factor in causing runway excursion events can be analyzed and evaluated in detail.

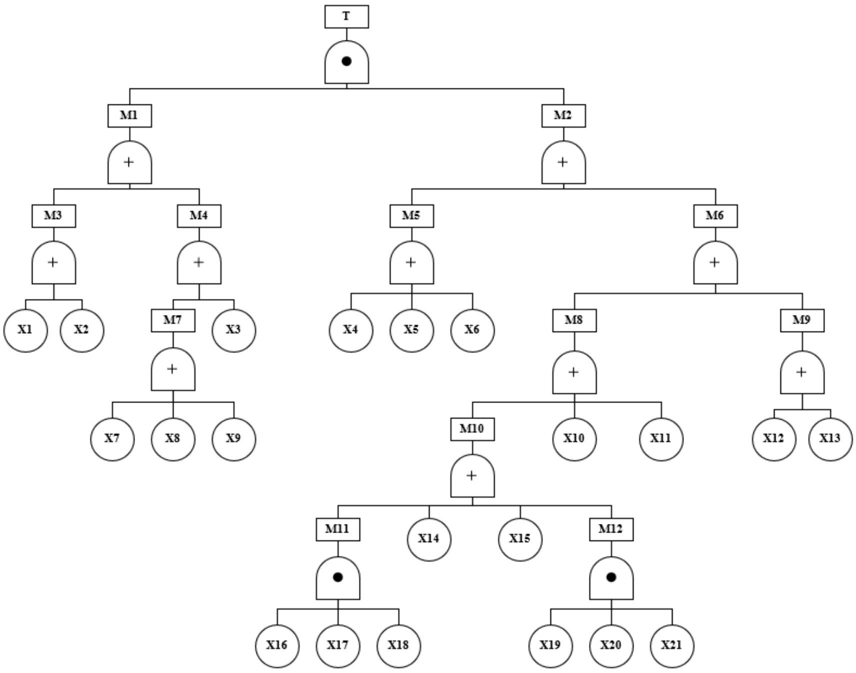


Fig.2. Fault tree model for runway excursions in the aircraft landing stage

(1) Solving of minimum cut sets

By analyzing the fault tree model, 66 groups of minimum cut sets are obtained as per Equation (1):$\{X_1, X_4\}$, $\{X_1, X_5\}$, $\{X_1, X_6\}$, $\{X_1, X_{10}\}$, $\{X_1, X_{11}\}$, $\{X_1, X_{12}\}$, $\{X_1, X_{13}\}$, $\{X_1, X_{14}\}$, $\{X_1, X_{15}\}$, $\{X_2, X_4\}$, $\{X_2, X_5\}$, $\{X_2, X_6\}$, $\{X_2, X_{10}\}$, $\{X_2, X_{11}\}$, $\{X_2, X_{12}\}$, $\{X_2, X_{13}\}$, $\{X_2, X_{14}\}$, $\{X_2, X_{15}\}$, $\{X_3, X_4\}$,

$\{X_3, X_5\}$, $\{X_3, X_6\}$, $\{X_3, X_{10}\}$, $\{X_3, X_{11}\}$, $\{X_3, X_{12}\}$, $\{X_3, X_{13}\}$, $\{X_3, X_{14}\}$, $\{X_3, X_{15}\}$, $\{X_4, X_7\}$, $\{X_4, X_8\}$, $\{X_4, X_9\}$, $\{X_5, X_7\}$, $\{X_5, X_8\}$, $\{X_5, X_9\}$, $\{X_6, X_7\}$, $\{X_6, X_8\}$, $\{X_6, X_9\}$, $\{X_7, X_{10}\}$, $\{X_7, X_{11}\}$, $\{X_7, X_{12}\}$, $\{X_7, X_{13}\}$, $\{X_7, X_{14}\}$, $\{X_7, X_{15}\}$, $\{X_8, X_{10}\}$, $\{X_8, X_{11}\}$, $\{X_8, X_{12}\}$, $\{X_8, X_{13}\}$, $\{X_8, X_{14}\}$, $\{X_8, X_{15}\}$, $\{X_9, X_{10}\}$, $\{X_9, X_{11}\}$, $\{X_9, X_{12}\}$, $\{X_9, X_{13}\}$, $\{X_9, X_{14}\}$, $\{X_9, X_{15}\}$, $\{X_1, X_{16}, X_{17}, X_{18}\}$, $\{X_1, X_{19}, X_{20}, X_{21}\}$, $\{X_2, X_{16}, X_{17}, X_{18}\}$, $\{X_2, X_{19}, X_{20}, X_{21}\}$, $\{X_3, X_{16}, X_{17}, X_{18}\}$, $\{X_3, X_{19}, X_{20}, X_{21}\}$, $\{X_7, X_{16}, X_{17}, X_{18}\}$, $\{X_7, X_{19}, X_{20}, X_{21}\}$, $\{X_8, X_{16}, X_{17}, X_{18}\}$, $\{X_8, X_{19}, X_{20}, X_{21}\}$, $\{X_9, X_{16}, X_{17}, X_{18}\}$, $\{X_9, X_{19}, X_{20}, X_{21}\}$.

According to the analysis, the runway excursion during aircraft landing may occur in 66 ways, which indicates that the occurrence probability and criticality of such unsafe events are large. This finding is consistent with the statistical data in practical operation.

(2) Analysis of structural importance of basic events

The structural importance ranking of basic events solved by Equation (2) is as follows: $I[X_1] = I[X_2] = I[X_3] = I[X_7] = I[X_8] = I[X_9] > I[X_4] = I[X_5] = I[X_6] = I[X_{10}] = I[X_{11}] = I[X_{12}] = I[X_{13}] = I[X_{14}] = I[X_{15}] > I[X_{16}] = I[X_{17}] = I[X_{18}] = I[X_{19}] = I[X_{20}] = I[X_{21}]$.

By calculating structural importance, the system failure, the influence of the surrounding environment of the airport, and the insufficient cleaning of the runway pavement among basic events have greater influence on the occurrence of runway excursions during aircraft landing than other events.

(3) Critical importance analysis of basic events

The critical importance ranking of basic events solved by Equation (4) is as follows: $I_c[X_1] > I_c[X_4] > I_c[X_5] > I_c[X_7] = I_c[X_8] > I_c[X_{10}] = I_c[X_6] > I_c[X_3] = I_c[X_9] > I_c[X_{13}] > I_c[X_{14}] = I_c[X_{12}] > I_c[X_{11}] > I_c[X_2] > I_c[X_{15}] > I_c[X_{18}] = I_c[X_{16}] = I_c[X_{17}] > I_c[X_{19}] = I_c[X_{20}] = I_c[X_{21}]$.

The specific calculation results are listed in Table 2.

Table 2. Qualitative and quantitative analysis results of basic events

Basic events	Structural importance	Probability importance	Critical importance
X_1	0.031250	0.126684	0.491754
X_2	0.031250	0.122340	0.016387
X_3	0.031250	0.122939	0.081939
X_4	0.008755	0.113145	0.296236
X_5	0.008755	0.112484	0.222166
X_6	0.008755	0.111823	0.148103
X_7	0.031250	0.123688	0.163885
X_8	0.031250	0.123688	0.163885
X_9	0.031250	0.122939	0.081938
X_{10}	0.008755	0.111823	0.148103
X_{11}	0.008755	0.110698	0.022214
X_{12}	0.008755	0.110831	0.037023
X_{13}	0.008755	0.111161	0.074048
X_{14}	0.008755	0.110831	0.037023
X_{15}	0.008755	0.110632	0.014809
X_{16}	0.002927	0.000083	0.000133
X_{17}	0.002927	0.000083	0.000133
X_{18}	0.002927	0.000069	0.000133
X_{19}	0.002927	0.000001	0.000001
X_{20}	0.002927	0.000001	0.000001
X_{21}	0.002927	0.000001	0.000001

(4) Occurrence probability of the top event

Combining the fault tree model and the occurrence probability of basic events, the occurrence probability of the top event is solved using Equation (5) as $P(T)=1.6454\times10^{-6}$.

4.3 Bayesian Model Analysis Results of Aircraft Runway Excursion Accidents

The occurrence probability of each basic event is substituted into the Bayesian model, and the logic of each basic event is combined and analyzed to establish the BN model of aircraft runway excursion accidents, as shown in Fig. 3.

The occurrence probability of the top event is calculated by Equation (6) as $P(T) = 1.6454\times10^{-6}$.

Taking the violation of basic events against standard operating procedures (X_5) as an example, the calculation process for the influencing factor of relative importance is explained. If the operation obeys the standard procedure, then $P(X_5) = 0$, and the BN model in this case is as shown in Fig. 4. The runway excursion probability declines from 1.6454×10^{-6} to 1.2799×10^{-6}. The influencing factor of relative importance of basic event X_5 is solved as 22.21 according to Equation (7).

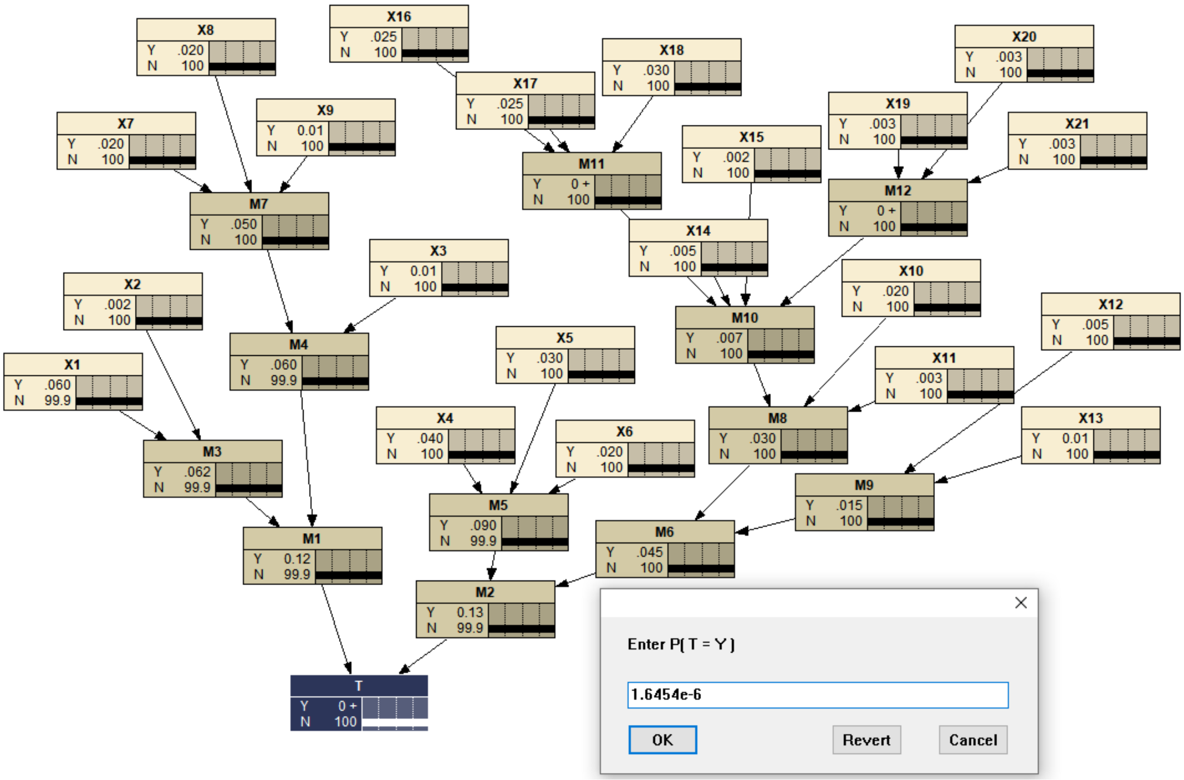
The influencing factor of relative importance of each basic event is sorted as follows: $\eta_1 > \eta_4 > \eta_5 > \eta_7 = \eta_8 > \eta_6 = \eta_{10} > \eta_3 = \eta_9 > \eta_{13} > \eta_{12} = \eta_{14} > \eta_{11} > \eta_2 > \eta_{15} = \eta_{16} = \eta_{17} = \eta_{18} = \eta_{19} = \eta_{20} = \eta_{21}$.

The specific calculation results are listed in Table 3.

Table 3. Influencing factor of relative importance of each basic event

Basic events	Occurrence probability of the top event while $P(X_i)$=0	Influencing factor of relative importance
X_1	8.3635×10^{-7}	49.17
X_2	1.6185×10^{-6}	1.63
X_3	1.5106×10^{-6}	8.19
X_4	1.1581×10^{-6}	29.62
X_5	1.2799×10^{-6}	22.21
X_6	1.4018×10^{-6}	14.80
X_7	1.3758×10^{-6}	16.39
X_8	1.3758×10^{-6}	16.39
X_9	1.5106×10^{-6}	8.19
X_{10}	1.4018×10^{-6}	14.80
X_{11}	1.6089×10^{-6}	2.22
X_{12}	1.5845×10^{-6}	3.70
X_{13}	1.5236×10^{-6}	7.40
X_{14}	1.5845×10^{-6}	3.70

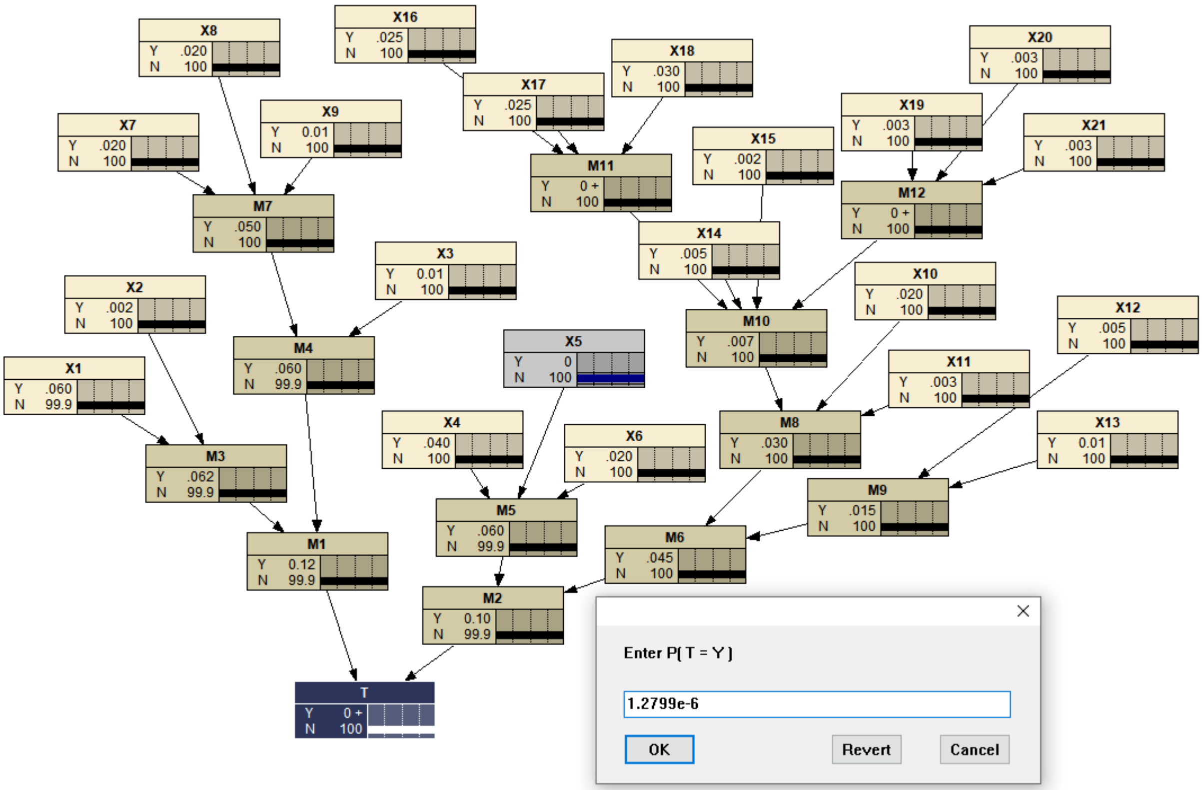
Basic events	Occurrence probability of the top event while $P(X_i)$=0	Influencing factor of relative importance
X_{15}	1.6210×10^{-6}	1.48
X_{16}	1.6253×10^{-6}	1.22
X_{17}	1.6253×10^{-6}	1.22
X_{18}	1.6253×10^{-6}	1.22
X_{19}	1.6253×10^{-6}	1.22
X_{20}	1.6253×10^{-6}	1.22
X_{21}	1.6253×10^{-6}	1.22



Enter P[T = Y]

1.6454e-6

Fig.3. BN model of aircraft runway excursion accidents



Enter P[T = Y]

1.2799e-6

Fig.4. BN model under $P(X_5)$=0

4.4 Analysis Results of Aircraft Runway Excursion Accidents Based on Integrated FTA-BN

The FTA result is identical with the calculation result for the occurrence probability of the top event based on the BN. Both results are $P(T)=1.6454\times10^{-6}$ and remain at the same order of magnitude as the statistical result of runway excursion events in the landing process. The calculation results are proven to be reasonable and reliable.

In FTA, the results of the analysis in the second part of this section show the structural importance of the basic events, where the system failure (X_1), the influence of surrounding environment of the airport (X_2), insufficient cleaning of airport runway pavement (X_3), ice and snow accumulation on airport runway pavement (X_7), water accumulation on airport runway pavement (X_8), and pavement non-grooving (X_9) greatly affect the occurrence probability of the top event.

In the risk evaluation study based on BN, the relative importance of basic events is sorted as follows: $\eta_1 > \eta_4 > \eta_5 > \eta_7 = \eta_8 > \eta_6 = \eta_{10} > \eta_3 = \eta_9 > \eta_{13} > \eta_{12} = \eta_{14} > \eta_{11} > \eta_2 > \eta_{15} = \eta_{16} = \eta_{17} = \eta_{18} = \eta_{19} = \eta_{20} = \eta_{21}$. System failure ($X_1$), deficiency in pilot technique (X_4), violation against standard operating procedures (X_5), ice and snow accumulation on airport runway pavement (X_7), and water accumulation on airport runway pavement (X_8) are relatively important basic events, with large influencing factors.

System failure (X_1), ice and snow accumulation on airport runway pavement (X_7), and water accumulation on airport runway pavement (X_8) are the critical events that cause aircraft runway excursion, followed by the influence of surrounding environment of the airport (X_2), insufficient cleaning of airport runway pavement (X_3), deficiency in pilot technique (X_4), violation against standard operating procedures (X_5), and pavement non-grooving (X_9). Therefore, emphasis should be placed on checking the failure of the aircraft system itself before flight activities, reducing the probability of system failure during the flight process, timely cleaning the runway pavement, avoiding ice, snow, and water accumulation, ensuring the aircraft landing environment, and finally realizing effective risk prevention and control of aircraft runway excursion events.

5. Conclusions

The integrated FTA-BN method was adopted to classify the basic events related to runway excursion accidents and analyze their risk causes during aircraft landing. A fault tree model was established, the runway excursion events during aircraft landing were qualitatively and quantitatively analyzed, and the critical events with great influences were clarified. Specifically, the following conclusions were drawn:

(1) In FTA, the minimum cut sets should be determined first to calculate the probability of the top event, followed by calculation via a tolerance formula. In BN, the probability of the top event can be directly calculated using the joint probability distribution without needing to seek for the cut sets. This approach avoids the complex discretization in FTA and contributes to the easier calculation process.

(2) FTA closely resembles BN in aspects of reasoning mechanisms and applications. However, BN is more suitable for identifying critical components because of its probability updating capability and stronger modeling and analysis ability, which make it incomparable to the traditional FTA method. During fault tree-based reasoning, the analysis should be conducted from top down to find the basic events correlated with the occurrence of the top event and further comprehensively analyze various causes of the top event. BN not only has this reasoning function but also is capable of describing the varied and nondeterministic logical relationships of events.

(3) The FTA method is featured with rigorous logic and high conciseness. However, it is accompanied by some unavoidable defects. The relative importance of basic events is introduced by the integrated FTA-BN method. In this way, BN is more practical in event risk analysis. It is more intuitive than the single FTA method, displays the causal relationship between nodes, and acquires richer and more accurate information.

In summary, if the integrated FTA-BN analysis method is applied to the risk cause study of aircraft runway excursion events, then it can clarify the influencing degree of each basic factor, capture critical influencing factors, and better manage and control the risk of runway excursions. "System failure" is the most critical influencing factor, and the emphasis should be laid on checking the failure of the aircraft system itself before flight activities to reduce the probability of system failure during the flight process.

Meanwhile, the integrated FTA-BN analysis method proposed in this study can analyze the influencing degree of basic events on aircraft runway excursion events and provide references for management and control countermeasures. This integrated method is applicable to the accident risk analysis of aircraft landing process in this study. It can also be promoted in other types of safety events to realize in-depth analysis and utilization of accident data and provide data support for scientifically managing and controlling unsafe events in civil aviation.

Acknowledgments
This study was funded by the Training Program for Young Core Teachers in University of Henan Province (No. 2020GGJS174), Key Research Projects of Higher Education Institutions in Henan Province (No. 24A620005), Key Research and Development Project in Henan Province (No. 221111321000).

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