Aviation Accident Causation Analysis Based on Complex Network Theory

YUE Rentian[*], *LI Junwei*, *HAN Meng*

College of Air Traffic Management, Civil Aviation University of China, Tianjin 300300, P. R. China

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Abstract: Accident causation analysis is of great importance for accident prevention. In order to improve the aviation safety, a new analysis method of aviation accident causation based on complex network theory is proposed in this paper. Through selecting 257 accident investigation reports, 45 causative factors and nine accident types are obtained by the three-level coding process of the grounded theory, and the interaction of these factors is analyzed based on the "2-4" model. Accordingly, the aviation accident causation network is constructed based on complex network theory which has scale-free characteristics and small-world properties, the characteristics of causative factors are analyzed by the topology of the network, and the key causative factors of the accidents are identified by the technique for order of preference by similarity to ideal solution (TOPSIS) method. The comparison results show that the method proposed in this paper has the advantages of independent of expert experience, quantitative analysis of accident causative factors and statistical analysis of a lot of accident data, and it has better applicability and advancement.

Key words: aviation safety; accident causation; complex network theory; grounded theory; "2-4" model

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0 Introduction

Air transportation system is a complex system with high safety requirements. The Annual Statistical Report on Aviation Safety in 2019 released by International Civil Aviation Organization (ICAO)[1] shows that with the rapid development of air transportation, the accident rate is also rising. Consequently, it is very important to improve aviation safety level through accident causation analysis.

The early research on the causation of aviation accidents focused on human factors. After the application of system science in the study of accident causation, some system accident models have been proposed, such as: Systems-theoretic accident modeling and process (STAMP)[2], failure mode and effect analysis (FMEA)[3] and "2-4" model[4]. Besides, there are other methods to analyze the causation of aviation accidents. For example, a Bayesian network of aviation accidents is established to analyze the change of accident probability[5].

The complex network theory is applied to the field of safety management. And the event analysis of systemic teamwork (EAST) methodology is proposed to analyze the aviation accidents[6]. The key risk factors of seaplane take-off and landing safety are identified and the accident prevention measures are proposed through the network attack experiments[7]. Based on the complex network and the cascading failure theory, a new accident causation model is proposed for the railway accidents analysis[8].

In this paper, the causation of aviation accidents is analyzed by the complex network theory. Firstly, the aviation accident investigation reports are collected to classify and sort out the causative factors of aviation accidents based on the grounded theory[9], and then, the causative chain of each accident is analyzed to determine the relationship between factors based on the "2-4" model[4]. According to the complex network theory, the causation

*Corresponding author, E-mail address: rtyue@cauc.edu.cn.

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analysis network of aviation accident is constructed. Secondly, according to the topological properties of complex network theory, the aviation accident causation network is analyzed from degree, average path length, network diameter and clustering coefficient[7-8,10]. Thirdly, combining with the technique for order of preference by similarity to ideal solution (TOPSIS) method, a method for determining the critical causative factors of aviation accidents is proposed. Finally, several aviation accident causation analysis models are compared.

1 Construction of Aviation Accident Causation Network

Aviation accident causation network is constructed by taking the causative factors of aviation accidents as the nodes and the relationship between the causative factors as the edges.

The Report of Aviation Accident Investigation can be used as the data source for the study, because it records in detail of the accident. And 257 investigation reports published in Ref.[11] from 2009 to 2019 are selected as the data source for the study.

1.1 Determination of network nodes

There are a lot of factors described in the investigation report of accidents, and the same or similar factors may be described differently due to the difference of accident investigation institutions. If the exhaustive method is used to list all causative factors, it is not conducive to the subsequent analysis work.

Therefore, the causative factors of 257 aviation accidents are extracted by the coding method based on the grounded theory as nodes for the network. The core process of the extraction is data analysis, which includs three steps: Open coding, axial coding and selective coding. The causative factors extracted by the grounded theory is shown in Fig.1.

Based on the grounded theory, the causative factors of aviation accidents and the accident types are sorted out. Suppose $P = \{P_1, P_2, \cdots, P_n\}$ is a set of human causative factors, $A = \{A_1, A_2, \cdots, A_n\}$ a set of facilities and equipment causative factors,

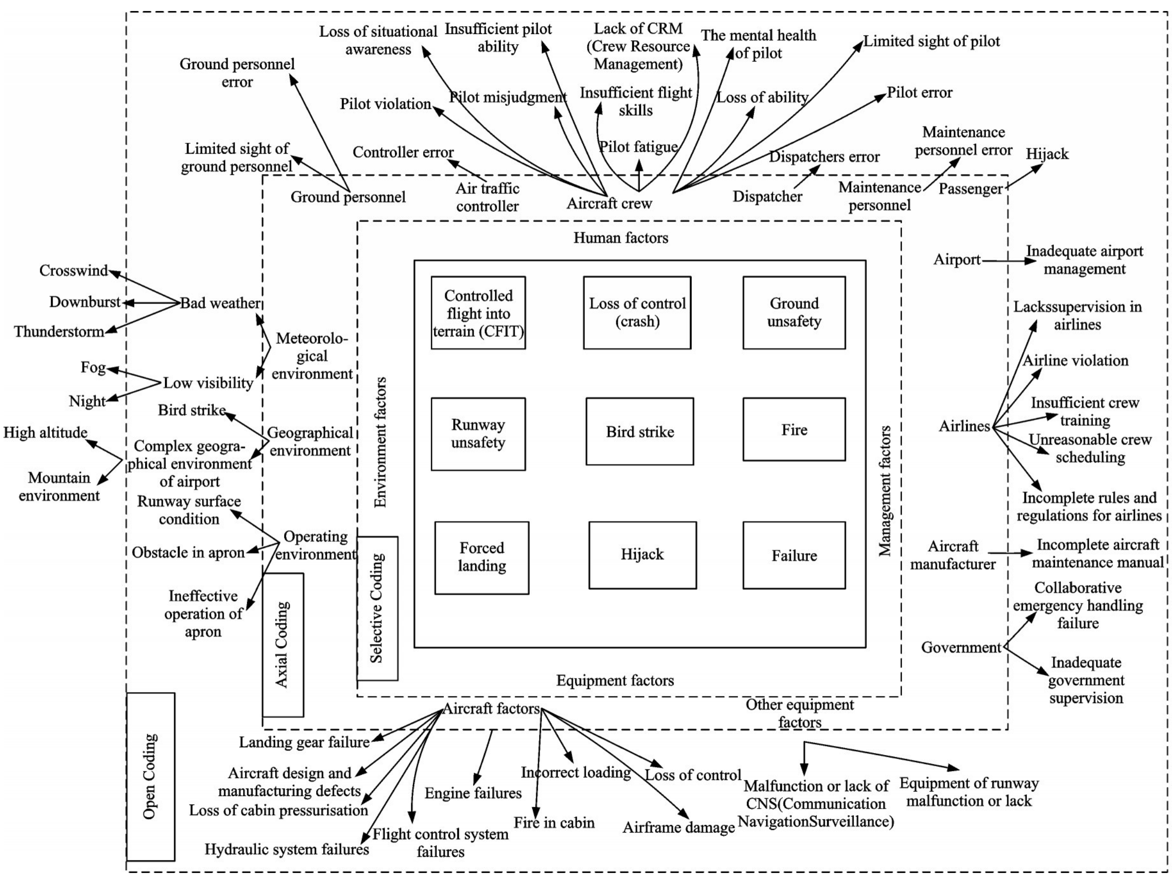

Fig.1 Causative factors extracted by grounded theory

$E=\{E_1, E_2, \cdots, E_n\}$ a set of environment causative factors, $M=\{M_1, M_2, \cdots, M_n\}$ a set of management causative factors, and $Z=\{Z_1, Z_2, \cdots, Z_n\}$ a set of accident types, shown in Table 1.

Table 1 Causative factors of aviation accidents

Node	Description	Node	Description
P_1	Insufficient flight skills	A_{11}	Malfunction or lack of CNS
P_2	Pilot violation	A_{12}	Equipment of runway malfunction or lack
P_3	Pilot error	E_1	Low visibility
P_4	Pilot fatigue	E_2	Bad weather
P_5	Loss of situational awareness	E_3	Runway surface condition
P_6	Limited sight of pilot	E_4	Ineffective operation of apron
P_7	Lack of safety awareness	E_5	Bird strike
P_8	The mental health of pilot	E_6	Complex geographical environment of airport
P_9	Lack of CRM	E_7	Obstacle in apron
P_{10}	Loss of ability	M_1	Insufficient crew training
P_{11}	Pilot misjudgment	M_2	Unreasonable crew scheduling
P_{12}	Ground personnel error	M_3	Incomplete rules and regulations for airlines
P_{13}	Limited sight of ground personnel	M_4	Lacks supervision in airlines
P_{14}	Controller error	M_5	Airline violation
P_{15}	Maintenance personnel error	M_6	Inadequate airport management
P_{16}	Dispatchers error	M_7	Incomplete aircraft maintenance manual
P_{17}	Hijack	M_8	Inadequate government supervision
A_1	Landing gear failure	M_9	Collaborative emergency handling failure
A_2	Hydraulic system failures	Z_1	Controlled flight into terrain
A_3	Engine failures	Z_2	Loss of control (crash)
A_4	Flight control system failures	Z_3	Runway unsafety
A_5	Fire in cabin	Z_4	Ground unsafety
A_6	Loss of cabin pressurization	Z_5	Bird strike
A_7	Airframe damage	Z_6	Fire
A_8	Loss of control	Z_7	Forced landing
A_9	Incorrect loading	Z_8	Hijack
A_{10}	Aircraft design and manufacturing defects	Z_9	Failure

1.2 Determination of network edges

The relationship between accident causative factors is abstracted as the edge of the network and the aviation accident causation network should be a directed weighted network.

The occurrence path of the "2-4" model is described as system network, where "2" means two levels (individual, organization) and "4" means four stages (guidance, operation, unsafe behavior and individual factors). The model is suitable to construct the accident causation network for its network structure, and makes the analysis more comprehensive. So, the "2-4" model is applied to the analysis of the relationship between the factors.

The "2-4" model is taken as the logical framework to get an event chain composed of causative factors based on each aviation accident. According to the complex network theory, each causative factor is regarded as an independent node. However, it can be found that some factors do not completely form the causal relationship but promotion and interaction. Therefore, the causal relationship or the promotion relationship between factors is regarded as a directed edge, and the number of co-occurrence between the same factors is taken as the weight of the edge. Moreover, the corresponding adjacency matrix is established.

An aviation accident investigation report is selected as an example to analyze the relationship between the accident causative factors based on the

"2-4" model. On January 25, 2010, at 00:41:30 UTC, Ethiopian Airlines Flight ET409, B737-800, crashed into the southwest region of Beirut Rafik in the Mediterranean Sea. Analysis for this accident by the "2-4" model is shown in Fig.2.

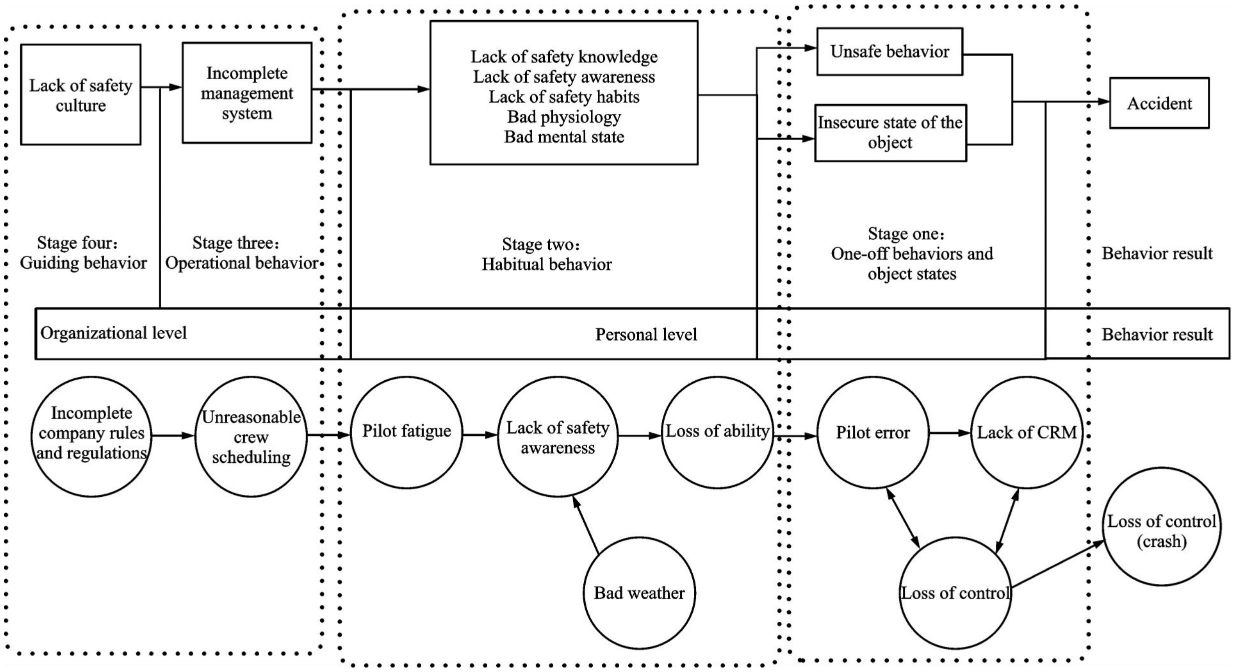

Fig.2 Analysis for an accident by the "2-4" model

When the flight took off, there were thunderstorms and low clouds in the area. At this time, the controller gave the instruction of a right turn, then the aircraft bumped, and finally the aircraft went through two recoverable stalls. During this period, the pilots were fatigued and lost situation awareness due to the poor crew scheduling. In addition, the pilots' capability declined under the bad weather condition. For the poor CRM level, the pilots failed to correctly operate the aircraft, and the flight control inputs of the captain and the co-pilot were inconsistent. In the final stage, the aircraft made an uncontrolled spiral dive.

According to the causation analysis process for 257 aviation accidents, the adjacent matrix can be established as the basis of constructing the accident causation network.

2 Analysis of Topological Characteristics

According to the network nodes identified in Table 1 and the network edges identified in the "2-4" model, the aviation accident causation network is constructed by the Pajek software[12].

The aviation accident causation network is comprised of 45 nodes (causative factors) and 304 edges. Most of the factors are affected by others, which proves that the occurrence of accidents is not the result of a single factor.

According to the in-degree analysis of accident type nodes, the runway safety accounts for 38.5% of the total accidents, and it can be seen that the approach and landing are the critical nature of those flight phases. Moreover, the ground safety accounts for 19% of the total accidents, indicating that it is also an important factor of aviation accident causation.

The causative process of aviation accidents can be analyzed from different topological characteristics, which provides some theoretical basis for the accident prevention. Therefore, combined with the topology characteristic formula of complex network, the node degree, the average path length, the network diameter and the clustering coefficient are selected for analysis.

2.1 Node degree

The aviation accident causation network is a directed-weighted network, so the node degree of the network can be analyzed from three aspects: Out-degree, in-degree and total degree. The total degree is equal to the sum of in-degree and out-degree. The total degree varies from 1 to 41. In Fig.3, the causative factors of aviation accident with the total degree greater than 15 are displayed respectively. Besides, about 30% of total node-degrees account for 53% of all total-node degrees.

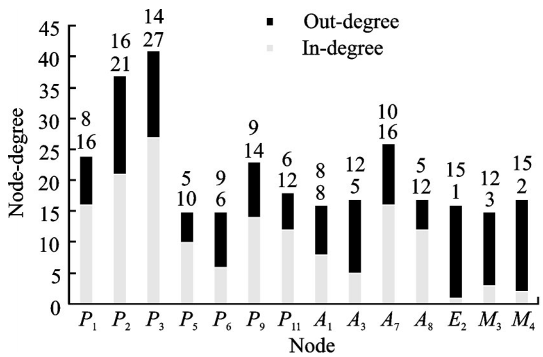

Fig.3 Causative factors with total degree greater than 15

In Fig.3, the total degree of the human factor accounts for the largest proportion of all factors, indicating that the pilot factor is more related to other factors. In addition, the factors with larger total node-degree are the aircraft-related factors, management factors and weather factors in turn.

Among them, the nodes with larger in-degree are as follows: Pilot error P_3, pilot violation P_2, insufficient flight skills P_1, airframe damage A_7, lack of CRM P_9. These factors are easily affected by other factors and become the direct accident causation.

The nodes with larger out-degree are as follows: Pilot violation P_2, pilot error P_3, bad weather E_2, lacks supervision in airlines M_4, incomplete rules and regulations for airlines M_3. These factors can easily promote other factors and become the essential accident causation.

Especially, in-degree and out-degree of the nodes, pilot error P_3 and pilot violation P_2, are nearly the largest nodes, which shows that the two factors are easy to interact with other factors and are the key causative factors of aviation accidents.

2.2 Average path length and network diameter

The average path length reflects the influence ability of the factors and indicates the degree of separation between the nodes. If the average path length is short, the information exchange between the causative factors passes through few nodes. The average path length is reflected in the number of causative factors that need to go through in the occurrence of the accident. The obtained results show that the average path length of the accident causation network is 2.543, which indicates that the accident can be reached through three factors on average.

The network diameter of the accident causation network is 7, and the path is from aircraft design and manufacturing defects A_{10} to loss of ability P_{10}. In the real situation, A_{10} is difficult to directly lead to P_{10}, but the analysis of the network diameter shows that there is an indirect relationship between the two involved factors. It can be seen that the new accident causation analysis method can effectively identify the causal relationship which is difficult to find directly.

2.3 Clustering coefficient

The clustering coefficient reflects the aggregation of nodes in the complex network. The greater the clustering coefficient of nodes is, the closer the connection between the nodes and the surrounding nodes is. The clustering coefficient is defined as

$$C_i = \frac{E_i}{k_i(k_i - 1)/2} = \frac{2E_i}{k_i(k_i - 1)} \tag{1}$$

where k_i is adjacent nodes in the network and E_i the number of edges between adjacent nodes.

In addition, the clustering coefficient and average path length can judge whether the network obeys small world properties[13]. The clustering coefficient of nodes varies from 0.05 to 0.67. The nodes with the clustering coefficient greater than 0.25 are selected, shown in Fig.4.

In Fig.4, nodes with larger clustering coefficients are: Unreasonable crew scheduling M_2, malfunction or lack of CNS A_{11}, insufficient crew training M_1, controller error P_{14}, loss of situational awareness P_5, lack of safety awareness P_7, and these factors have strong aggregation ability. If

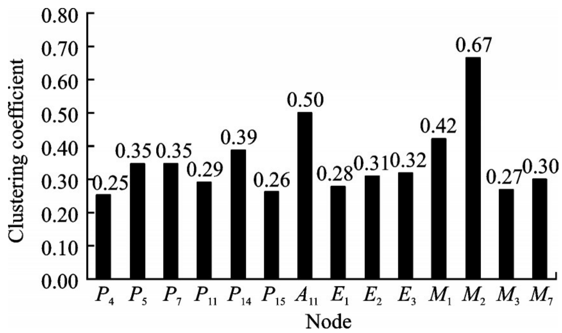

Fig.4 Network nodes with clustering coefficient greater than 0.25

these factors are abnormal, it is easy to interact with other factors and lead to the formation of event chain. Therefore, in order to prevent the chain reaction in the network, it is necessary to remove these nodes with larger clustering coefficient.

The clustering coefficient of the network is 0.217 6 and the average path length of the network is 2.543, then it can be concluded that the aviation accident causation network obeys small-world properties. This also means that the connectivity between the causative factors of accidents is random, and the factors propagate quickly in the network. If a factor occurs, it is easy to produce a chain of events, which further aggravates the situation and increases the difficulty of emergency response.

3 Determination and Analysis of Key Nodes

3.1 Determination algorithm based on TOPSIS

According to the analysis of the topological characteristics of the aviation accident causation network, the causation network has both scale-free characteristics and small world properties. The scale-free characteristic reflects that the network follows the Pareto principle, which shows that a small number of nodes control the efficiency of the whole network. The robustness of the network can be achieved by taking deliberate attacks. The key nodes are identified and deleted, which can cut off the formation of event chain, reduce the propagation rate and achieve the purpose of accident prevention.

The network topology feature can be used as the index to determine the key nodes (causative factors), but sometimes it has limitations. TOPSIS is a multicriteria decision-making approach. Degree centrality, betweenness centrality, closeness centrality and clustering coefficient of nodes are normalized and set as four objectives of the TOPSIS method.

The ideal solution and the negative ideal solution of objectives are calculated to obtain the approaching between the node and the ideal solution, which is defined as

$$C_{\mathrm{T}}(i)=\frac{S_i^-}{S_i^-+S_i^+} \tag{2}$$

where C_{T} is the value of TOPSIS centrality of node i, S_i^- the distance between the node and the negative ideal solution, and S_i^+ the distance between the node and the ideal solution.

The value of the ideal solution approaching of each node is closer to 1, and the node plays an important role in network. It can be used as the basis for evaluating the key nodes[14].

3.2 Normalized results of key nodes and their ranking

According to Eq.(1), the degree centrality, the betweenness centrality, the closeness centrality and the clustering coefficient of each node are normalized. The normalized values, the TOPSIS values and their ranking are shown in Table 2.

From Table 2 we can see that, considering degree centrality, betweenness centrality, closeness centrality and clustering coefficient of nodes, the ranking of nodes has a certain change compared with the single network topology.

According to the TOPSIS value and ranking of each node, it is also seen that P_2, P_3, M_9, P_{14}, P_9 are the key causative factors, which focus on the errors of professional of air transportation and also verify the importance of human factors in aviation safety management.

In addition, when an emergency occurs, the multi-party collaborative emergency response fails to work, and the crew resource management is not enough, which indicates that team cooperation, collaborative linkage and decision-making play an im-

Table 2 Normalized and TOPSIS values of each node and their ranking

Node	Degree centrality	Betweenness centrality	Closeness centrality	Clustering coefficient	TOPSIS value	Ranking
P_1	0.243 0	0.085 7	0.177 1	0.120 3	0.320 0	8
P_2	0.374 7	0.552 0	0.195 4	0.093 0	0.697 2	1
P_3	0.415 2	0.501 7	0.209 0	0.081 4	0.682 7	2
P_4	0.121 5	0.083 6	0.155 1	0.144 5	0.230 5	21
P_5	0.151 9	0.008 8	0.158 4	0.197 3	0.257 6	18
P_6	0.151 9	0.039 9	0.155 1	0.137 8	0.224 3	23
P_7	0.141 8	0.033 5	0.153 6	0.196 4	0.257 9	17
P_8	0.050 6	0.021 1	0.130 9	0.141 9	0.149 0	35
P_9	0.232 9	0.205 2	0.171 0	0.127 8	0.404 8	5
P_{10}	0.050 6	0.001 7	0.120 4	0.141 9	0.142 9	37
P_{11}	0.182 3	0.023 9	0.165 4	0.165 5	0.263 1	16
P_{12}	0.121 5	0.120 2	0.144 7	0.072 2	0.214 8	26
P_{13}	0.050 6	0.005 9	0.130 9	0.141 9	0.145 1	36
P_{14}	0.131 6	0.292 9	0.144 7	0.220 7	0.467 7	4
P_{15}	0.070 9	0.008 5	0.129 7	0.148 6	0.161 0	33
P_{16}	0.040 5	0.002 0	0.125 4	0.094 6	0.088 4	40
P_{17}	0.070 9	0.006 8	0.133 2	0.054 0	0.077 7	44
A_1	0.162 0	0.124 9	0.156 8	0.141 9	0.289 4	9
A_2	0.091 1	0.019 5	0.142 0	0.141 9	0.171 4	32
A_3	0.172 1	0.050 3	0.167 2	0.115 9	0.235 9	20
A_4	0.141 8	0.146 9	0.158 4	0.123 7	0.282 8	10
A_5	0.121 5	0.061 7	0.153 6	0.043 0	0.160 0	34
A_6	0.050 6	0.002 6	0.133 2	0.085 1	0.085 6	41
A_7	0.263 3	0.143 4	0.175 0	0.093 4	0.362 2	6
A_8	0.172 1	0.112 1	0.160 1	0.129 7	0.280 7	11
A_9	0.101 3	0.053 4	0.144 7	0.126 1	0.180 3	29
A_{10}	0.101 3	0.040 0	0.144 7	0.132 4	0.178 5	30
A_{11}	0.020 3	0.000 0	0.125 4	0.283 8	0.270 3	13
A_{12}	0.101 3	0.197 0	0.132 0	0.078 8	0.279 8	12
E_1	0.091 1	0.006 9	0.136 8	0.157 6	0.181 5	28
E_2	0.162 0	0.060 5	0.158 4	0.175 7	0.269 7	14
E_3	0.101 3	0.027 7	0.147 5	0.181 3	0.217 1	25
E_4	0.131 6	0.096 0	0.153 6	0.134 6	0.239 1	19
E_5	0.070 9	0.024 0	0.147 5	0.094 6	0.119 2	39
E_6	0.050 6	0.019 9	0.126 5	0.028 4	0.050 5	45
E_7	0.040 5	0.000 0	0.129 7	0.141 9	0.140 8	38
M_1	0.111 4	0.004 9	0.153 6	0.239 6	0.266 6	15
M_2	0.030 4	0.000 0	0.111 5	0.378 3	0.339 9	7
M_3	0.151 9	0.023 1	0.156 8	0.152 8	0.228 6	22
M_4	0.172 1	0.023 7	0.167 2	0.106 4	0.219 7	24
M_5	0.050 6	0.004 2	0.129 7	0.085 1	0.084 6	42
M_6	0.101 3	0.135 2	0.144 7	0.056 8	0.209 7	27
M_7	0.050 6	0.005 0	0.118 5	0.170 3	0.172 8	31
M_8	0.060 8	0.000 0	0.123 4	0.075 7	0.080 1	43
M_9	0.141 8	0.358 9	0.150 5	0.141 9	0.489 8	3

portant role in dealing with the emergency or avoiding the deterioration of the situation.

From the perspective of various factors, the pilot factor is the most important causative factor among the human factors. Among them, the flight skills are the key to the safe operation of the aircraft.

The training of flight skills should be strengthened. The landing gear and engine of aircraft are easy to fail, which may lead to unsafe incidents.

The ranking of TOPSIS values of environmental factors is in the middle part, indicating that environmental factors belong to the transitional causative factors, which are the leading causative factors of human factors and the facilities and equipment factors. Moreover, bad weather is the key causative factor to affect the flight safety, and the operation of apron is the key factor to affect the ground safety.

Among the management factors, the effectiveness and timeliness of the emergency response are the key to avoid the serious situation. Besides, the management factors of the airline company are easy to cause human factors, such as: Unreasonable crew scheduling and insufficient crew training.

In sum, the key factors are those nodes with high importance in the network, so dealing with the key factors preferentially can effectively paralyze the network and achieve the purpose of accident prevention.

4 Comparative Analysis

The software, hardware, environment and liveware (SHEL) model, the Reason model and the functional resonance analysis method (FRAM) are classic aviation accident causation analysis models widely applied in the aviation safety field. They are selected to compare with the method proposed in this paper, shown in Table 3.

SHEL and Reason models are very common and mature in the field of aviation accident analysis. They have the characteristics of simple structure and easy operation.

The human-centered characteristics of the SHEL model are consistent with the situation of aviation accidents dominated by human factors. The innovation of Reason model lies in its vision of system view. The causation analysis of the accident is extended from the human factors to the potential organizational factors.

However, these two models are not enough for the analysis of accident causation details, and the dynamic interaction description of various factors is insufficient, so they are not suitable for a lot of accident data analysis. In addition, the analysis objects covered by these two models are not comprehensive enough.

Different from the modular structure of the SHEL model and the chain structure of the Reason model, FRAM and the method proposed in this paper adopt a reticular structure, which has the advantage of being able to analyze the evolution path of the accident and the interrelationship between the causative factors and the propagation mechanism in detail, and the analysis objects covered are more comprehensive.

Compared with SHEL and Reason models, the model structure of complex network theory is more advanced, the dynamic interaction and propagation mechanism between causative factors are much clearer, and the accident analysis is more detailed.

Compared with FRAM, the complex network theory model does not rely too much on expert experiences, and is more suitable for analyzing a lot of accident data at the same time with higher efficiency.

In addition, the new method can identify key factors that cannot be achieved by conventional methods. By controlling the identified key factors, the purpose of accident prevention and control can be effectively achieved.

Therefore, the method of analyzing the causation of aviation accidents based on complex network theory described in this paper has better applicability and advancement.

5 Conclusions

The feasibility of applying complex network theory to analyze aviation accident causation is explored. The conclusions are drawn as follows:

(1) The 45 causative factors from 257 aviation accident investigation reports are selected as network nodes based on the grounded theory, and the causative chain of each accident is established as network edge based on the "2-4" model. Then the aviation accident causation network is constructed for analysis.

Table 3 Comparison of aviation accident causation analysis models

Model	Advantage	Disadvantage	Structure
SHEL	(1) Easy to operate. (2) Taking the human factors as the core, it fits well with the actual situation of the human factors of an aviation accident.	(1) Extension of accident analysis is not enough. (2) It cannot describe the dynamic interaction between humans and other factors in a complex system. (3) Not suitable for statistical analysis of a lot of accident data.	Module
Reason	(1) Easy to operate. (2) It reveals the development process of the accident and highlights the responsibility of the organization in the accident. (3) It analyzes the potential organizational factors that affect human factors in a deeper level, and connects all relevant factors theoretically with a logically unified accident response chain.	(1) Extension of the causative factors analysis is not enough. (2) The linear description of the system cannot describe the dynamic and nonlinear interactions between system components in a complex system. (3) Not include factors outside the organization. (4) Not suitable for statistical analysis of a lot of accident data.	Chain
FRAM	(1) Extension of the accident analysis is sufficient and detailed. (2) The affected objects of the accident analysis are complete and comprehensive. (3) System description has the advantage of being dynamic.	(1) Application process is complex. (2) Relying on specific experts for detailed analysis which leads to low efficiency. (3) Not suitable for statistical analysis of a lot of accident data.	Reticular
Complex network theory	(1) Be able to sort out the context of accidents and the interrelationships and propagation mechanisms of the causation. (2) The accident evolution path is described in the form of system network. The causative factors have both hierarchical and causal relationships. (3) Identify the key causative factors of the accident. (4) It is suitable for statistical analysis of a lot of accident data.	Application process is complex.	Reticular

(2) The topological characteristics of the aviation accident causation network is analyzed. Considering the different characteristics of nodes, the key nodes are identified by the TOPSIS method.

(3) Several aviation accident analysis models are compared and analyzed, and it is concluded that the method proposed in this paper has better applicability and advancement than conventional aviation accident analysis models.

The new method can also analyze the characteristics of different network topologies according to the actual needs of safety management work, and obtain the analysis results of different dimensions.

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Author Dr. **YUE Rentian** received the B.S. degree in industrial engineering and the M.S. degree in safety technology and engineering from Shandong University of Science and Technology, Tai'an, China, in 2000 and 2003, respectively. He received the Ph.D. degree in safety engineering from China University of Geosciences, Beijing, China, in 2008. In 2003, he joined College of Safety Science and Technology, Civil Aviation University of China, as an assistant. In 2009, he joined College of Air Traffic Management, Civil Aviation University of China, as an assistant researcher, and was employed as an associate researcher in 2011. His main research fields are aviation safety, air traffic planning and management, and so on.

Author contributions Dr. **YUE Rentian** designed the research, compiled the model, explained the model results, analyzed the results, and wrote the manuscript. Miss **LI Junwei** provided data and complex network model components. Mr. **HAN Meng** participated in data analysis and manuscript writing. All authors commented on the manuscript draft and approved the submission.

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基于复杂网络理论的航空事故致因分析

岳仁田，李君尉，韩　蒙

（中国民航大学空中交通管理学院，天津 300300，中国）

摘要：为提高航空安全，提出了一种基于复杂网络理论的航空事故致因分析方法。通过选取257份事故调查报告，采用扎根理论的三级编码过程，得到了45个致因因素和9个事故类型，并基于“2-4”模型分析了这些因素之间的相互作用。在此基础上，基于复杂网络理论构建了航空事故致因网络，该网络具有无标度特性和小世界效应，并通过网络拓扑结构分析了致因因素的特征，采用TOPSIS方法识别了事故的关键致因。结果表明，本文提出的方法具有不依赖专家经验、定量分析事故致因因素和统计分析大量事故数据的优点，有较好的适用性和先进性。

关键词：航空安全；事故致因；复杂网络理论；扎根理论；“2-4”模型