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Risk Analysis of Organic Coating Failure on Aluminum-based Aircraft Skin

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Abstract

The coating of aluminum-based aircraft skin can be damaged because of complex flight environment during service, which restricts the sustained aircraft airworthiness and safety operation. The focus of existing studies regarding the field of aircraft surface technology has been on identifying the influencing factors of organic coatings and analyzing the dynamic association patterns between factors. To extract more risk factors for organic coating failures and define their conduction path systematically and comprehensively, the leading research literature related to organic coating failure during 2015-2022 were combed and analyzed first in this study. Then, a total of 14 risk factors that lead to organic coating failure on aluminum-based skin were identified and extracted through the three-stage encoding method of grounded theory. Furthermore, the overall network characteristics, as well as the outdegree, indegree, betweenness centrality, and core-periphery characteristics, were analyzed through the social network analysis (SNA) method. Subsequently, the conduction path of risk factors, the control ability, and their position structure in the risk network was clarified. Results show that the outdegree of environmental risks and external mechanical risks is large, whereas their in-degree is small, indicating that such factors can extremely easily affect other factors in the organic coating failure system. The indegree of coating risks is large, whereas their outdegree is small, manifesting that such factors can be extremely easily affected by other factors, being the factors directly leading to the organic coating failure. The betweenness centrality of maloperation is the largest, reflecting that this factor is of strong control ability as a “bridge” in the organic coating failure system. The conclusion reveals that the SNA method is feasible in analyzing the dynamic association between organic coating failure factors and compensates for the deficiencies of pure experimental measurement means. Moreover, it provides theoretical support to prevent and control organic coating failure scientifically.

Keywords: Skin, Organic coating, Risk factors, Grounded theory

1. Introduction

Aluminum-based skin, an important external structural part of an aircraft, exerts the effect of bearing and transmitting aerodynamic loads [1]. As the aircraft coat, skins directly contact the external environment, and skins or other structural parts are usually combined in an overlapping form. The corrosion problem in the overlapping zone is non-negligible because of the material composition, local crevices, and stress concentration [2]. In the aviation manufacturing industry, organic coatings are extensively used to slow down corrosion. Under the action of multiple factors, such as corrosive media and loads during service, the organic coatings will be subjected to all kinds of physical or chemical performance decays [3], thereby accelerating the failure of the protective performance of the skin and even leading to the crack propagation in it, which causes potential safety risks and endangers flight safety. The preconditions for exploring the failure of organic coating systems and reducing the safety risks of organic coating failures lie in identifying the risk factors for organic coating failures on aluminum-based skins and analyzing the mutual correlations among such factors.

However, existing studies on the risk factors for organic coating failures have mainly concentrated on the organic coating performance evaluation and the failure mechanism under single environmental or environmental/mechanical comprehensive simulation conditions [4-7], whereas little attention has been paid to the systematicness and correlation of risk factors. In the research on the organic coating performance evaluation and the failure mechanism under different influencing factors, the adhesive force, glossiness, corrosion resistance, and electrochemical properties of organic coatings have been characterized using all kinds of simulation experiment sets by various testing means. Since risk factors are complex and varying, exploring the action mechanism of risk factors on organic coatings purely by experimental testing means is extremely challenging. In most of the existing studies on the organic coating failure on aircraft skin, the coating performance decay under different factor simulation conditions has been discussed by experimental means, whereas the critical risk factors that influence the organic coating failure on the skin have been screened scarcely. Meanwhile, the conduction between risk factors has been insufficiently concerned. Hence, the risk factors for organic coating failures were screened out in this research from multiple dimensions, such as organic coating, technology, environment, and external machinery. Then, the network association pattern and the conduction among factors were analyzed. Next, the action mechanism of critical influencing factors on the organic coating failure of skin was explored. This study is of practical guiding significance to probe high-efficiency and low-cost organic coating maintenance deeply.

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2. State of the Art

In the existing studies on organic coating failures, the influences of different factors on the performance of organic coating have been mostly analyzed by combining experimental simulations and performance tests, based on which the hydrolysis mechanism, the photo-oxidation aging degradation mechanism, and the foaming mechanism of organic coatings have been explored [8,9]. In the actual service environment, the performance of organic coatings is comprehensively affected by environmental (e.g., temperature, humidity, salt fog, UV light radiation, etc.) or mechanical factors [10, 11]. Duarte et al. [12] investigated the influences of UV, temperature, pH, humidity, and SO_2 on the behaviors of polyester coating systems through the variation trends of their electrochemical impedance and then pointed out that the degradation effects of different factors on the coating performance are not simply accumulated but mutually collaborated and coupled. Nichols et al. [13] indicated that the stress concentration first occurred at imperfections, and aging resulted in the component change in the coating and the reduction of its fracture energy. When the fracture energy was lower than the critical energy generated by coating cracks, the coating cracked under the stress action, and the crack continued to propagate. Lee [14] assumed that a coating was a line elastomer and calculated its internal residual and thermal stresses through the boundary element method. The results showed that due to the stress at corners and free edges, the coating would crack or peel off, thereby leading to coating failure. Moreover, given the complexity and diversity of the service environment, the risk of organic coating failures is nothing negligible. Chawla et al. [15] systematically analyzed the basic causes for fungus-induced aluminum degradation and corrosion of aircraft coatings layer by layer through the FTA method from two aspects: the presence of fungal biofilms and the fungal attack on the base material. Based on five measurable failure modes, Bigdeli et al. [16] established a comprehensive evaluation model for a drilling coating system using the AHP method and verified its effectiveness through EIS. The laboratory simulation of influencing factors revealed that various factors exerted a coupled action on the performance of the organic coating, but the coupling action mechanism could be hardly revealed purely by experimental testing means. Although risk analysis has been proved to be effective in assisting the experimental means from theoretical and empirical angles, the risk evolution mechanism of organic coating failures remains to be analyzed further.

Most of the existing studies on the organic coating failure of aluminum-based aircraft skin have been carried out starting from a weak point: the organic coating in the overlapping zone. Considering that order differences may be generated on the coating surface in the overlapping zone because of local irregular structural features, the coating is extremely susceptible to erosion and damage in the service process. According to statistics, 85% of coating failures take place in the overlapping zone. Domestic (Chinese) and foreign scholars have begun investigating the effects of environmental and stress factors on coating systems in dissimilar metal overlapping zones. Kotadia et al. [2] investigated the variation trends of the protective performance and mechanical properties of coatings on riveted parts under simulated marine environmental conditions and emphasized that the mechanical properties of riveted parts would be degraded due to coating corrosion. Kamińska et al. [17] evaluated the corrosion process of lap joints of single-sided and double-sided rivets under aging conditions cyclically accelerated by salt fog. Hua [18] reviewed the failure modes, the joint corrosion problem, and optimization techniques of riveted joints and proposed the stress corrosion-induced failure of joints. In addition to environmental and stress factors, galvanic corrosion between dissimilar metals or crevice corrosion has been proven to pose threats to organic coatings in overlapping zones [19, 20]. Karim et al. [21] explored the influences of different rivet coatings on the corrosion behaviors and the strength degradation of riveted joints of different materials. Results showed that the strong galvanic effect among dissimilar metals accelerated the coating corrosion, accompanied by the obvious strength degradation of riveted joints. Studies have shown that besides the conventional influencing factors of organic coatings, the stress of lap joints and the corrosion among dissimilar metals will also trigger the organic coating failure of aluminum-based skin. However, due to the large experimental workload, performing a comprehensive laboratory simulation of factors (e.g., environmental factors), the stress of lap joints, and the corrosion among dissimilar metals, not to mention exploring the interaction laws further among different factors, is difficult.

To sum up, in the present research on the failure of organic coating systems of aluminum-based skin, the influences of environmental factors and mechanical factors on the performance of organic coatings, as well as the failure mechanisms, have been mostly analyzed by means of experimental exploration, but the conduction, superposition, and coupling relations among influencing factors have not been deeply considered. The research on coating failure risks has been carried out mainly from angles of failure causes and organic coating performance risk evaluation, whereas the dynamic relations between risk factors have been less analyzed, not to mention revealing the action mechanism of risk factors and the risk evolution process of organic coating failures.

Directing at the existing research deficiencies, hence, literature analysis and empirical documentation were combined in this research to extract the risk factors of organic coating failures of aluminum-based skin based on grounded theory. Next, a risk factor influence matrix was established through the SNA method, and the dynamic associations between risk factors were explored. Moreover, the conducting power and control ability of risk factors, as well as their position structure in the organic coating failure network, were fully considered. Then, the action mechanism of risk factors on the organic coating was analyzed comprehensively from multiple dimensions, which facilitated the key factor control in the subsequent simulation experiment and the coating maintenance and management.

The remainder of this study was organized as follows: In Section 3, the screening and extraction method of the risk factors for organic coating failures on aluminum-based skin, the influence matrix construction based on SNA, the overall network analysis, and the individual network analysis were expounded. Section 4 presented the result analysis and discussion and pointed out the conduction and control ability of each risk factor in the organic coating failure network. In the last section, relevant conclusions were drawn.

3. Methodology

3.1 Extraction of risk factors for organic coating failures on aluminum-based skin

The organic coating system of aluminum-based skin mainly consists of aluminum substrate-pretreatment film-primary coat-top coat (Figure 1). The laboratory simulation of influencing factors is an important path to explore the failure mechanism of organic coatings [22], while the precondition for the simulation lies in extracting influencing factors. Based on a literature review, the risk factors for organic coating failures of aluminum-based skin were extracted through grounded theory. Grounded theory is a qualitative research method that extracts concepts and categories for the original data analysis, teases the logical relations between categories, and is sublimated into a complete theory [23-24]. This theory completes data analysis and processing through data collection, open coding, axial coding, core coding, and saturability verification (Figure 2). Open coding mainly refers to conceptualizing and categorizing the original data without adding subjective consciousness. Axial coding mainly explores category relations and defines the main category. Core coding mainly aims to analyze the main category and identify the core category.

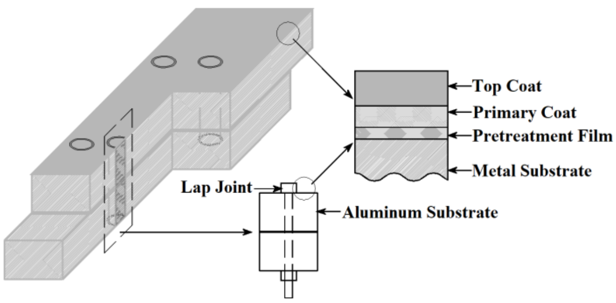

Fig. 1. Schematic diagram of the organic coating system on aluminum-based skin

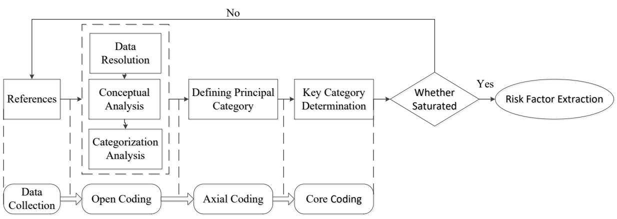

Fig. 2. Schematic diagram of risk factor extraction

3.2 SNA-based risk factor analysis

SNA is used to quantitatively analyze the relations between nodes in a social network structure, as well as the overall structure of the social network composed of nodes and the individual attributes with the help of relation matrices and graph theories [25]. SNA has been proved to be effective and pragmatic in revealing the dynamic associations between risk factors [26-29]. In SNA, the association tightness and connection relations between nodes are judged preliminarily from a macroscopic angle through the overall network analysis. Furthermore, the positions of each node and their driving relations in the network are judged by means of centrality analysis. Specific to the quantified relation data of the organic coating failure system on aluminum-based skin, the SNA method was used to explore the dynamic associations among risk factors and further provide a basis for formulating scientific prevention and maintenance measures for organic coatings on aluminum-based skin based on SNA results.

3.2.1 Establishment of risk network relation matrix

Quantifying the influence relations of risk factors is the foundation for SNA. After identifying the risk factors, the data about the influence relations of risk factors were collected in this research through the Delphi method. With aircraft coating maintenance personnel and experts and scholars dedicated to the field of surface technology as the information acquisition objects, the relations between risk factors influencing the organic coating failures of aircraft were judged and evaluated by relying on expert knowledge and experience, and the concrete data were acquired through a questionnaire survey.

In this research, the relations between risk factors were only considered instead of their values. Hence, the influence data of risk factors were surveyed and calculated through a dual-value matrix. In the influence matrix of risk factors, if the occurrence of "row" did not influence that of "column," then it was expressed by "0." If the influence existed, then it was expressed by "1." In the case of inconsistent opinions among respondents, corrections would be made based on the principle of "the minority is subordinate to the majority," thus obtaining the influence matrix $X=\left(x_{ij}\right)_{n*n}$ of risk factors, where x_{ij} is the direct influence degree of the factor c_i on the factor c_j, and $x_{ij}=0$ when $i=j$.

3.2.2 Overall network analysis

The overall network characteristics are analyzed mainly through network density and block modeling, where the network density denotes the tightness of all risk points in the risk network, as expressed by the formula (1):

$$D\left(G\right)=\frac{S}{N\left(N-1\right)} \tag{1}$$

Where $D\left(G\right)$, S and N stand for the network density, the total number of relations in the risk network, and the number of risk factors in the risk network, respectively.

As for the block model analysis, all risk factors in the directed risk network diagram were divided into mutually independent "blocks" through the CONCOR method. Next, a density matrix was acquired according to the number of real internal relations of each block and the ratio of possible maximum values in blocks. Then, the value was assigned to each block based on the a-density criterion. Furthermore, the connection relations between blocks in the risk network were analyzed through Burt's position division theory [30].

3.2.3 Overall network analysis

Centrality analysis mainly aims to identify the critical risk factors and analyze their conduction mechanisms by measuring the centrality of risk factors in the network. In this research, the centrality measurement was implemented through degree centrality and betweenness centrality.

(1) Degree centrality

Degree centrality denotes the relation tightness between risk factors, which are mainly divided into absolute degree centrality and relative degree centrality.

Absolute degree centrality $\left(C_{AD}\right)$ is the total sum of factors forming direct relations with the same risk factor.

Relative degree centrality (C'_{AD}) refers to the ratio of absolute degree centrality of risk factors to the maximum possible degree among the risk factors, as follows:

$$C'_{AD} = \frac{C_{AD}}{n-1} \tag{2}$$

where n stands for the number of risk factors in the risk network.

In the directed graph, degree centrality is divided into outdegree and indegree, where the former represents the number of direct relations sent by a risk factor, and the latter expresses the number of direction relations entering this risk factor. The conduction of risk factors can be revealed by analyzing the outdegree and indegree of each risk factor.

(2) Betweenness centrality

Betweenness centrality denotes the ability of a risk factor to control the relations of other risk factors, namely, the degree of betweenness of this risk factor between other risk factors to investigate its bridging effect, as below:

$$C_{ABi} = \sum_j^n \sum_k^n b_{jk}(i) = \sum_j^n \sum_k^n \frac{g_{jk}(i)}{g_{jk}}, i \neq k \neq I, j < k \tag{3}$$

where $b_{jk}(i)$ is the ability of the point i to control the interaction between points j and k ; $g_{jk}(i)$ denotes the number of shortcuts that pass through point i between points j and k ; g_{jk} stands for the total number of shortcuts between points j and k; and I is a unit matrix.

3.2.4 Overall network analysis

The core-edge structure is a special structure constituted by the mutual relations of several risk factors, which are featured by a tightly connected center and loose and dispersive periphery [31]. The core degree index reflects the relation tightness between risk factors in the network and measures the important position of risk factors. In this research, the core-edge structural analysis was implemented using the positive correlation-type data of the core-edge discrete model and the CORR algorithm based on the influence matrix data of risk factors. Moreover, the differences between the actual model and the ideal model were tested by comparing the initial fitted value and the terminal fitted value.

4. Results Analysis and Discussion

4.1 Risk factor extraction

A total of 58 related core kinds of literature were collected by inputting keywords, such as “skin,” “organic coating,” “failure,” “influencing factor,” and “risk,” in databases, including CNKI, Scopus, Web of Science, and Elsevier, among which 48 were original data information for coding analysis. Then, failure risk factors were extracted preliminarily by means of "three-stage coding" followed by the verification of result saturability with 10 remaining literature. Concrete grounded theory analysis was carried out via the NVIVO 11 software package in three stages: open coding, axial coding, and core coding.

Disordering was performed to document literature related to organic coating failures. The statements associated with organic coating failures were reserved after reading and organizing. Next, open coding influencing the organic coating performance was identified preliminarily through analysis and summarization, which was divided into 28 categories, including laboratory simulation experiment, the influence of corrosive media, lighting, temperature, humidity, color change, bulging, fissurization, efflorescence, crevice corrosion, sealing failure at lap joints, impact failure, shattering effect, alternate load effect, and galvanic corrosion.

In the axial coding stage, the categories related to the same category were searched each time. For instance, “radiation, temperature, and water” were chosen as the axis, and they corresponded to “high temperature and humidity,” “high-temperature difference,” “high radiation,” “UV irradiation,” “high-temperature damage,” “humid and hot environment,” “marine atmospheric environment,” “industrial atmospheric environment,” and “sunlight,” which, therefore, were classified into the same category. By parity of reasoning, the 28 categories obtained through axial coding and open coding were reduced to 14 main categories, namely, coating’s mechanical property degradation coating surface appearance changes, degradation of coating environmental adaptability, collocation error for coating system, improper selection of metal substrates, coating process error, skin lap technique, inappropriate maintenance, climatic environment, chemical environment, induced environment, fatigue load, abrasion, and vibration.

Based on the systematicness of organic coating system composition on the aluminum-based skin (Figure 1), the core categories were identified from perspectives of failure-related factors and the whole life cycle according to the idea of grounded theory. It could be known from the organic coating system composition on the aluminum-based skin that the coating failure-related factors included aluminum substrate, dissimilar metal overlapping zone, and coating. In full consideration of the environment and operating conditions, the 14 main categories were mainly classified into 4 types, namely, coating risk, technical risk, environmental risk, and external mechanical risk, which were numbered in Table 1. The grounded theory analysis was repeated with the 10 remaining references and compared with the above results, without adding or changing conclusions, thereby proving the saturation of the above-grounded theory analysis results.

4.2 Risk network analysis results

4.2.1 Establishment of risk network relation matrix

The organic coating failure on the aluminum-based skin was a complex system, and the identified risk factors were mutually coupled. To acquire the influence relations of risk factors, a questionnaire was designed in the form of an influence relation matrix of risk factors using the Delphi method in this research. A total of 30 questionnaires were distributed, and 24 valid ones were recovered. Through a comprehensive analysis of expert opinions, the influence matrix $X = (x_{ij})_{14\times14}$ (Table 2) of risk factors was acquired based on the principle of “the minority is subordinate to the majority”, where $x_{13} = 1$ indicated that coating’s mechanical property degradation (R1) would have a bearing on the degradation of coating environmental adaptability (R3); $x_{51} = 0$ reflected that coating’s mechanical property degradation(R1) was free from the influence of improper selection of metal substrates (R5). It could be known from Table 2 that this influence matrix of risk factors belonged to a dual-value asymmetric matrix, namely, the constructed risk network was directed.

Table 1. List of risk factors extracted

Classification	Risk Factor
Coating Risk	Coating's Mechanical Property Degradation R1 Coating Surface Appearance Changes R2 Degradation of Coating Environmental Adaptability R3
Technical Risk	Collocation Error for Coating System R4 Improper Selection of Metal Substrates R5 Coating Process Error R6 Skin Lap Technique R7 Inappropriate Maintenance R8
Environmental Risk	Climatic Environment R9 Chemical Environment R10 Induced Environment R11
External Mechanical Risk	Fatigue Load R12 Abrasion R13 Vibration R14

Table 2. Influence matrix of risk factors

X	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
R1	0	0	1	0	0	0	0	1	0	0	0	0	0	0
R2	0	0	1	0	0	0	0	1	0	0	0	0	0	0
R3	0	0	0	0	0	0	0	1	0	0	0	0	0	0
R4	1	1	1	0	0	0	0	0	0	0	0	0	0	0
R5	0	0	1	0	0	0	1	0	0	0	0	0	0	0
R6	1	0	1	0	0	0	0	1	0	0	0	0	0	0
R7	1	0	1	0	0	1	0	0	0	0	0	0	0	0
R8	1	1	1	0	0	1	0	0	0	0	1	0	0	0
R9	1	1	1	0	1	1	0	1	0	1	1	1	1	0
R10	1	1	1	0	0	1	0	1	1	1	1	0	0	0
R11	1	1	1	0	0	0	0	1	0	1	0	0	0	0
R12	1	1	1	0	0	0	0	1	0	0	1	0	0	0
R13	1	1	1	0	0	0	0	1	0	0	0	0	0	0
R14	1	1	1	0	0	0	0	1	0	0	1	1	0	0

4.2.2 Overall characteristic analysis of risk network

The overall network density of the organic coating failure risk factor network for the aluminum-based skin was calculated as 0.3187 via UCINET software. Such value indicates relatively evident interactions between risk factors leading to organic coating failures. To contribute to a clearer overall network structure, the nodes in the risk network were further classified through the "block model" method, with the concrete block modeling results seen in Figure 3 and the density matrix seen in Table 3. With the overall network density value combined, the values greater than 0.3187 in the density matrix was replaced by "1," and those smaller than 0.3187 by "0," thus obtaining a block model image matrix (Table 4). According to Burt's position division theory, blocks 1 and 2 could not only send relations but also accept relations, both of which showed internal relations, manifesting that blocks 1 and 2 were at critical positions in the network. Meanwhile, the relations accepted by blocks 1 and 2 were greater than those sent by them, indicating that the risk factors in the two blocks were at influenced positions. That is, risk factors, such as R1, R2, R3, R6, R8, and R11, could be more easily affected by other risk factors, thereby leading to the risk of organic coating failures. Blocks 3 and 4 only sent relations while not accepting relations, manifesting that such risk factors (e.g., R4, R5, R7, R9, R10, R12, R13, and R14) generally sent relations outward, and it could easily result in the occurrence of other risk factors.

4.2.3 Centrality result analysis of risk factors

In the directed network diagram, the conduction direction of risk factors was explored through the outdegree and indegree analyses of the degree centrality of risk factors. The conduction path of risk factors generally extended from the nodes with a great outdegree to those with a great indegree. The outdegree and indegree of risk factors for organic coating failures on the aluminum-based skin were calculated using UCINET software (Table 5). The outdegree of R9 was the greatest, indicating that the climatic environment could directly lead to the occurrence of other risk factors, which play a dominant position in the network and belong to initial risk source; the indegree of R3 was the greatest, manifesting that the coating's environmental adaptability was the most susceptible to the influence of other factors.

In general, the risk factors with great outdegree and small indegree would result in the occurrence of risk factors with small outdegree and great indegree. To express the conduction direction of risk factors more intuitively, the outdegree–indegree coordinate graph of risk factors was drawn, as shown in Figure 4, where arrows indicate the conduction directions of risk factors. R9, R10, R11, R12, and R14 at the upper left of Figure 4 had great outdegree and small indegree, thereby belonging to spontaneous risk factors and serving as the starting point and the source of organic coating failures on the aluminum-based skin.

Table 3. Risk network density matrix

	Block 1	Block 2	Block 3	Block 4
Block 1	0.333	0.333	0.000	0.000
Block 2	0.889	0.667	0.056	0.000
Block 3	1.000	0.611	0.167	0.083
Block 4	0.500	0.167	0.000	0.500

R1, R2, and R3 at the lower right of Figure 4 had great indegree and small outdegree, thereby belonging to passive risk factors, which could be generally considered the consequences triggered by other risk factors and as the risk factors most directly related to organic coating failures on the aluminum-based skin.

At the upper right of Figure 4, R8 showed great outdegree and indegree, manifesting that such risk factors would not only result in the occurrence of other factors but could also be easily impacted by other factors, thus being the key prevention and control objects of organic coating failures on the aluminum-based skin.

Betweenness centrality aimed to measure the ability of a risk factor to control other risk factors and conduction. The betweenness centrality results of risk factors for organic coating failures on the aluminum-based skin are listed in the third column of Table 5. The calculation results suggest that the betweenness centrality of R8 was the greatest, followed by that of R11, indicating that the two risk factors belonged to advantageous individuals in the risk network with a stronger control ability for other risk factors and a more obvious bridging effect in risk conduction.

According to the conduction and control action of risk factors in the network, environmental risks and external mechanical risks belonged to root risk factors that lead to organic coating failures on the aluminum-based skin. Therefore, environmental and external mechanical risks should be watched strictly, and the organic coating maintenance management should be strengthened to block or reduce the conduction of such risk factors to coating risk factors and enhance the management and control ability for organic coating failures on the aluminum-based skins.

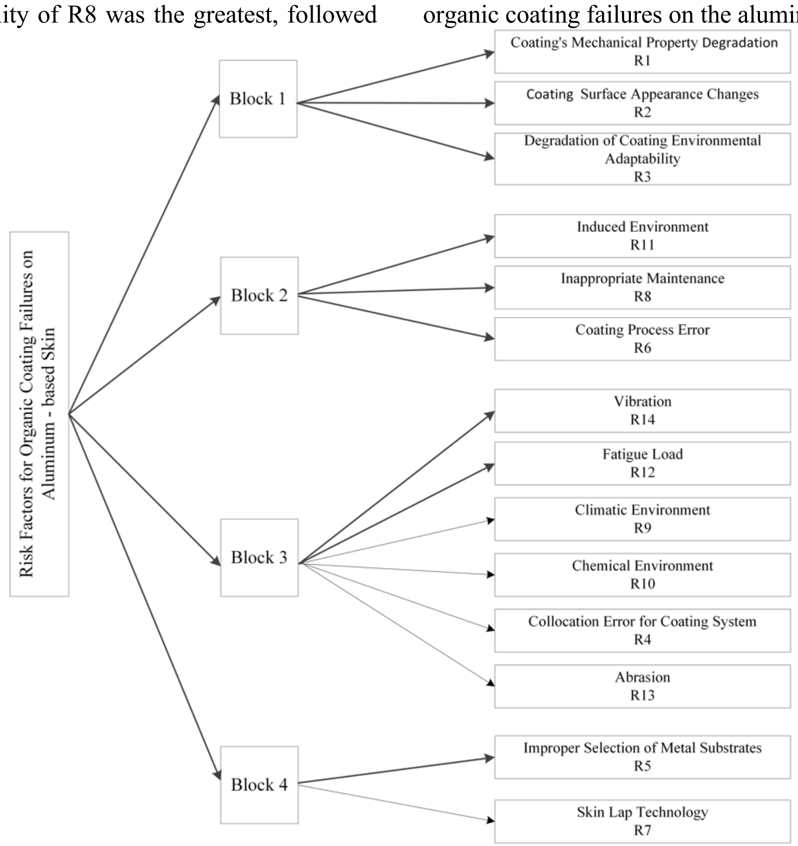

Fig. 3. Block diagram of risk factors

Table 4. Image matrix of risk network block model

	Block 1	Block 2	Block 3	Block 4	Relations Sent	Self-relation
Block 1	1	1	0	0	1	1
Block 2	1	1	0	0	1	1
Block 3	1	1	0	0	2	0
Block 4	1	0	0	1	1	1
Relations Accepted	3	2	0	0		
Self-relation	1	1	0	1		

Table 5. Centrality analysis results of risk factors

Risk Factor	Outdegree	Indegree	Betweenness
Coating’s Mechanical Property Degradation R1	2	10	5.667
Coating Surface Appearance Changes R2	2	8	3.000
Degradation of Coating Environmental Adaptability R3	1	13	12.667
Collocation Error for Coating System R4	3	0	0.000
Improper Selection of Metal Substrates R5	2	1	12.000
Coating Process Error R6	3	4	2.667
Skin Lap Technique R7	3	1	2.000
Inappropriate Maintenance R8	5	10	66.500
Climatic Environment R9	10	1	46.000
Chemical Environment R10	7	2	54.500
Induced Environment R11	5	5	60.000
Fatigue Load R12	5	2	0.000
Abrasion R13	4	1	0.000
Vibration R14	6	0	0.000

4.2.4 Core-edge result analysis

The connection tightness of risk factors for organic coating failures on the aluminum-based skin was analyzed through the core-edge discrete model in UCINET software. Then, the core risk factors were identified by dividing the core area and edge area and combining the risk network block model analysis and the risk factor centrality analysis. The core-edge analysis results are presented in Table 6. The analysis results show that the density of risk factors in the core area was 0.571, indicating a tight connection, whereas that in the edge area was 0.067, manifesting a loose connection. With the block model and the comparative centrality analysis combined, most risk factors in the core area had a great outdegree or indegree, R6 was in block 2, which not only accepted relations but also sent relations. Hence, it also belonged to the core area.

Table 6. Classification of core-edge position

Type	Risk factor	Density
Core area	R1 R2 R3 R6 R8 R9 R10 R11	0.571
Edge area	R4 R5 R7 R12 R13 R14	0.067

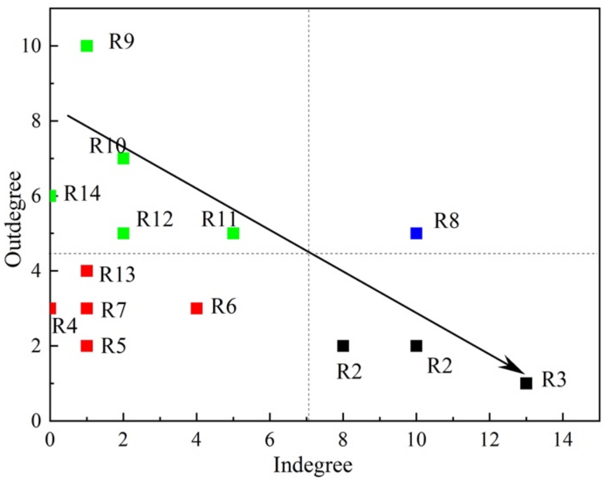

Fig. 4. Conduction diagram of risk factors

The outdegree, indegree, and betweenness centrality analyses of risk factors were taken as the criterion for measuring the node size in the network diagram, and a risk network model was drawn (Figure 5). Comparisons show that environmental risks R9, R10, and R11 could affect other risk factors with a stronger risk conducting power more easily. Coating risks R1, R2, and R3 could be influenced more easily by other risk factors, and R8 showed a stronger risk control ability. With the core-edge analysis results combined, the critical risk factors for organic coating failures on the aluminum-based skin were mainly related to environmental risks, coating risks, and maintenance management, specifically including R1, R2, R3, R9, R10, R11, and R8. Hence, environmental factors are the root factors that influence the organic coating performance on the aluminum-based skin. Maintenance management is an effective means of guaranteeing the organic coating performance, and the organic coating performance guarantee is the key to the sustained airworthiness of organic coatings on the aluminum-based skin. Meanwhile, this further proves the importance of environmental factors in the study on organic coating failure mechanisms.

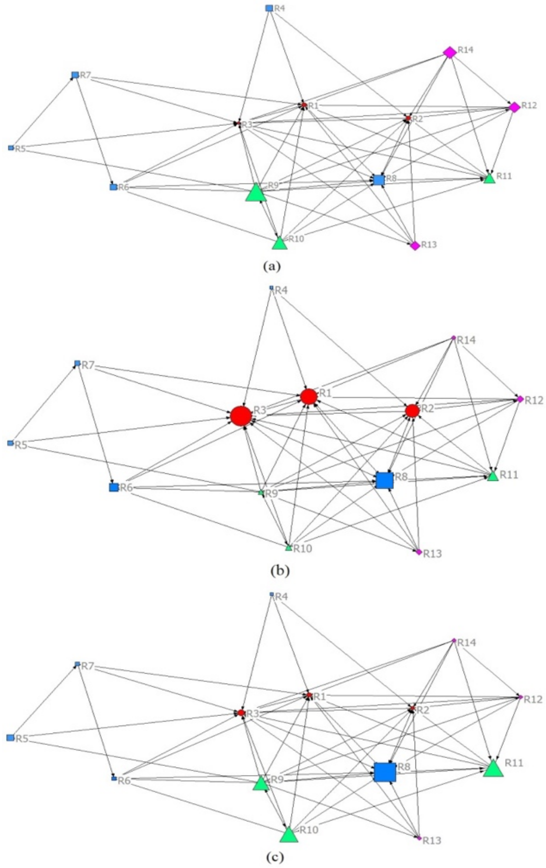
Fig. 5. Risk network model: (a) outdegree; (b) indegree; (c) betweenness centrality

5. Conclusion

Directing at the risk factors for organic coating failures on the aluminum-based skin and their dynamic associations, the set of risk factors was extracted on the basis of the original references using grounded theory and the SNA method. Next, the conduction between risk factors and the control ability was analyzed, and the critical risk factors of organic coating failures were determined. The conclusions were drawn as follows:

(1) The organic coating failure mechanism of aluminum-based skin is a complex system under the multi-factor coupling action. Through the coding program based on grounded theory, the risk factors were extracted from core references, thereby compensating for the incomprehensive risk factors for organic coating failures in existing research and providing an effective path to test the influencing factors of organic coating failures systematically.

(2) The structural characteristics of the risk network were defined more objectively from two dimensions (e.g., overall and individual) by means of the SNA block model and core-edge analyses to identify the critical risk factors for organic coating failures on the aluminum-based skin and lay a foundation for exploring the deep relations among risk factors.

(3) The conduction path and control ability of risk factors could be identified on the basis of the degree centrality and betweenness centrality analysis of the directed SNA model. Climatic environment, chemical environment, induced environment, fatigue load effect, and vibration belong to root risk factors, whereas inappropriate maintenance shows a strong control ability, serving as a "bridge" in the risk network. This research comprehensively

reveals the threats of environmental factors to organic coatings and their importance to coating maintenance management.

In short, when applied to the risk factor analysis for organic coating failures on the aluminum-based skin, the SNA method can help identify the conduction path of risk factors and their action mechanisms in the risk network, formulate pertinent prevention and control measures within the whole life cycle of organic coatings, provide a basis for the maintenance of organic coating failures on the aluminum-based skin, and enhance maintenance efficiency.

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References

1. Grbović, A., Sedmak, A., Kastratović, G., Petrašinović, D., Vidanović, N., Sghayer, A. "Effect of laser beam welded reinforcement on integral skin panel fatigue life". *Engineering Failure Analysis*, 101, 2019, pp.383-393.
2. Kotadia, H. R., Rahnama, A., Sohn, I. R., Kim, J., Sridhar, S. "Performance of dissimilar metal Self-Piercing Riveting (SPR) joint and coating behaviour under corrosive environment". *Journal of Manufacturing Processes*, 39, 2019, pp.259-270.
3. Lyon, S. B., Bingham, R., Mills, D. J. "Advances in corrosion protection by organic coatings: What we know and what we would like to know". *Progress in Organic Coatings*, 102, 2016, pp.2-7.
4. Sun, W., Xing, C., Tang, X., Zuo, Y., Zhao, X. "Comparative study on the degradation of a zinc-rich epoxy primer/acrylic polyurethane coating in different simulated atmospheric solutions". *Journal of Coatings Technology and Research*, 18(2), 2020, pp.397-413.
5. Feickert, A. J., Croll, S. G. "Failure of coatings over joints and gaps: finite-element models". *Journal of Coatings Technology and Research*, 15(2), 2017, pp.281-291.
6. Szociński, M., Darowicki, K. "Performance of organic coatings upon cyclic mechanical load". *Progress in Organic Coatings*, 146(6), 2020, pp. 105718.
7. Shreepathi, S., Naik, S., Vattipalli, M. R. "Water transportation through organic coatings: Correlation between electrochemical impedance measurements, gravimetry, and water vapor permeability". *Journal of Coatings Technology and Research*, 9(4), 2012, pp.411-422.
8. Williams, G., Kousis, C., Mcmurray, N., Keil, P. "A mechanistic investigation of corrosion-driven organic coating failure on magnesium and its alloys". *npj Materials Degradation*, 3(1), 2019, pp.1-8.
9. Prošek, T. "Mechanisms of degradation of organic coatings". *Corrosion and Material Protection Journal*, 61(4), 2017, pp.155-161.
10. Chemin, A. E. A., Saconi, F., Bose Filho, W.W., Spinelli, D., Ruchert, C. O. F. T. "Effect of saline corrosion environment on fatigue crack growth of 7475-T7351 aluminum alloy under TWIST flight loading". *Engineering Fracture Mechanics*, 141, 2015, pp.274-290.
11. Silva, T., Mallarino, S., Touzain, S., Margarit-Mattos, I. "DMA, EIS and thermal fatigue of organic coatings". *Electrochimica Acta*, 318, 2019, pp.989-999.
12. Duarte, R. G., Castela, A. S., Ferreira, M. G. S. "Influence of ageing factors on the corrosion behaviour of polyester coated systems: A EIS study". *Progress in Organic Coatings*, 59(3), 2007, pp.206-213.
13. Nichols, M. E. "Anticipating paint cracking: the application of fracture mechanics to the study of paint weathering". *Journal of Coatings Technology*, 74(924), 2002, pp.39-46.
14. Lee, S. S. "Analysis of interface crack in polymer liner subjected to hygrothermal stress". *Key Engineering Materials*, 324, 2006, pp.1249-1252.
15. Chawla, S., Payer, J., Giai, C. "Fault tree analysis for fungal corrosion of coated aluminum". *Corrosion*, 70(11), 2014, pp.1101-1113.
16. Bigdeli, F., Javidi, M., Pakshir, M., Khezrloo, A., Tayebi, M. "Risk assessment of the corrosion resistance performances for epoxy coatings under drilling environments using AHP method". *International Journal of Pressure Vessels and Piping*, 193, 2021, pp.104470.
17. Kamińska, P., Synaszko, P., Ciak, P., Dragan, K. "Analysis of the corrosion resistance of aircraft structure joints with double-sided rivets and single-sided rivets", *Fatigue of Aircraft Structures*, 12, 2020, pp.57-68.
18. Hua, Q. A. "An Overview of Self-piercing Riveting Process with Focus on Joint Failures, Corrosion Issues and Optimisation Techniques". *Chinese Journal of Mechanical Engineering*, 34, 2021, pp.2.
19. Shaik, L. A., Thamida, S. K. "Studies on galvanic corrosion of tri-metallic joint of steels in sodium chloride solution". *Materials Today: Proceedings*, 15(1), 2019, pp.57-62.
20. Mandel, M., Krüger, L. "Determination of pitting sensitivity of the aluminium alloy ENAW-6060-T6 in a carbon-fibre reinforced plastic/aluminium rivet joint by finite element simulation of the galvanic corrosion process". *Corrosion Science*, 73, 2013, pp.172-180.
21. Karim, M. A., Bae, J.-H., Kam, D.-H., Kim, C., Choi, W.-H., Park, Y.-D. "Assessment of rivet coating corrosion effect on strength degradation of CFRP/aluminum self-piercing riveted joints". *Surface & Coatings Technology*, 393, 2020, pp.125726.
22. Yong, X., Hu, X., Lin, J., Ma, Q., Chen, R. "Damage assessment of the corrosion-resistant performances for organic coating systems after accelerated tests using analytic hierarchy process". *Engineering Failure Analysis*, 93, 2018, pp.1-12.
23. Holt, N. L., Pankow, K., Ormond, I., Jørgensen, H., Deal, C. J., Pynn, S. R. "Grounded theory". *International Review of Sport and Exercise Psychology*, 15(1), 2022, pp.199-225.
24. Xu, R., Luo, F., Chen, G., Zhou, F., Abdulahi, E. W. "Application of HFACS and grounded theory for identifying risk factors of air traffic controllers' unsafe acts". *International Journal of Industrial Ergonomics*, 86, 2021, pp.103228.
25. Guo, X., Niu, L., Guan, H. "The mechanism of crowd stampede based on case statistics through SNA method". *Technical Gazette*, 28(2), 2021, pp.548-555.
26. Ongkowijoyo, C., Doloi, H. "Determining critical infrastructure risks using social network analysis". *International Journal of Disaster Resilience in the Built Environment*, 8(1), 2017, pp.5-26.
27. Nunes, M., Abreu, A. "Applying social network analysis to identify project critical success factors". *Sustainability*, 12(4), 2020, pp.1-32.
28. Khoshsabegheh, H. Y., Ardalan, A., Takian, A., Hedayatifar, L., Saeedi, B. "Social network analysis for implementation of the sendai framework for disaster risk reduction in Iran". *Society for Disaster Medicine and Public Health*, 2021, pp.1-9. doi:10.1017/dmp.2021.167
29. Ciarapica, F. E., Bevilacqua, M., Antomarioni, S. "An approach based on association rules and social network analysis for managing environmental risk: a case study from a process industry". *Process Safety and Environmental Protection*, 128, 2019, pp.50-64.
30. Burt, R. S. "Positions in networks". *Social Forces*, 55(1), 1976, pp.93-122.
31. Rombach, P., Porter, M. A., Fowler, J.H., Mucha, P.J. "Core-periphery structure in networks". *Society for Industrial and Applied Mathematics*, 59(3), 2017, pp.619-646.