Application of BOWTIE Model in Safety Management System of Civil Aviation Maintenance Enterprises

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***Abstract*—Safety risk model is helpful for systematically analyzing and evaluating the safety risk status of an enterprise, and is an important part of establishing a safety management system. Based on the BOWTIE model and the characteristics of civil aviation maintenance enterprises, this paper establishes the BOWTIE safety risk model of civil aviation maintenance enterprises, and verifies the model by applying the historical data of general accident symptoms in China's civil aviation maintenance industry.**

Keywords—BOWTIE, Maintenance, Safety Management System

I. INTRODUCTION

In order to ensure the safety of civil aviation operation, it is urgent to continuously improve the management level of civil aviation maintenance enterprises. Consequently, the safety management system, as a means of self-improvement and self-promotion of civil aviation maintenance enterprises, has been widely used in maintenance enterprises.

The safety management system is a set of system practices for managing safety. The ultimate goal of building a safety management system is to achieve safe and efficient operation of the enterprise. According to ICAO documents, the safety management system consists of the following four components and 12 elements:

- Safety Policies and Objectives: management commitment and responsibility, safety accountability, appointment of key safety personnel, coordination of emergency plan, documentation of safety management system.
- Safety Risk Management: identification of hazards, safety risk assessment and mitigation measures.
- Safety Assurance: safety performance monitoring and measurement, management of change, continuous improvement of safety management system.
- Safety Promotion: training and education, safety communication[1].

The effective operation of the safety management system requires the synergy of the various components. Risk management is an important part of making the safety management system work and different from other management systems. In many organizations, because of the lack of effective risk prevention and control, some of the consequences caused by accidents are too costly. Therefore, measures must be taken to manage them. It is wise to prepare for “one size fits all”: imagine possible Risks and assess the readiness of the organization's response.

Traditional risk assessment methods generally use quantitative tools for risk calculation. These methods are applicable to certain types of devices, but do not make much sense for organizational risk assessment. Human prediction is less than machine, and various factors (human thoughts, equipment, time, weather, organizational factors, etc.) interact in the operation process, making prediction more difficult. To make accurate predictions about the future in a complex environment like the world, the probability is almost zero. In more complex operating systems, risk analysis is influenced by people and organizations. Even if the same device is installed, it may have different failure rates when installed in different companies. How to deal with facilities and processes, and how operators and managers make decisions cannot be quantified. The management of civil aviation maintenance enterprises has the above-mentioned complex characteristics, which makes its risk assessment and management difficult to implement, and greatly weakens the role of the safety management system.

The BOWTIE model is a method for qualitative risk analysis of complex operating environments and has been widely used in accident analysis in petroleum and chemical industries. Compared with the traditional risk assessment method, the BOWTIE model has an incomparable advantage in organizational risk assessment. It combines the event tree, the accident tree and the cheese model, and can analyze and evaluate the risks in management more comprehensively and intuitively. Although the application of BOWTIE model in the safety management of civil aviation maintenance enterprises is still in its infancy, its advantages in organizational risk analysis make the safety management system working highly feasible.

II. BOWTIE MODEL

BowTie analysis is a method of risk analysis in the form of bows, mainly including fault tree analysis, event tree analysis and Swiss cheese model. BowTie analysis takes top-level events as its core, analyses the possible causes (fault tree analysis) leading to the occurrence of top-level events forward, analyses the possible follow-up events (event tree analysis) after the occurrence of top-level events backward, and then sets up barriers to prevent and control (Swiss cheese model). Refer to Fig.1.

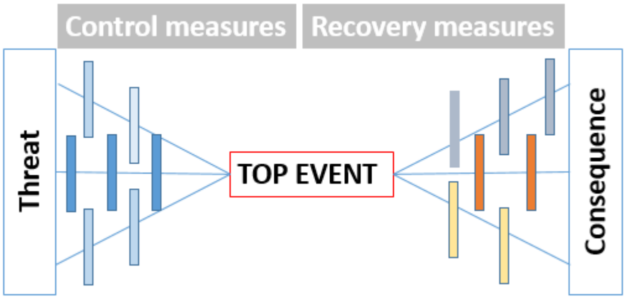

Fig. 1 BowTie Schematic Diagram

Note: The intermediate node is the top event, the left side is the threat (the possible cause of the top event), the right side is the consequence (the possible follow-up event after the top event occurs), and the barrier is set between the threat and the top event, the top event and the consequence for Risk prevention and control (control measures and recovery measures, respectively).

The fault tree analysis focuses on logically analyzing the cause of the accident, not involving its possible consequences and measures; the event tree focuses on analyzing the derivative consequences after the event, not paying attention to why, what went wrong and how to control it. The Swiss cheese model is only at the level of theory and thinking and has not been implemented in risk control. The BowTie method combines the strengths of the three to enable qualitative risk analysis of complex work environments[2]. Combining the BOWTIE model with event analysis provides a quantitative reference for qualitative risk analysis and improves the feasibility of this method.

The BOWTIE model analyses risks from the relationships among hazards, top-level events, threats and consequences. Barriers are used to indicate what measures the organization has taken to control risks. Refer to Fig.2, elements in the BOWTIE model are defined as follows:

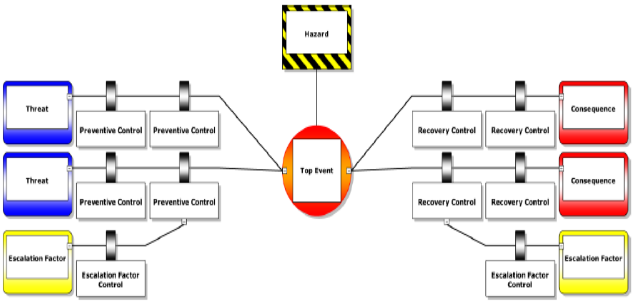

Fig. 2 BowTie Analysis Structure Diagram

Hazards: refers to the source, state or behavior, or combination thereof, that may lead to personal injury and/or health damage or property loss[3].

Hidden dangers: refers to the violation of safety production laws, regulations, rules, standards and orders of safety production management by production and business units, or dangerous state of the object, unsafe behavior of people and management defects that may cause accidents due to other factors in production and business activities. Hidden dangers are defects or loopholes that are formed after the failure of risk management[4].

Top Event: Time node for failure of hazard control. Top events are not yet catastrophic, but they are the first in a series of adverse events.

Threats: Possible causes of top-level events.

Consequences: Accidents caused by top-level events.

Barrier: Measures to prevent or mitigate incidents. An active barrier is a measure taken to prevent a hazard from triggering a top event. A passive barrier is a measure taken to prevent adverse consequences from top events.

Disturbance factor: The state or condition or factor that reduces or interferes with the effectiveness of barriers[2].

III. The Basis of the Application of BOWTIE Model in Civil Aviation Maintenance Enterprises

With reference to the definition of safety in Annex 19 of ICAO, the safety management objective of the maintenance enterprise is to reduce and control the safety risks associated with aircraft operations caused by maintenance to an acceptable level.

Maintenance enterprise's maintenance and support work for aircraft mainly includes three aspects:

- Based on the initial certification basis of the aircraft, ensure that personnel and organizations perform organized maintenance and support work in accordance with the approved technology to ensure the safe operation of the aircraft.
- Carry out reliability monitoring of aircraft and its components.
- Gather design and manufacture problems in the aircraft and its components during operation, and urge the designer and manufacturer to improve.

Maintenance enterprise management mainly involves five elements, such as facilities, tools/equipment, materials, personnel and technical data, and five systems, such as quality system, training system, production system, engineering system and safety management system.

Maintenance is an extension of aircraft design and manufacture, which is technically dependent on design and manufacture. Maintenance enterprises mainly ensure the safety of aircraft operation through the management of elements and systems. The root cause of safety accident caused by maintenance is the problems existing in the various elements and in the management of each element. Therefore, maintenance-related risk assessment and event analysis mainly focus on the analysis and evaluation of enterprise management elements and their interaction.

Normally, problems in the reliability of aircraft and its components and the design of aircraft belong to designer and manufacturer. Therefore, in general, the unsafe incidents caused by them are not in the scope of maintenance, but the maintenance enterprises also undertake the reliability management and the tracking of design problems. Responsibilities, therefore, improper reliability management and improper tracking of design issues lead to unsafe incidents, still need to be attributed to the scope of maintenance.

In maintenance enterprises, aircraft operation events caused by errors in maintenance management involve many levels, such as accidents, accident symptoms, unsafe events and maintenance errors.

According to the rules and relevant management requirements of the maintenance industry, at present, the safety information of the maintenance industry mainly includes: Service Difficulty Report, unsafe incident report, Defect and Unairworthiness Conditions, warranty claims, customer complaints, and problems found in the audit. Safety information may be reported according to the requirement by the enterprise or voluntarily reported. Maintenance enterprises have accumulated a large amount of safety information, which makes systematically safety information analysis possible.

IV. Establishment of BOWTIE Safety Risk Model for Civil Aviation Maintenance Enterprises

A. BOWTIE Safety Risk Model

The main activity of the maintenance company is aircraft maintenance. Incorrect maintenance behavior will bring safety risks to the aircraft. Therefore, this maintenance behavior can be regarded as a hazard of aircraft, which leads to the top-level event that is the first in a series of events after aircraft maintenance runs out of control, that is, maintenance errors. If not properly controlled,, maintenance errors may have certain consequences. The severity of the consequences usually includes several levels of major accidents, general accidents, severe accident symptoms, general accident symptoms and general unsafe events. Based on the characteristics of the maintenance enterprises, all maintenance activities are based on five elements: facilities, personnel, tools, equipment, technical data, etc. The correct maintenance activities are based on five elements and comprehensive management of the five elements. Therefore, we can regard the five elements and their relationship as threats in the scenario of hazard maintenance activities, and use the management for hazard and threats as barriers to establish a safety risk management model for aircraft maintenance/maintenance errors. In the process of establishing a threat, reference is also made to the classification of threats used in general: people, equipment, environment, cross-operation, and SHELL classification: people, hardware, environment, and software[5][6]. The threat of aircraft maintenance/maintenance errors is finally defined as follows:

- Human: There may be problems in people's physical or psychological factors, and barrier measures should be set up separately.
- Hardware: It can also be divided into two threats: aircraft and technical data. It is necessary to identify the possible problems and barrier measures separately.
- Environment: It can also be divided into three threats: tools/equipment, materials and facilities. It is necessary to identify the possible problems and barrier measures respectively.
- Software: There may be problems in maintenance control, training, responsibility and authority management, corporate culture and other issues, and barrier measures should be set up separately.
- Interface: There may be problems in customer interface management, outsourcing work management, human-hardware interface, human-human interface, human-software interface and so on. Barrier measures should be set up separately.

After the maintenance errors occur, in order to avoid the consequences, it is necessary to take preventive and mitigation measures. For system failure, perform test. For structural damage, structural inspection are carried out. At the same time, emergency control need to be set up separately.

Refer to Fig.3 for the final BOWTIE risk model for aircraft maintenance/maintenance errors.

In the BOWTIE safety risk model of maintenance enterprise, the barrier of each threat may include the following contents:

- Requirements of enterprise management;
- Enterprise procedures;
- Task.

In general, for each threat, enterprises have a number of barriers such as requirements, procedures and tasks to control. Enterprises can predict risks according to the current management level of each barrier. Because of the complexity of management system, it is still difficult to evaluate risk based on this model alone.

B. Quantitative reference value of safety risk assessment

Although the BOWTIE safety risk model provides a good means for enterprise safety risk analysis and evaluation, there are still some difficulties in relying solely on the BOWTIE model for safety risk assessment. Since the BOWTIE safety risk model has visually reflected the relationship among threats, hazards and events in specific hazard/top event scenarios, we can first use the model for event analysis and use the quantitative results of event analysis for risk prediction.

Refer to the risk model in Fig. 3 to define the safety risk of aircraft maintenance/maintenance errors as R. Each maintenance error corresponds to a consequence level, which is usually divided into: major accident, general accident, serious accident symptom, general accident symptom and general unsafe event. The consequences are assigned to C_5, C_4, C_3, C_2, C_1 according to the level. If during a certain period of time, the total number of flight take-off/landings is N_l, assuming that there are n maintenance errors due to aircraft maintenance, and the corresponding consequence value of i^{th} maintenance error is L_i, then during that period, the reference quantified safety risk of aircraft maintenance/maintenance errors is:

$$R = \sum_{i=1}^{n} L_i / N_l,\ L_i \in \{C_5, C_4, C_3, C_2, C_1\} \quad (1)$$

According to the BOWTIE safety risk model, each maintenance error may involve one or several threats, and may also involve one or several barriers in a threat. In other words, a threat or barrier may cause several maintenance errors. The sum of the consequences of maintenance errors caused by threats or barriers can reflect the safety risks of threats and barriers, and can be used to calculate the reference quantified safety risk of threats and barriers. Assuming that the reference quantified safety risk associated with the j^{th} threat in the model is R_{T_j}, G_{ij} is the correlation coefficient between the j^{th} threat and the i^{th} maintenance error, if the j^{th} threat is related to the i^{th} maintenance error, G_{ij} is 1, and if not, G_{ij} is 0. As a result, it can be concluded that:

$$R_{T_j} = \sum_{i=1}^{n}(L_i \cdot G_{ij})/N_l, \quad G_{ij} \in \{0,1\};\ j \in \{1,2 \ldots 8\} \quad (2)$$

Similarly, assuming that the reference quantified safety risk associated with the k^{th} barrier of the j^{th} threat in the model is $R_{B_{jk}}$, F_{ijk} is the correlation coefficient between the k^{th} barrier of the j^{th} threat and the i^{th} maintenance error, if the k^{th} barrier of the j^{th} threat is related to the i^{th} maintenance error, the F_{ijk} is 1, and if it is unrelated, the F_{ijk} is 0. If there are m_j barriers in the j^{th} threat, there are:

$$R_{B_{jk}} = \sum_{i=1}^{n}(L_i \cdot F_{ijk})/N_l,$$

$$F_{ijk} \in \{0,1\};\ j \in \{1,2 \ldots 8\};\ k \in \{1,2 \ldots m_j\} \quad (3)$$

In summary, according to the value of R value, we can preliminarily judge the safety risk situation in a certain period of time. According to the value of R_{T_j} and $R_{B_{jk}}$, the risk of each threat and barrier in this period can be preliminarily determined. According to the comparison of R_{T_j} values of different threats and $R_{B_{jk}}$ values of barriers, the threats and barriers that play a major role in this period can be determined.

C. Comprehensive Assessment of Safety Risk

Based on the results of the BOWTIE model event analysis in IV*(B)*, the risk level of the enterprise can be directly determined, and key threats and hidden dangers can be identified. It is also possible to comprehensively analyze the problems found in the enterprise audit and the experience of enterprise management, and use a brainstorming method to correct the safety risk levels of each barrier and threat in 3.2, and then determine the final comprehensive assessment value of safety risks of aircraft maintenance /maintenance errors.

V. Application of BOWTIE Safety Risk Model in Maintenance Enterprises

This paper collects data of the general accident symptoms of the industry in year 2016 and 2017, and uses the BOWTIE risk model of maintenance enterprises to analyze them.

TABLE I. List of General Accident Symptoms of the Industry in Year 2016 and 2017

Date	Maintenance Error	Root Cause
Jun-16	Work omissions	Personnel negligence
Jul-16	Wrong operation	1. Maintenance personnel fail to perform their work as authorized. 2. Supervisors fail to perform their duties of management and supervision 3. Error in Work Card 4. Errors in temporary work orders
Nov-16	Exchange wrong parts	1. The supervisors fail to perform their duties; 2. Maintenance personnel make wrong records; 3. maintenance personnel has insufficient skills
Apr-17	Wrong operation	1. The size design of the two parts is the same, hard to tell difference. 2. Maintenance personnel fail to carry out their work according to their authorization; 3. The sign is missing. 4. Maintenance personnel did not seek help when not knowing.
Apr-17	Wrong operation	1. Failure to complete the first article evaluation according to the procedure; 2. Insufficient personnel skills.
May-17	Install unreliable parts	Quality of subcontracted repair
Sep-17	Wrong operation by subcontractor	Quality of subcontracted repair
Oct-17	Work omissions	1. Failure to operate as required; 2. Personnel apply for resignation with scattered thoughts
Dec-17	Wrong operation by subcontractor	Quality of subcontracted repair

The BOWTIE analysis model is used to analyze the root causes of the 9 incidents mentioned above, and the results are shown in Fig. 4.

According to the data, there are 9 general accident symptoms and N_l =8422.461 thousands takeoff/landings in the industry in year 2016 and 2017. Set the consequence level value C_2 = 1. According to formula *(1)*, the reference quantified safety risk value (thousands rate) of aircraft maintenance/maintenance errors in year 2016 and 2017 is $R=9/N_l=0.0010686$.

According to the sequence in Fig. 3 risk model from top to bottom, the first threat is human and the second threat is aircraft... The 8^{th} threat is interface. According to the results of Fig. 4 analysis, the reference quantified safety risk values of each threat are as follows:

R_{T_1}=0.000475; R_{T_2}=0; R_{T_3}= 0.000119; R_{T_4}=0.000119; R_{T_5}=0.000119; R_{T_6}=0.000475; R_{T_7}=0; R_{T_8}=0.00059365

Similarly, the barriers in Fig. 3 are numbered from top to bottom, left to right. According to the results of Fig. 4 analysis, the safety risk values of each barrier are as follows:

$R_{B_{12}}$ =0.000475; $R_{B_{31}}$ =0.000119; $R_{B_{45}}$ =0.000119; $R_{B_{53}}$ =0.000119; $R_{B_{62}}$ =0.000475; $R_{B_{82}}$ =0.000356; $R_{B_{85}}$ =0.000237

The reference quantified safety risk values of the other barriers are all *0*.

Therefore, it can be concluded that the safety risk value of the aircraft maintenance/maintenance error is *0.001069*. According to the results of the reference quantitative safety risk calculation of the threat, we can know that the eighth threat, the interface threat safety risk is the greatest. It is a major threat to the safety risks of aircraft maintenance. The referenced quantitative safety risk value of the human psychological barrier and the responsibility and authority barrier in the software is *0.000475*. Compared with other barriers, the psychological barrier of human beings and the barrier of responsibility and authority in software have the greatest risk, and there are more hidden dangers in leading to the safety risk of aircraft maintenance. Through the BOWTIE safety risk model and event analysis results, we can intuitively understand the safety risk status, threats and hidden dangers of enterprises, so as to take better measures to improve the safety level.

It should be noted that for the failure to follow the procedure, there may also be problems such as the procedure itself, personnel training, tools and equipment management, and these problems cannot be reflected systematically. Since the various hazards, measures and hidden dangers have been considered in the BOWTIE model, the cause analysis is required to be thorough in the event analysis. If the root cause is that there are problems in the existing measures in the model, the cause should fall on the existing hidden dangers. If, after eliminating the hidden dangers of other measures, there are still problems that do not follow the procedure, then it can be judged that there are problems in the management that are not reflected in the model, usually the general violations or the problems of industry culture, policy, etc.

Through the maintenance enterprise BOWTIE safety risk model, the weak links of the enterprise can be clearly found, which is convenient for enterprises to carry out more systematic risk analysis, evaluation and control. Only 9 general incidents are analyzed here. There are many safety incidents and error information inside the maintenance enterprise. Through the analysis of a large amount of data, the results obtained will more truly reflect the safety management status within the enterprise. In addition, this article only provides a model of a typical enterprise. Since each enterprise has its own characteristics, it can be appropriately adjusted according to the actual situation within the enterprise in actual use.

VI. Conclusion

Based on the BOWTIE model, combined with the characteristics of civil aviation maintenance enterprises, a risk analysis model suitable for civil aviation maintenance enterprises was established, and the model was verified by the historical data of Chinese civil aviation fleet maintenance error, reflecting the aircraft maintenance safety risk level for a period and realizing the intuitive and clear identification of enterprise safety risks, which has the value of promoting and improving the safety management level of maintenance enterprises.

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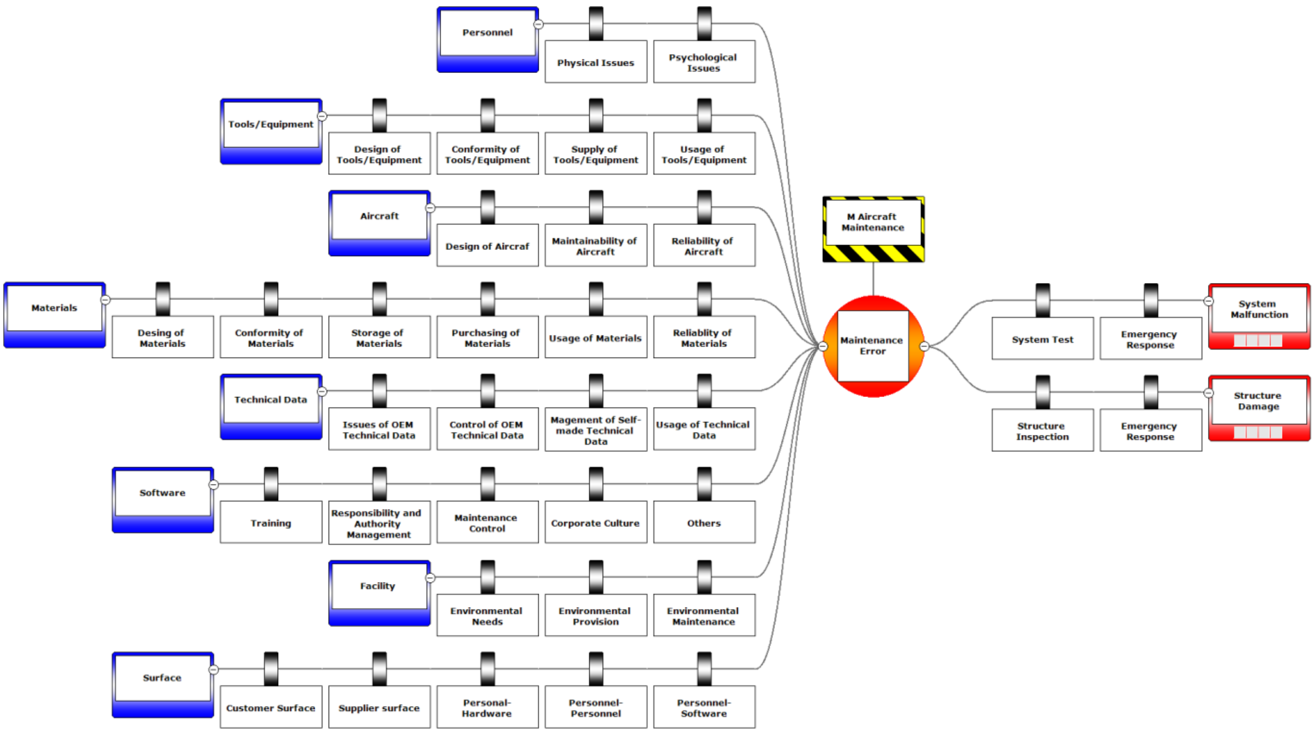

Fig. 3 BOWTIE Risk Model for Aircraft Maintenance/Maintenance Errors

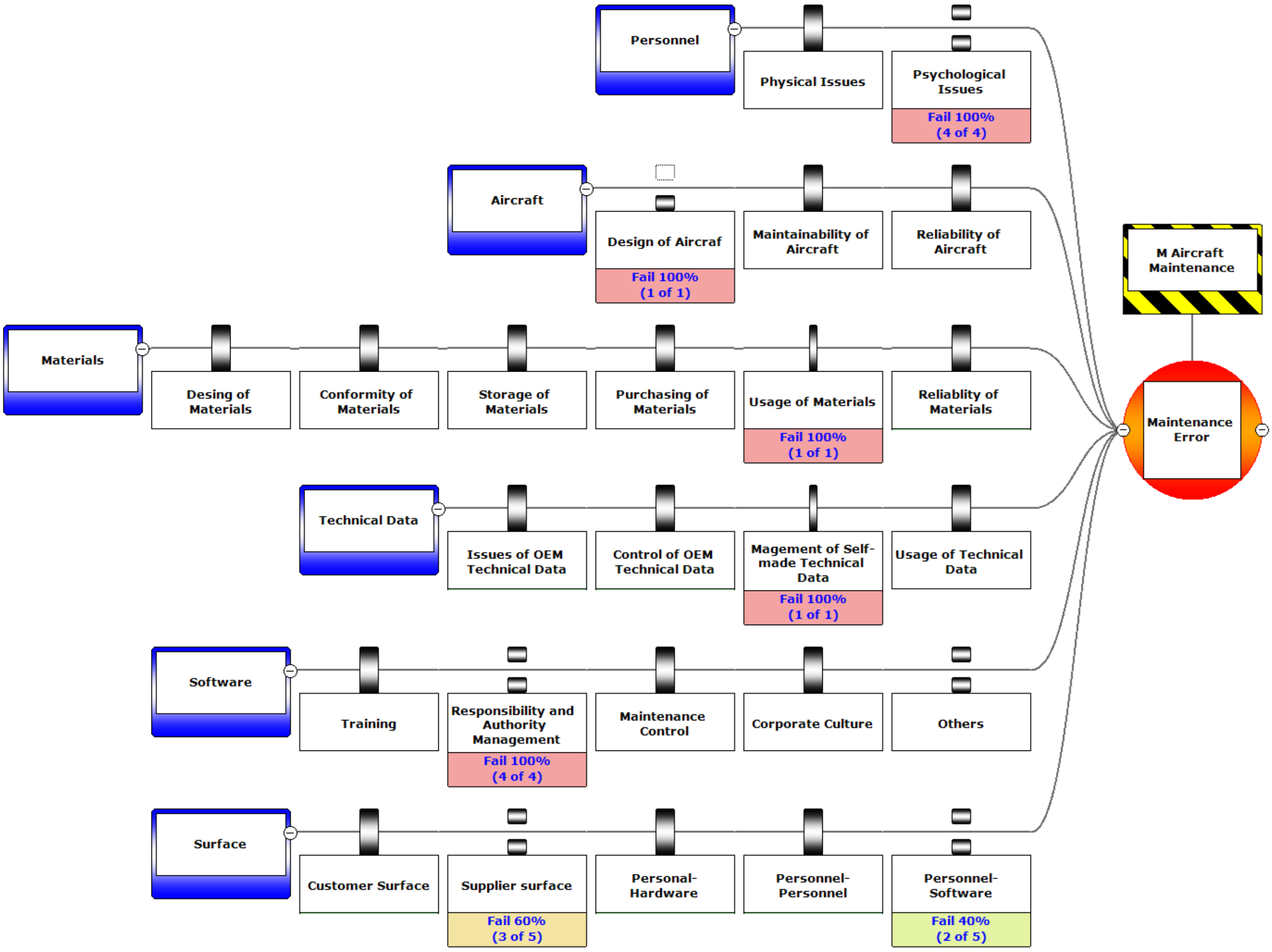

Fig. 4 Distribution of Root Causes of General Accident Symptoms