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PRIMARY RESEARCH

Methodology for visualizing system risk and its application to sky sports

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Abstract

Prior research highlights the limitations in current mainstream troubleshooting techniques used to assess accidents and ensure future safety. This study proposes a methodology to promote safety in sky sports and discusses its effectiveness and future research directions. The System of System Failures (SOSF) and Failure Factors Structuring Methodology (FFSM), categorized and distributed under the SOSF, are applied to sky sports safety. The three dimensions of the SOSF are represented by the coupling of the system (tight vs. loose), the degree of interaction with the external environment (linear vs. complex), and the frequency of failures. These dimensions allow the SOSF to be configured as a three-dimensional space. By introducing the distance phase (i.e., topological metrics), the risk trajectories of the system can be quantitatively visualized. This allows each instance of failure to be represented as a point in the SOSF space as a System Risk Location. Therefore, the system risk situation can be quantitatively discussed for comparisons between and within systems and learning from other systems. Stakeholders can thus share the recognition of failure cases and discuss problem-solving. The FFSM facilitates double-loop learning by structuring the complex factors that lead to failure and visualizing the trajectory of failure in the SOSF space, thereby clarifying the overall and precise countermeasures. Specifically, the study clarifies the insights that promote safety in sky sports and identifies directions for future data accumulation. Therefore, we demonstrated the possibility of expanding the SOSF and FFSM utilized in this study to other fields (human activity systems).

I. INTRODUCTION

As the population of sky sports enthusiasts becomes increasingly diverse, there is a need for updated research on accidents, near-miss occurrences, and safety in this area. The population with hang-gliding enthusiasm in Japan is approximately 5,000. The population with paragliding enthusiasm is approximately 25,000. Their age groups ranged from teens to 80s, and a woman was one of the four paragliding geniasts. The author analyzed the current situation in Japan based on an existing database of near misses [1] and considered the direction of measures to promote safety in the future.

For this analysis, the author used the System of System Failures (SOSF) [2, 3], a meta-methodology that considers system failures from a bird' s-eye view and ensures the totality of countermeasures, and the Failure Factors Structuring Methodology (FFSM), which promotes double-loop learning by structuring the factors that cause failures [4]. Additionally, a factor-structuring methodology [5] was applied. The causes of failures identified in this study and the direction of countermeasures will be proposed to related organizations to explore the direction of specific measures in the future. Nakamura and another sky sports enthusiast with experience in sky sports (mainly paragliding) were responsible for the methodology and appropriateness of the countermeasures, respectively.

A. *Overview of Organization and Data Accumulation to Promote*

Safety

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The JHF promotes safety-related awareness through its Safety Committee, a permanent committee that conducts accident investigations, collects accident statistics, and disseminates cautions and recommendations for accident prevention on its website [6]. Accident data are accumulated and entered by the parties involved as soon as possible after an accident occurs (Figure 1). This study used the accident data published on the JHF website as an accident report summary [6].

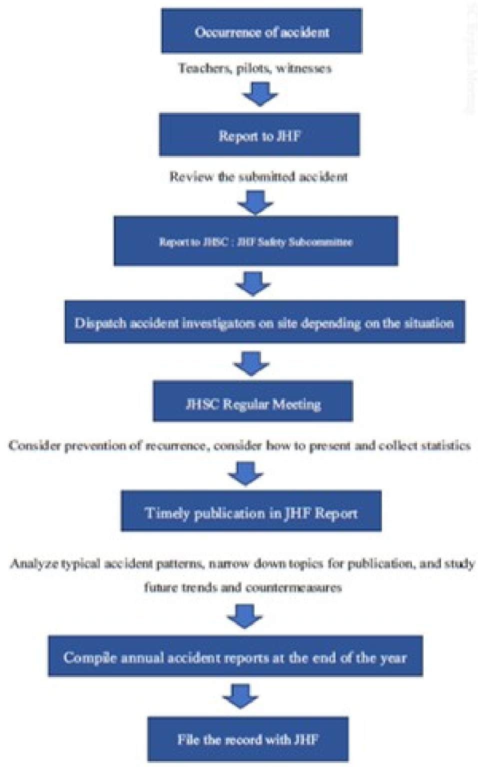

Fig. 1. Incident reporting flow [Source: [6], translation by author.]

B. *Survey of Troubleshooting Methodologies*

Common Limitations

Current mainstream troubleshooting techniques rely on models that pursue the goals determined during design. These techniques have several limitations, as highlighted by [7]. First, these techniques attempt to determine the cause of system failure—defined as "a characteristic of a subsystem that does not contribute to achieving the goals of a higher-level system" or "the end of its ability to achieve its required functionality" [8] —within the target system in which the failure occurred. This makes it difficult for a higher-level system, in which the target system is contained, to determine the cause of the failure.

Second, the search for the cause of the failure tends to focus on restoring system operation to within predetermined target values, and the effect tends to be temporary. Furthermore, organizations tend to view once-determined goals as absolute and continue to maintain the status quo without considering the differences between the external environment at the time the goals were set and the present. System improvement in such an organizational culture is not sufficiently effective as it leads engineers to follow the design requirements rather than reforming and leading the process. Engineers who design systems must avoid making false assumptions and pursuing incorrect goals by designing and leading the status quo and not maintaining predetermined goals.

Another limitation of current methods is highlighted by [9] and [10], who find that the elemental reductionist approach (a method that decomposes the whole system into its constituent parts and determines the causes of failure within those parts) is not useful for accurately understanding system failures or building better systems. They identify four characteristics common in current troubleshooting methodologies:

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(1) Although current methodologies are elaborately structured and managed by the technical standards of the [11] and the International Electrotechnical Commission [12], it is difficult to judge the effectiveness of the measures established by these standards from a technical standpoint. This is because most of the current methodologies are based on an element-reduction approach.

(2) Current methodologies use the event chain method to identify root causes. Failure mode and effect analysis [13] prospectively pursues causal relationships among the components, and fault tree analysis [14] digs deeper into the causes of the final event. However, these methods are mainly used in the design phase and rarely simultaneously. In particular, it has been identified that the effectiveness of FTA depends on the experience of the analyst.

(3) The rapid pace of information technology evolution creates misunderstandings among stakeholders regarding the failure of systems built using information technology. This gap in responsibility cannot be accurately addressed using the current methodologies.

(4) [7] argues that improving current operations cannot handle system failures. He points to three characteristics of current troubleshooting methods:

- The focus is on already-defined goals.
- The results produced are different from what was planned.
- The system does not work as originally intended.

These characteristics prevent a bird's-eye view of the system's failures and, therefore, do not allow the creation of appropriate countermeasures.

C. Current Troubleshooting Methods

Heinrich's law [15] states that, behind every major incident, there are 29 minor error events and 300 non-failure events. This is effective in considering countermeasures from a broad viewpoint of incident events. However, it is limited by the issues described in the previous section.

[16] proposed a "man-made disasters model," which articulates the circumstances leading up to a fatal accident. [17] proposed the normal accident theory to understand failures in social systems, attempting to determine the causes of accidents and identify countermeasures by placing the target system in a two-dimensional plane with the coupling of the system (tight vs. loose) and the degree of interaction with the external environment (linear vs. complex). He argued that various defenses (e.g., adding alarm devices and redundancy) to prevent errors fail because the measures are superficial.

However, both of these models are subjective and qualitative and do not capture the quantitative aspects that are necessary when determining specific countermeasures.

Finally, [18] studied accidents caused by "bad decisions" due to "the normalization of deviance," particularly the NASA space shuttle Challenger. This study is valuable as a post-accident analysis of the causes; however, it does not propose any concrete measures to prevent such accidents from occurring in the future.

Major risk-analysis techniques (including FMEA [13] and FTA [13] are discussed in [19], [20], and [21]. Most studies analyzing failure are based on FMEA or FTA. From a software methodology viewpoint, the following three characteristics are required [22]:

- Facilitation of double-loop learning that not only maintains the functionality of the target system but also revises its goals.
- Structuring and visualizing the factors that lead to system failure, allowing examination of countermeasures from a bird's-eye perspective, and;
- Support for decision-making regarding countermeasures by structurally understanding the nature of the resulting problems.

[23], 'Chapter 7, pp 126') argues that "errors are consequences, not causes." If this is the case, then we need a new methodology that looks at errors as consequences. In other words, we must look for the real causes behind the superficial errors.

This study proposes a methodology to overcome the issues identified by [7], [9], [10] and [22] applies it to real-world problems. This new methodology should be soft (i.e., not just a hard approach that decomposes the system into its parts and pursues goals for each part) and promote double-loop learning that allows for structuring, visualizing, and dynamically tracking problems involving multiple stakeholders.

D. Safety Analysis

[5] and [2] developed a methodology to promote the safety of Information and Communication Technology (ICT) systems, and its effectiveness has been demonstrated with the FFSM, a methodology for structuring failure factors. The characteristics of systems to which the FFSM can be applied are listed below.

- Human activity processes are among the components of the system.
- The system depends on the knowledge of operators and users.
- The relationship between cause and effect is not linear but complex and unclear.

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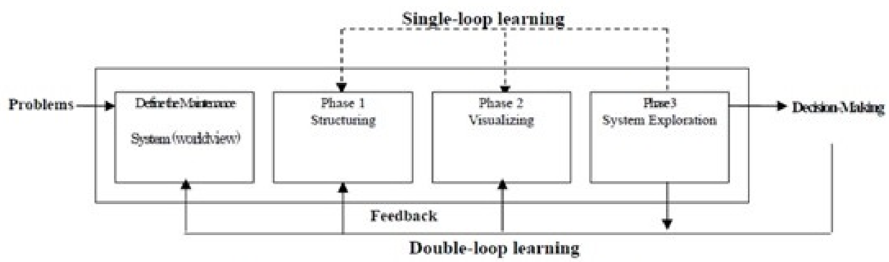
Based on these characteristics, it is necessary to introduce a distance phase (i.e., topological metrics) into the SOSF space, quantitatively represent individual failures (expressed as points in the SOSF space), and visualize the direction in which the system risk changes by arranging failures in the SOSF space in a time series. The method for introducing a distance phase (i.e., topological metrics) into the SOSF space is explained in.

In light of the above, this study aims to expand the application of the FFSM to the safety of sky sports. It examines whether the methodological issues described in the previous sections have been overcome by this effort. The specific research question is whether the new methodology should be soft (i.e., a systemic, emergent, and dynamic methodology that involves multiple stakeholders rather than a hard approach that decomposes a system into its parts and pursues goals for each part) and whether it should be able to promote system safety. The aspect to be implemented is a systemic, emergent, and dynamic methodology involving multiple stakeholders and promoting systemic safety.

II. FFSM: A NEW METHODOLOGY FOR LEARNING FROM FAILURE

Figure 2 shows the three phases comprising the FFSM and double-loop learning. These satisfy the characteristics that a new methodology should possess, as described previously. Maintenance systems refer to various human activity systems [24]. This methodology is based on the method developed by [5].



	Feature	Objective
Phase 1	● Holistic approach (Structuring factor relationships)	Discover root causes by clarifying the relationships between factors
Phase 2	● Holistic approach (Grouping factors and problems)	Extract hidden factors behind complex symptoms by grouping factors and problems
Phase 3	● Viewing a system from a conceptual viewpoint as well as a real-world viewpoint ● Double-loop learning	Discover preventative measures for emergent properties by mapping factors into maintenance subsystems

Fig. 2. Three phases and a learning loop (failure factors structuring methodology)

A. Phase 1 Analysis (Interpretive Structural Modeling [ISM])

Using ISM [25] as a method for structuring failure factors, the author analyzed 167 incidents that resulted in crashes over six years (2016–2021) from the public database accumulated at the JHF. Eleven factors leading to crashes were identified by experienced sky sports personnel: S0, crash; S1, open umbrella; S2, stall; S3, crush; S4, air contact; S5, twist; S6, cravat; S7, in-flight maneuvers; S8, spin; S9, weather; S10, prior ground preparation; and S11, force majeure and other factors (engine malfunction, etc.).

B. Phase 2 Analysis (Quantification III)

To extract hidden factors that were not visible in the structure of the factors leading to the crashes identified in Phase 1, a Quantification III analysis [26, 27], a type of principal component analysis, was conducted on the failure factor group consisting of S0–S11 for the 167 incidents. Excel Statistics [28] was used for analysis.

C. Phase 3 Analysis (Close Code Analysis)

The author analyzed 167 major incidents in chronological order over six years at sky sports to determine the causes of the crashes. The System Risk Location (SRL) was plotted in three-dimensional space using a method for quantifying and visualizing the system risk [29] with a cause analysis code for each incident.

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III. APPLICATION RESULTS AND FUTURE STEPS

A. Phase 1 Results

According to the ISM analysis in Phase 1 (Table 1 and Figure 3; only factors with a weight of 0.1 or more are shown), the largest factor leading to S0 (crash) was S7 (in-flight maneuvers) followed by S4 (contact in air), S9 (weather), S2 (stall), S8 (spin), and S3 (crush). In particular, S7 (in-flight operations) led to S0 (crash) via S2 (full stall), and S9 (weather) had a compound factor leading to S0 (crash) via S3 (collapse). It was therefore necessary to analyze the hidden main factors.

B. Phase 2 Results

Countermeasures were examined for factors up to Axis 6, which were identified through the analysis of Phase 2 Quantification III. The cumulative contribution of the categories up to Axis 6 accounted for approximately 70% of the total, which was the majority of the crash factors (Table 2). Category scores up to the sixth axis are listed in Figure 4. Table 3 shows the countermeasures for the two major categories of factors (Axes 1–3: force majeure and operational categories; Axes 4–6: phenomenon categories).

C. Phase 3 Results

The x-row in Table 4 represents the degree of coupling of the failure factors (percentage of in-flight incidents in the 167 incidents in Table 5), the y-row represents the degree of complexity (percentage of complexity in the in-flight incidents in Table 5), and the z-row represents the frequency of occurrences with larger values indicating tighter coupling, greater complexity between system elements, and an increased incidence of incidents. Figure 5 displays Table 4 in three dimensions. Figure 5 shows the entire SOSF space and details of the spatial configuration can be found in [2, 3]. The time-series monitoring of the SRLs in the SOSF space enables the prediction of changes in the risk of the target system and the consideration and implementation of proactive countermeasures.

TABLE 1

TOTAL INFLUENTIAL MATRIX OF 11 FACTORS

Total influential Matrix (X*(I-x)-1)								
	S0	S1	S2	S3	S4	S5	S6	S7
S0	0.26	0	0	0	0	0	0	0
S1	0.29	0	0	0	0	0	0	0
S2	0.62	0.03	0	0.02	0.02	0	0	0
S3	0.48	0.05	0.05	0	0.02	0.02	0.07	0
S4	0.71	0.09	0.05	0	0.02	0	0	0
S5	0.1	0.05	0	0	0	0	0	0
S6	0.09	0.02	0	0	0	0	0	0
S7	0.99	0.01	0.26	0.05	0.05	0	0	0
S8	0.55	0.02	0.01	0	0	0.02	0	0.02
S9	0.63	0.01	0.06	0.14	0.07	0	0.01	0
S10	0.33	0	0	0.02	0	0	0	0
S11	0.2	0	0	0.05	0	0	0	0

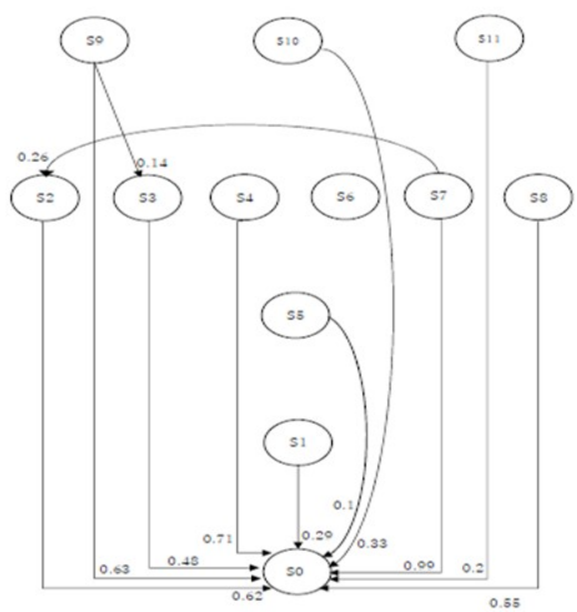

Fig. 3. Structured graph of 11 factors

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TABLE 2
EIGENVALUE TABLE AND CUMULATIVE CONTRIBUTION RATIO

Axis	Eigenvalue	Contribution Ratio	Cumulative Contribution Ratio	Correlation Coefficient
1	0.9585	14.06%	14.06%	0.9790
2	0.9017	13.23%	27.29%	0.9496
3	0.8381	12.30%	39.58%	0.9155
4	0.7610	11.16%	50.75%	0.8723
5	0.7373	10.82%	61.56%	0.8586
6	0.6329	9.28%	70.85%	0.7955
7	0.6039	8.86%	79.71%	0.7771
8	0.5297	7.77%	87.48%	0.7278
9	0.5038	7.39%	94.87%	0.7098
10	0.3497	5.13%	100.00%	0.5913

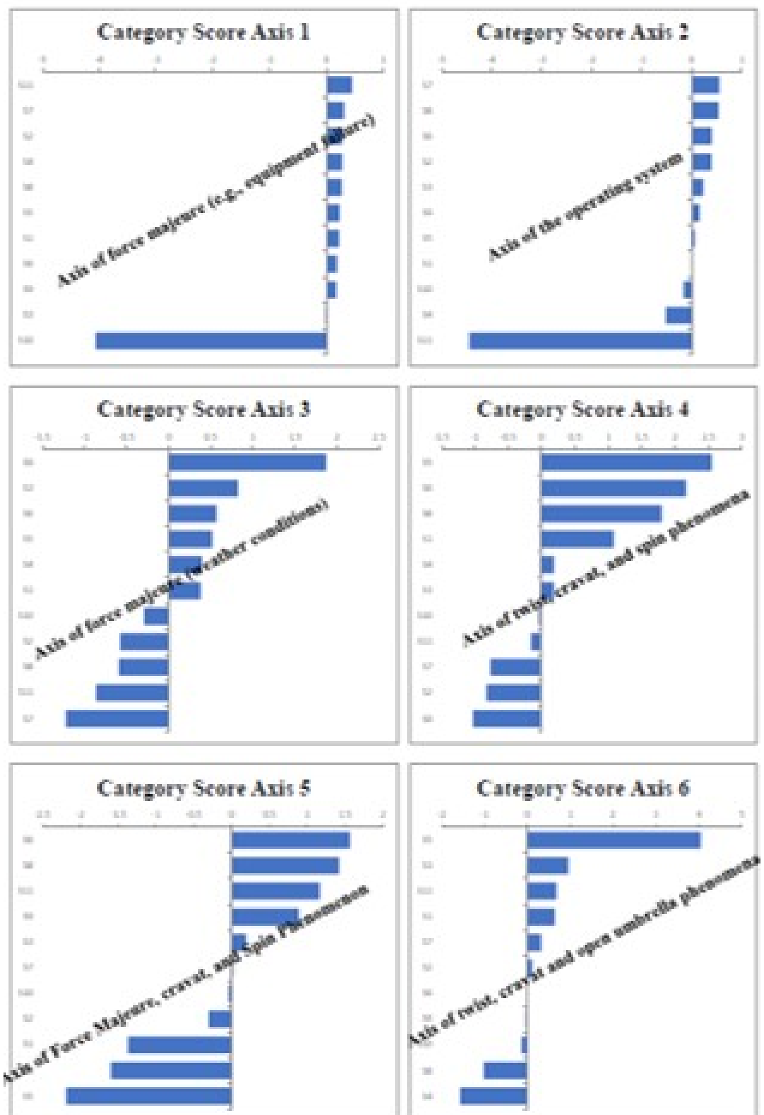

Fig. 4. Structured graph of 11 factors

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TABLE 3
FACTOR CATEGORIES AND MEASURES

Factor Category	Knowledge Enlightenment	Operation System Technical Training
Factor axes of force majeure and operation systems (Axes 1 to 3)	"Enlighten knowledge of aircraft, air and wind (meteorology), and develop tolerance for panic in the event of force majeure events (weather and other). "	"[Awareness] Training to develop imagination and predictability. "
Factor axes of Phenomena (Axes 4 to 6)		"[Technology] Recovery training from intentional situations. (Currently, practice in recovery from stalls is not being implemented.) →For training in abnormal behavior, computer-based simulations and educational courses should be developed. →Consider facilities and equipment for simulated experience. (Overseas benchmarks are needed, e.g., for indoor spiral training.)"

TABLE 4
FACTOR CATEGORIES AND MEASURES

Close code classification (2D)			
	Design	Pre-Flight	In-Flight
Simple		7	63
Complex		5	60

TABLE 5
EIGENVALUE TABLE AND CUMULATIVE CONTRIBUTION RATIO

	2016	2017	2018	2019	2020	2021
X	0.86	0.85	0.95	0.93	0.85	0.9
Y	0.09	0.31	0.59	0.54	0.55	0.76
Z	15.0%	16.2%	22.2%	19.8%	13.8%	13.2%
Incident No.	25	27	37	33	23	22

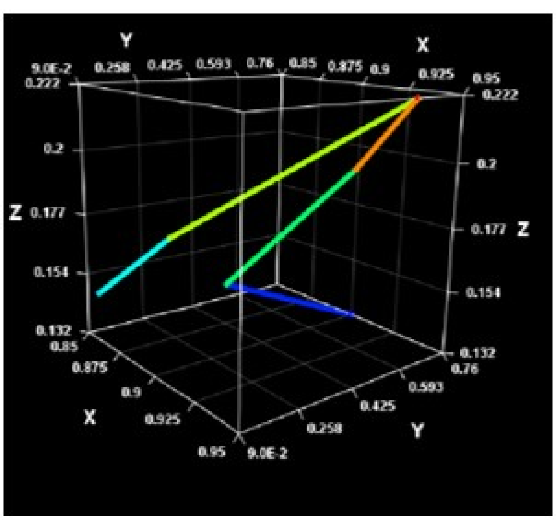

Fig. 5. Structured graph of 11 factors

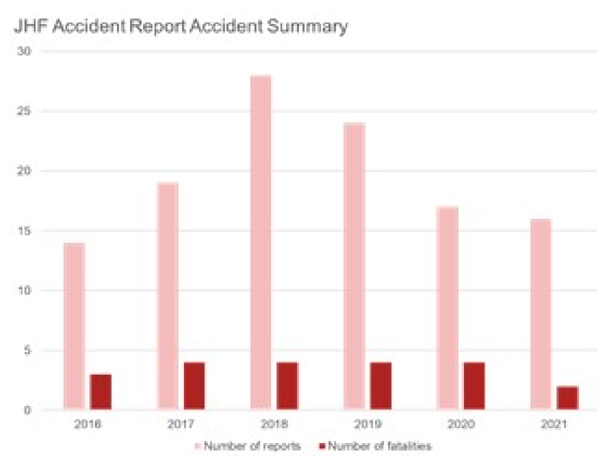

Fig. 6. Japan Hnag & Paragliding Federation (JHF) incident transition

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D. JHF Incident Transition Status

Figure 6 shows the status of JHF incident reports; after peaking in 2018, the accident situation declined. This can be attributed to the efforts of the JHF and other sky sports organizations. The age structure of sky sports is broad, ranging to people in their 80s. In the next section, we discuss the current situation and future measures that can be taken by applying the introduced methodology in anticipation of future environmental changes. Specifically, the situation in which we cannot be optimistic about the risk trends behind incidents is explained.

To further clarify the prevention perspective, a time series of risk trends was observed, and a Phase 3 close code analysis was conducted. The main conclusions are as follows. Referring to the y-row of Table 4, the SRL (risk trend) has increased with each passing year (9% ⇒ 35 % ⇒ 59% ⇒ 54% ⇒ 55% ⇒ 76%). The main factors that lead to crashes, particularly those that are complex during flight (Table 4 and Figure 5), are

- paraglider crash with engine (drowning),
- drowning owing to landing in the water and inability to detach from the water because of the buoyancy of the harness,
- spare swing line falls off,
- rescue parachute falls, and
- mistook a radio call for guidance from a novice for a call to himself.

In addition, the following are the main factors leading to crashes among the complex preparation factors (five cases in Table 5):

- unauthorized flight without membership.
- Forgetting to tighten the leg belt (get-up type) (ingenuity of part of flight gear), and
- mask stuck to face due to COVID-19 disaster, resulting in lack of oxygen.

For all these items, it is desirable to take measures from the management and aircraft perspecive rather than seeking causes only on the pilot's perspective.

It is important to discuss countermeasures with relevant associations, implement them, and continuously monitor accident situations to confirm the effectiveness of any improvements.

This effort also showed that meta-methodology (SOSF) and structured methodology (FFSM) can be applied to human activity systems other than ICT [24].

IV. DISCUSSION

As mentioned in the Survey of Troubleshooting Methodologies, there is currently no methodology to quantitatively express dynamic changes in system risk over time. However, this study has shown that it is possible to quantitatively express trends in system risk, thereby enabling consideration of essential measures (i.e., facilitating double-loop learning to review current standards).

We believe that the SOSF and FFSM used in this study overcome the conventional methodological challenges (structuring, visualization, and double-loop learning) described in the Survey of Troubleshooting Methodologies. Specifically, the SOSF and FFSM have led to measures for multiple stakeholders (e.g., aircraft manufacturers, JHF as an industry association, and pilots) that are difficult to derive using conventional methodologies. Furthermore, the direction in which measures should be taken was clarified by visualizing the transition trend of the system risk in chronological order. The new knowledge gained from these activities provides clarification on the conditions under which the methodology can be applied. Specifically, the following four points were identified: (1) The activity must have a purpose. (2) The definition of failure must be clear or able to be clarified. (3) The history of failures must be recorded. (4) The causes of failures must be classified, or if not, they must be discussed and clarified among the parties concerned based on the history of failures. This shows that the meta-methodology (SOSF) and structured methodology (FFSM) can be applied to human activity systems other than ICT [24].

Despite its strengths, the relatively small data size is a limitation of this study, as it means that incidents that do not result in major accidents may not be reported, and there may be bias in the attributes of those who report them. This requires educating the public about the importance of reporting minor incidents and adding the attributes of the reporter to the collected data. In future efforts, it will also be necessary to verify whether safety has been concretely improved by implementing countermeasures in cooperation with related parties.

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