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Evaluating Cause-Effect Relationships in Accident Investigation Using HFACS-DEMATEL

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Abstract: This paper addresses the 'routes to failure' in the causal chain of events as categorized using the Human Factors Analysis and Classification System (HFACS) framework. By using the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to evaluate the comparative influence of each HFACS category on other categories, the present research aims to classify each HFACS category as either an overall 'cause' or an overall 'effect' factor, and to give each HFACS category a comparable statistical value of their overall level of influence. Analysis of N=30 responses from aviation safety experts identified that frontline perception faults had the potential to influence higher-level preconditions, and that 'Environmental Factors' were found to have the highest overall influence amongst HFACS categories at levels 1 and 2. The findings support the use of the DEMATEL method in the selection and direction of safety interventions. Safety remedies focusing on 'cause' factors are likely to have additional second-order benefits on associated 'effects', and more influential categories are likely to be more effective in influencing overall system safety. The methodology can assist safety managers in selecting and prioritizing safety initiatives, especially when faced with issues such as monetary or time constraints in the industrial context.

Keywords: Human Factors Analysis and Classification System (HFACS), Human Factors Interventions, Safety Management Systems

1 Introduction

The investigation and analysis of accidents and incidents form the basis for safety management objectives and human factors interventions. Contemporary investigation processes typically utilize a wide range of information sources, such as flight data and psychometric assessments, to ensure the objectiveness of the findings [1]. Yet, the collection, interpretation, and projection of these sources by accident investigators are known to be affected by subjective demographic and cultural factors [2], and investigative taxonomies often fail to sufficiently account for human contexts behind decisions and behaviors [3]. To illustrate, expert pilots may choose to accept minor deviations (that are within a certain safety margin) to free up mental capacity for other tasks.

As most investigative methods are still exceedance-based, i.e., focus on deviation from acceptable performance and do not primarily focus on everyday performance, these deviations are typically considered as performance deficiencies and different investigators will attribute these deficiencies to different causes. Moreover, latent conditions are not inherently visible from an airline's flight safety perspective (e.g., through Flight Data Monitoring and Air Safety Reports) [4]. By failing to understand how underlying human contexts interact with latent conditions in the causal sequence of events, investigative processes are like "focusing on a fever without understanding the underlying illness that is causing it" [5].

1.1 The Human Factors Analysis and Classification System

To improve the objectivity of accident investigations, Wiegmann & Shappell (2003) developed the Human Factors Analysis and Classification System (HFACS) to provide investigators with a taxonomy of latent and active failures implicated in the causal sequence of events. By providing a system-wide taxonomy, the HFACS encourages investigators to associate human factors deficiencies to latent conditions originating from across multiple organizational levels, rather than simply attributing faults to acts committed by frontline crew members.

Human factors deficiencies can be attributed to failure modes across four levels representing different parts of the organizational hierarchy (Table 1). The HFACS has been widely used for safety investigation purposes across multiple domains including aviation, maritime, rail, nuclear, and medical fields. More recent applications of HFACS suggested the integration of failure modes at the 'Preconditions for Unsafe Acts' level (L2) into three underlying categories (i.e., 'Environmental Factors', 'Condition of Operators', and 'Personnel Factors' categories) [6]. Notably, whilst the four error and violation types at the 'Unsafe Acts of Operators' level (L1) can also be simply integrated into the two categories errors and violations, previous research indicated that this was not desirable if the data contained sufficient detail, in order to provide a level of granularity required for accident investigation purposes [5].

Table 1. Levels and categories of the Human Factors Analysis and Classification System (HFACS).

Level		Categories
L4	Organisational Influences	1. Resource Management 2. Organizational Climate 3. Organizational Process
L3	Unsafe Supervision	4. Inadequate Supervision 5. Planned Inappropriate Operations 6. Failed to Correct a Known Problem 7. Supervisory Violations
L2	Preconditions for Unsafe Acts	8. Environmental Factors • Physical Environment • Technological Environment 9. Condition of Operators • Adverse States • Adverse Physiological States • Physical/ Mental Limitations 10. Personnel Factors • Crew Resource Management • Personal Readiness
L1	Unsafe Acts of Operators	11. Decision Errors 12. Skill Based Errors 13. Perceptual Errors 14. Violations

As HFACS was developed on the basis of Reason's (1990) Swiss Cheese model of accident causation, the framework has an implicit assumption of cause-effect directionality with each "slice" of cheese considered to influence the "slice" at the next lower level [5]. 'Routes to failure' are considered to flow in a top-down direction within the organizational hierarchy [8]. For example, in relation to the interaction between cabin crew and cockpit crew, psychological and physical barriers complicate communication which affects flight safety [9]. A prominent example of missing communication between cabin and cockpit crew is the Air Ontario Flight 1363 accident in Dryden, Canada, which crashed shortly after take-off as it was unable to attain sufficient terrain clearance due to ice accretion on the wing [10]. Although the cabin crew noticed ice build-up on the wings prior to take-off they did not inform the cockpit crew. In this case, historical 'Organizational Influences' (HFACS level 4) were found to have created psychological barriers between cabin and cockpit crew members, resulting in the lack of communication and teamwork (representative of 'Personnel Factors' at level 2) in the incident.

1.2 Directionality of Associative Pathways

There is a research gap as previous studies do not adequately address the possibility that converse, bottom-up relationships may also exist within the HFACS. To illustrate, it is logical to conceive how aircraft control errors at the lowest, frontline level can cause the loss of situation awareness. The loss of situation awareness can then be considered, in effect, as a ‘Condition of Operators’ deficiency at HFACS level 2, which may in turn play a part in subsequent events.

Aside from the directionality of relationships, other studies have found that each error or unsafe act can be associated with more than one precursor in a ‘many-to-one’ concept [8]. It has been argued that remedial safety actions will be most effective if they can be aimed at categories which share the greatest number of associations with other concomitant precursors [11]. However, the problem is that when each category is associated with multiple others, then amongst the numerous ‘routes to failure’, the category in question can on the one hand be the cause of failure for some ‘routes’ and on the other hand be the consequential effect in other ‘routes’. Similarly, some categories may be heavily influenced by other factors yet exert little influence over the wider system, whereas other categories may be resilient to external influences but nevertheless exert a strong influence onto others. A wider perspective looking into comparative influences at the whole-system level from a cause-effect perspective can paint a clearer picture of how factors in each category function and compare as a net ‘cause’ or ‘effect’ in the wider safety system.

Based on the literature review, the goals of the present research were to investigate cause-effect relationships amongst HFACS categories and to identify the comparative influence of each category as part of the wider system. Firstly, the results will be useful for safety managers in directing future safety actions to net ‘cause’ factors, which can help to ensure that remedial actions will rectify system-level root causes. Secondly, the ranking of relative influence amongst the various categories will enable safety managers to select more influential categories on which to spend precious resources.

2 Method

2.1 Participants

Responses from N = 30 subject matter experts in aviation safety were included in the present analysis. Participation was voluntary, no identifying information was collected, and participants had the right to terminate their participation at any time. Ethics approval was provided by the Cranfield University Research Ethics System (CURES/20576/2023).

2.2 Research Design

Interrelations amongst categories of human factors conditions at HFACS level 1 (‘Unsafe Acts of Operators’) and level 2 (‘Preconditions for Unsafe Acts’) were assessed using the Decision-Making Trial and Evaluation Laboratory method (DEMATEL: Fontela & Gabus, 1972)

HFACS Categories and Failure Modes. In the aviation environment, social and physical distances between frontline and back-office workplaces (pilots and cabin crew do not work in airline headquarters) are known to create a level of separation between operational personnel and conditions at higher supervisory and organizational levels

[13]. It was suspected that bottom-up relationships will mostly be amongst HFACS levels 1 and 2, as these categories are within the remit of operations personnel. Thus, HFACS categories in this study included four error and violation types at HFACS level 1 ('Decision Errors', 'Skill-Based Errors', 'Perceptual Errors', and 'Violations') and three categories at HFACS level 2 ('Environmental Factors', 'Personnel Factors', and 'Conditions of Operators').

DEMATEL Method. The DEMATEL method operates by pitting human factors categories against each other, comparing each category's contribution to the system (net given influence: Ri) against the effects that the other categories exert on them (net accepted influence: Ci). A category is considered as a 'cause' if its net given influence is greater than its net accepted influence (Ri - Ci > 0), whereas a category is considered as an 'effect' if its net accepted influence exceeds its net given influence (Ri – Ci < 0) [14].

Data collection was done by an online survey. The survey was designed to quantify the degree of interaction between HFACS categories as perceived by the participants. For DEMATEL calculations, all seven categories at HFACS levels 1 and 2 (Table 1) were listed both horizontally and vertically into a 7 x 7 matrix (Table 2). The survey items pits the row elements in the matrix with the column elements by asking participants to quantify the degree of interaction between exemplars of each element on 4-point scales ranging from 'no' (0) to 'high' (4) influence. For example, to quantify the level of influence that 'Environmental Factors' (L2-1) has over 'Personnel Factors' (L2-2), the survey item asks: "In your opinion, does physical or technological environment (e.g., lighting, ventilation, equipment design) influence crew resource management or personal preparation for duty?". Thus, for a 7 x 7 matrix, the survey had a total of 42 items.

2.3 Statistical Analysis

Statistical analysis was conducted using Microsoft Excel (version 2312). Following the steps of DEMATEL [12], survey responses from all N = 30 participants were (1) averaged and combined into a Direct-Influence Matrix which shows the strength of interaction that each row element has on each column element (Table 2); (2) Items in the Direct-Influence Matrix were normalized to adjust the data to a common scale, enabling the comparison of each element bi-directionally in terms of cause and effect; (3) The normalized matrix was multiplied with an identity matrix (where all the elements on the main diagonal are 1, and all other elements are 0), to generate a Total Relation Matrix where the row total represents the Net Given Influence (Ri) by the respective horizontal element category, and the column total represents the Net Accepted Influence (Ci) received by the vertical element category; (4) For each element, simple arithmetic deduction of the Net Accepted Influence (Ci) values from The Net Given Influence (Ri) values were calculated to find the directionality and strength of influence. The Net Accepted Influence (Ri), Net Given Influence (Ri), and 'cause' (Ri - Ci > 0) or 'effect' (Ri – Ci < 0) identity values for each HFACS category are presented in Table 3.

Table 2. The Direct Influence Matrix, based on N=30 responses, presenting the degree of interaction from 'no influence' (0) to 'high influence' (4) that each row element has on the column element.

Direct Influence Matrix	L2-1 Environmental Factors	L2-2 Personnel Factors	L2-3 Conditions of Operators	L1-1 Decision Errors	L1-2 Skill-Based Errors	L1-3 Perceptual Errors	L1-4 Violations
L2-1 Environmental Factors		3.14	3.33	3.19	3.14	3.57	2.81
L2-2 Personnel Factors	1.86		2.95	3.48	3.43	2.81	2.95
L2-3 Conditions of Operators	2.05	3.43		3.67	3.71	3.29	3.29
L1-1 Decision Errors	1.81	2.57	2.57		2.76	2.62	3.38
L1-2 Skill-Based Errors	1.75	3.14	3.00	3.50		3.14	3.33
L1-3 Perceptual Errors	2.10	2.67	3.00	3.71	3.52		3.33
L1-4 Violations	2.24	3.00	2.71	3.48	2.90	2.62	

3 Results and Discussion

3.1 Active Failures as the Cause of Human Factors Preconditions

Notably, 'Perceptual Errors' at HFACS level 1 functioned as a net 'cause' factor, and the 'Personnel Factors' category at level 2 was found to be an 'effect' factor (Table 3). The finding of 'Perceptual Errors' as a 'cause' factor is contrary to the accepted knowledge where categories at HFACS level 1 were considered as the 'bottom-level' final manifestation of the causal sequence. The finding of 'Personnel Factors' as an 'effect' factor was also unexpected, as within the HFACS framework the second level of 'Preconditions for Unsafe Acts' were conventionally presumed to be 'higher-level' preconditional causes.

Table 3. DEMATEL output of the Net Accepted (Ri) and Given (Ci) influence for each category, and the identity values (Ri – Ci) for each category as a cause or effect factor.

Category	Ri	Ci	Ri-Ci	Identity
L2-1 Environmental Factors	5.81	3.75	2.06	Cause
L2-2 Personnel Factors	5.32	5.45	-0.13	Effect
L2-3 Conditions of Operators	5.84	5.33	0.51	Cause
L1-1 Decision Errors	4.85	6.30	-1.45	Effect
L1-2 Skill-Based Errors	5.42	5.86	-0.44	Effect
L1-3 Perceptual Errors	5.54	5.44	0.10	Cause
L1-4 Violations	5.18	5.81	-0.64	Effect

A review into the failure modes associated within each category provides an explanation for the present findings. The 'Personnel Factors' (L2) category encompasses the failure modes of Crew Resource Management (e.g., teamwork, communication, etc.) and Personal Readiness (e.g., individual training and risk judgement) (Table 1). A possible explanation could be that 'Perceptual Errors' (L1) conferred amongst individual crew members a deluged "perception of the world [which] differs to reality" [5], in turn instigating a breakdown of crew resource management and risk judgement when this deluged individual has to work with others within multi-crew environments.

For safety management, fixes on 'effect' factors are likely to be limited to first-order conditions. Contrarily, interventions on 'cause' factors are likely to also rectify second-order 'effects' and may therefore be comparatively more effective. The present results provide evidence for the existence of multi-directional 'routes to failure', with bottom-up pathways likely to exist. In the future, a more encompassing perspective with the consideration of how 'Unsafe Acts of Operators' at level 1 can possibly create second-order influences at higher system levels can possibly assist safety managers in selecting safety recommendations and interventions with broader applicability.

3.2 Selecting System-Wide Remedial Actions

Although the finding of a 'cause' factor at level 1 and an 'effect' factor at level 2 suggests that a new, more inclusive interpretation of the direction of causal sequences within HFACS is desired, a review of cause-effect values (Ri – Ci) across the board nonetheless suggests that the conventional top-down direction is most dominant. The majority of level 2 categories were 'causes', and the majority of level 1 categories were 'effects'. As presented in Figure 1, cause-effect values for level 2 factors were leaning towards the 'cause' side, whereas three out of four level 1 factors were leaning towards the opposite 'effect' side. To an extent, this confirms previous assumptions of top-down 'routes to failure', with active failures at level 1 for the most part a manifestation of higher-level 'causes' in the sequence of events.

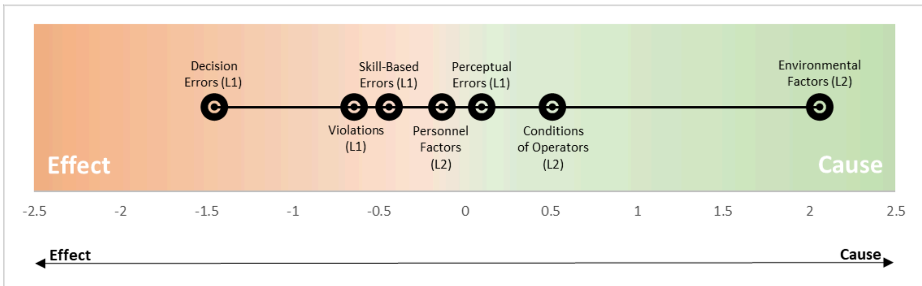

Fig. 1. Cause-effect values of categories at HFACS levels 1 and 2. Positive values signify that the category is an overall 'cause', and negative values signify an overall 'effect'.

In the present results it was notable that amongst the four 'effect' categories in HFACS levels 1 and 2, the level 1 categories of 'Decision Errors' (Ri – Ci = -1.45), 'Skill-Based Errors' (-0.44), and 'Violations' (-0.64) were comparatively stronger 'effects' (leaning further towards the left in Figure 1), than the level 2 category of 'Personnel Factors' (-0.13). In conventional safety management, the mindset was that safety actions should simply be directed at 'cause' categories which are associated with a high number of concomitant categories [11]. The present finding of comparative differences amongst the categories on the cause-effect spectrum showcases the need for user-centered design adaptations. Rather than focusing solely on the quantity of cause-effect relationships emancipating from each category, safety managers will be wise to also consider the comparative, 'qualitative' influence of each category on the basis of their strength as a cause or an effect factor. A comparison of the cause-effect (Ri - Ci) value can highlight categories which are stronger 'causes' as contributors to the overall system safety. Remedial actions focusing on these stronger 'causes' are likely to be more effective or have a stronger effect on system-wide outcomes.

3.3 Selecting Categories within Levels

According to the Standards and Recommended Practices of ICAO Annex 13, safety recommendations suggested as part of accident investigation processes are typically directed to specific addressees [15]. This means that consequential remedial actions are likely to be constrained to specific levels within the organizational hierarchy. However, within each level of the organizational hierarchy, there are typically multiple ways to remedy any given scenario.

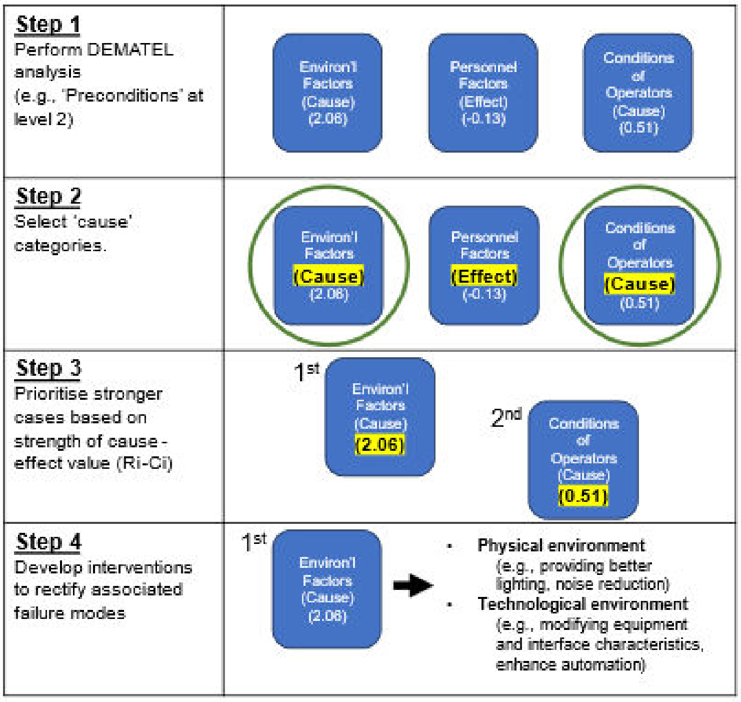

Fig. 2. Illustrative example of how the present methodology can be utilized by safety managers in selecting safety interventions for human factors preconditions at HFACS level 2.

The present finding of the co-existence of both 'cause' and 'effect' categories at each level can assist in the selection of more effective human factors intervention strategies within each level. To illustrate, consider a situation where the Annex 13 investigation addresses improvements to 'Preconditions for Unsafe Acts' at HFACS level 2 (Figure 2). Step 1: safety managers can conduct a DEMATEL analysis including the HFACS level 2 categories. Step 2: they can consider the cause-effect polarity of the various categories and select the 'causes', which in this example will direct them to focus on 'Environmental Factors' and 'Conditions of Operators'. Step 3: a comparison of the strength of the cause-effect (Ri – Ci) value between these two 'causes' will suggest a prioritization on modifying 'Environmental Factors' (Ri – Ci = 2.06) as it has an overall stronger causal effect than 'Conditions of Operators' (Ri – Ci = 0.51). If resources are limited, then prioritize improving the work environment over rectifying operator conditions. Step 4: create and incorporate 'Environmental Factors' interventions into the safety management system. As resources such as time and money are generally limited in the aviation industry, the process can assist safety managers in making more informed decisions related to the development and selection of remedial safety interventions.

4 Conclusion

For the improvement of safety, remedial actions and human factors interventions are often dictated by safety recommendations from accident investigations. However, the investigation process can be affected by subjective cultural factors amongst accident investigators, and existing models such as the Human Factors Analysis and Classification System (HFACS) do not sufficiently capture decision-making contexts and frontline effects on preconditions at higher levels in the system hierarchy. The present research was an attempt to determine whether frontline-level deficiencies can affect higher-level conditions, and to evaluate how each category comparatively influences or is influenced by other factors in the wider system in a cause-effect spectrum. Analysis of N = 30 responses from aviation safety experts using the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method found that frontline errors related to perceptual faults functioned as a 'cause' factor. Also, despite its designation as a 'preconditional' factor, personnel factors associated with crew resource management and risk judgement were found to be an overall 'effect', influenced in the second-order by other factors within the system. Evaluating human factors conditions using the DEMATEL method can assist safety managers in directing remedial actions to 'cause' categories with greater comparative influence, in this case, 'Environmental Factors' and 'Conditions of Operators', to achieve the most effective safety intervention outcomes.

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