International Journal of Industrial Ergonomics 107 (2025) 103743

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Creating more viable safety recommendations in accident investigation by revising the human factors intervention matrix (HFIX)

Wesley Tsz-Kin Chan [a,*], Wen-Chin Li [a], Richard Yeun [b], Thomas Wang [c]

[a] Safety and Accident Investigation Centre, Cranfield University, United Kingdom
[b] School of Engineering, RMIT University, Melbourne, Australia
[c] Taiwan Transportation Safety Board, Taiwan

1. Introduction

The objective of safety occurrence investigations is to determine the circumstances and causes, identify any safety issues, and propose corrective and remedial safety actions and training recommendations. These elements can be considered as the building blocks of safety management system frameworks that are utilised in a range of high reliability industries.

Safety management frameworks typically dictate that investigative processes be carried out in a multi-step process. In the aviation field, Annex 13 to the Convention on International Civil Aviation dictates that occurrence investigations should start with the identification of causal conditions and assessment of hazards and risks, and culminate in the formulation and communication of remedial safety recommendations (ICAO, 2020). In the marine safety field, similar processes progressing through components of human error identification, human error categorisation, and the proposal of necessary measures focusing on latent preconditions have been noted by safety experts as being able to prevent approximately 4 out of 5 accidents (Ugurlu et al., 2021). A high level of commonality in the structure of investigation frameworks across industries can also assist in identifying more global trends. Studies conducted in the mining field support the use of both within and between industry comparisons in the human error identification and categorisation phases to identify cross-industry cultural or temporal phenomena (Patterson and Shappell, 2010).

There are numerous techniques that can be used for the identification and categorisation of deficiencies during occurrence investigations. Notable examples include the AcciMap method which maps the physical and observable activities occurring within the sequence of events (Svedung and Rasmussen, 2002); the Systems Theoretic Accident Modelling and Processes model (STAMP) method which can be used to identify ineffective safety barriers between system components (Leveson, 2004); and the Human Factors Analysis and Classification System (HFACS) which provides a taxonomy for the plotting of latent failures and active errors involved in the accident scenario (Wiegmann and Shappell, 2003).

Comparisons of the various approaches suggested that the AcciMaps and STAMP methods are likely to be more comprehensive in terms of being able to identify a greater quantity of contributory factors and human factors deficiencies, but the downside is that the findings can be overly simplistic because they do not sufficiently represent the external environment, objects, or latent conditions in the lead up to the observable conditions (Salmon et al., 2012; Stanton et al., 2017). This means that whilst these human error identification methods are useful for explaining specific events, they may be inadequate in identifying deficiencies within components of the wider system (Kaptan et al., 2021a). In contrast, the taxonomic nature of the HFACS enables the categorisation of contributory factors across wider system components and for comparative analyses across multiple case studies (Salmon et al., 2012; Stanton et al., 2017).

1.1. Human Factors Analysis and Classification System

Originally developed for military naval aviation (Wiegmann and Shappell, 2003), the HFACS has proved to be relevant in civilian aviation (Li et al., 2008), marine (Aydin et al., 2022; Kaptan et al., 2021a,b), mining (Patterson and Shappell, 2010), and railway safety (Baysari et al., 2008; Reinach and Viale, 2006) applications. The HFACS provides a taxonomy that can be used by safety investigators to categorise causal factors related to an incident or accident. After gaining an understanding of the occurrence through accident reports or interview transcripts, investigators and safety managers can attribute the causal factors into 19 categories of human factors deficiencies distributed over four systemic levels (Fig. 1) (Wiegmann and Shappell, 2003).

As the HFACS was developed on the theoretical framework of James Reason's Swiss Cheese model of accident causation, each of the four HFCAS levels can be considered as a layer of cheese, and the entire block can be considered to represent a wider safety system (Reason, 1990;

* Corresponding author. Safety and Accident Investigation Center, Cranfield University, Martell House, Cranfield, Bedfordshire, MK43 0TR, United Kingdom.
E-mail address: wesley.chan@cranfield.ac.uk (W.T.-K. Chan).

https://doi.org/10.1016/j.ergon.2025.103743
Received 15 October 2024; Received in revised form 16 March 2025; Accepted 6 April 2025
Available online 10 April 2025

Wiegmann and Shappell, 2003). HFACS exercises are typically carried out starting from the lowest level (Level 1: 'Unsafe Acts'), where the observable active errors and violations committed by frontline operators are plotted.

Following the Swiss Cheese concept, errors and violations at HFACS level 1 are considered to be the end product of a series of latent conditions originating from higher system levels, which may be hiding inactive until the 'holes in the Swiss cheese' align to result in an active error. To identify these inactive latent conditions, analysts can move up the HFACS framework to attribute incident causal factors to HFACS categories at level 2 (L2: 'Precondition for Unsafe Acts'), which includes environmental factors, operator conditions, and personnel factors; level 3 (L3: 'Unsafe Supervision'), which covers supervisory non-conformities; and the highest Level 4 (L4: 'Organisational Influences'), which encompasses organisational structure and organisational culture factors.

Based on the analysts' opinions on which latent conditions are relevant to the accident sequence, the frequency of use of each category or descriptor can be compared to that of other systems and tracked over time for trend monitoring (Wiegmann and Shappell, 2001). Statistical analyses can also be carried out to examine the strength of associations between HFACS categories and across system levels (Li et al., 2008). The HFACS is therefore said to enable the creation of safety management strategies based on field-collected data rather than on theory and opinion alone (Shappell and Wiegmann, 2007).

1.1.1. Multiple 'routes to failure'

Conventionally, the 'routes to failure' are assumed to flow in a top-down direction. Organisational influences (HFACS L4) are considered to lead to unsafe supervision (L3), in turn creating preconditions for unsafe acts (L2) which results in observable active failures in the form of acts or errors committed at the frontline (L1) (Reason, 1990). More recent research has found that 'routes to failure' can exist in even more directions. Influential sequences can skip across levels, and each category can concurrently influence and/or be influenced by one or more other categories in a many-to-one mapping (Li et al., 2008). There can be multiple routes in the Swiss Cheese through which the active error or violation can perpetuate.

A possible explanation is that each active failure may be logically caused by more than one 'route' in the Swiss Cheese. In an ideal world, when given the exact same list of causal factors, all analysts should theoretically attribute them into the exact same HFACS categories. In reality, this may not be the case. The exact same set of factors may be attributed by different people into different categories or more than one category. According to the 'relevance paradox' concept, interpretive differences exist amongst different analysts as people have a natural inclination to be drawn towards factors that are readily explainable in their own relevant contexts (Williams, 2010).

Previous studies have investigated inter-rater differences in HFACS categorisations by asking different analysts to categorise identical lists of causal factors using HFACS. In an analysis of railway accidents, Baysari et al. (2008) found that factors associated with equipment design faults was attributed by some analysts as falling under 'Resource Management' (HFACS level 4) (51 times out of 40 'equipment failure' occurrences), whereas other analysts classified the same condition as falling under environmental preconditions at level 2 (13 times).

These inter-rater differences may be explained, at least in part, by cultural differences or (mis)leading keywords. In a comparison of U.K. and Taiwanese air accident investigators' analysis of the Uberlingen mid-air collision using HFACS, Li et al. (2007) found that U.K. participants were more likely to use the 'Adverse Mental States' category (U.K.: 98.3 %, vs. Taiwan: 51.7 %, $\chi^2 = 8.195$, $p = .004$), whereas Taiwanese participants were disposed to attribute the same conditions to the category of 'Perceptual Errors' (U.K.: 31.3 %, vs. Taiwan: 82.8 %, $\chi^2 = 11.939$, $p = .001$), which is considered to be less blameworthy in East Asian (i.e., Taiwanese) cultures.

Category or descriptor titles containing keywords or personnel roles may also trigger analysts to default to certain options. In a marine-based

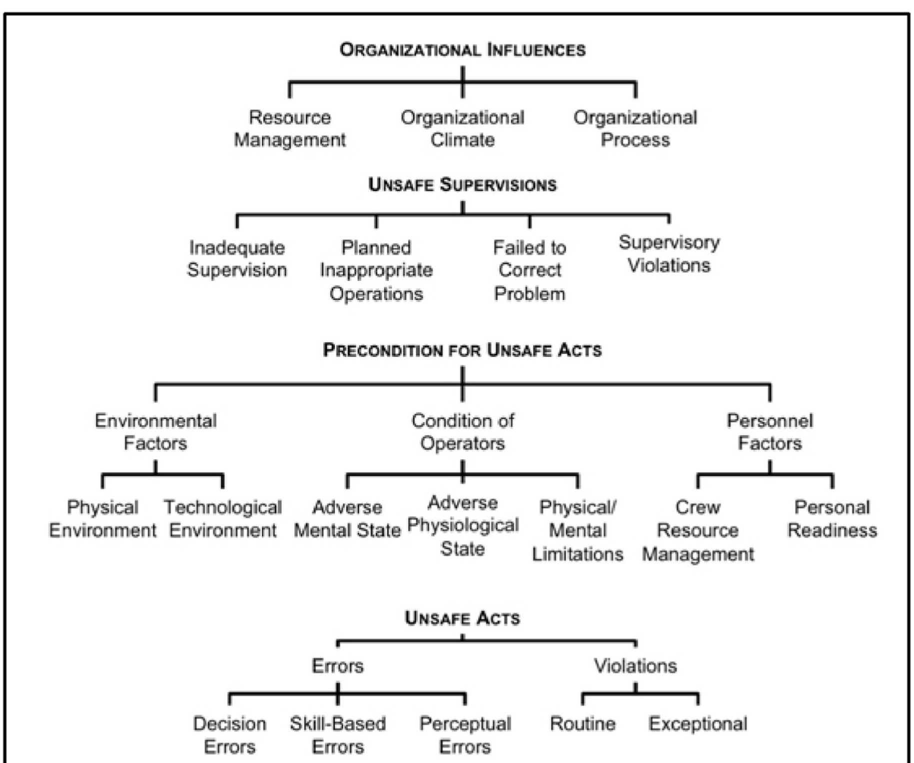

Fig. 1. The Human Factors Analysis and Classification System (HFACS) providing 19 categories over 4 levels for the attribution of causal factors and deficiencies (Wiegmann and Shappell, 2003).

example, Ergai et al. (2016) asked 125 participants to attribute the factor "The Captain chose to continue fishing despite the severe weather predictions and the exposed location of the ship". Whilst the most objective response would have been 'Decision Error' because the active human factor deficiency relates to the decision to continue fishing, more than 50 % of the participants attributed the error to 'Planned Inappropriate Operations' or 'Supervisory Violation' simply because they considered the Captain as being in a supervisory role.

1.1.2. Consolidating HFACS categories

Inter-rater differences in HFACS categorisation have generally been resolved using the consensus approach where multiple analysts will deliberate amongst themselves the most appropriate option (e.g. Kaptan et al., 2021a; Li et al., 2008). However, the consensus approach may not be appropriate for the subsequent creation of remedial safety interventions in the safety management process as it negates variations in individuals' perception of 'what went wrong'. Interventions developed in response to the group consensus may be viewed as irrelevant or be practically ineffectual to individuals whose views do not align with the consensus. This is relevant in real world practice because due to resource constraints it is usually unrealistic to simultaneously improve multiple criteria (Shieh et al., 2010). In addition, if investigators cannot agree on which category to attribute a certain factor, then trend monitoring for safety management purposes can also be difficult (Chan and Li, 2022).

The existence of a large number of 'routes to failure' and the scattering of causal factor attribution across multiple HFACS categories amongst different analysts can impair the reliability of HFACS categorisations. One solution is to limit the system size so that abstract categories can be harmonised and to reduce distraction (Olsen and Williamson, 2017).

According to Shappell (2020, as cited in Lew (2022), HFACS categories representing systemic latent conditions at levels 2, 3, and 4 can be consolidated into five deficiency groups of 'Environment', 'Task', 'Technology', 'Human', or 'Organisational' factors (Table 1). In theory, the reduction in size from 18 categorical options down to five groups should reduce distraction and hence improve the inter-rater reliability of the taxonomy. Nevertheless, it remains uncertain whether the output of such a simplified framework will still be applicable for the purposes of safety management, especially for the creation of remedial safety actions. Thus, the first objective of the present research was to validate the consolidation of HFACS categories into five groups for the purposes of safety management applications.

1.2. Human factors intervention matrix

The ultimate objective of safety management systems is to propose corrective and remedial safety actions. The HFACS has limited applicability for this purpose because it is simply a taxonomy for investigating existing human factors conditions (finding out 'what went wrong'). It is not a tool for instructional systems design, and it provides little guidance on the objective formulation of safety remedies ('what can be done about it'). Interventions based solely on human factors taxonomies such as HFACS can often lack sustained impact because although accidents often repeat the same sequence of events, relevant intervention strategies may change depending on current demands and resource limitations (Chen et al., 2014).

Table 1
HFACS categories consolidated into five deficiency groups.

Corresponding HFACS Categories	Consolidated Deficiency Group
'Physical Environment'	**Environment**
'Inadequate Supervision'	**Task**
'Planned Inappropriate Operations'	
'Failed to Correct Problem'	
'Supervisory Violations'	
'Technological Environment'	**Technology**
'Adverse Mental States'	**Human**
'Adverse Physiological States'	
'Physical/Mental Limitations'	
'Crew Resource Management'	
'Personal Readiness'	
'Resource Management'	**Organisational**
'Organisational Climate'	
'Organisational Process'	

To rectify these problems, Shappell and Wiegmann (2009a) proposed the Human Factors Intervention Matrix (HFIX) as an extension to HFACS. In the HFIX, active failures committed on the frontline (i.e., errors and violations, representing HFACS L1) are pitted against five intervention approach types of 'Environment', 'Task', 'Technology', 'Human', or 'Organisational' recommendations (Fig. 2A). Coincidentally, the five intervention approach types within HFIX correspond with the five consolidated HFACS deficiency groups (as presented in Table 1). The goal of the HFIX is to ensure that the selection of interventions covers as many failure and intervention types as possible by ensuring that as many boxes within the matrix are "filled in" as possible. A third dimension can also be included (becoming HFIX^3: Fig. 2B), representing evaluative criteria of 'Feasibility', 'Acceptability', 'Cost-Benefit', 'Effectiveness', and 'Sustainability' ('FACES': Table 2), so that the subjective ratings of each proposed intervention can be assessed (Shappell and Wiegmann, 2009a).

Simply explained, the HFIX or HFIX^3 can be used to determine which areas a safety management system has "covered". Imagine a situation where a safety analysis using HFACS finds 'Decision Errors' to be a safety deficiency within an organisation (top row of Fig. 2A). To rectify these deficiencies, the safety management system would ideally want to devise some safety interventions addressing 'Environment' deficiencies, some interventions addressing 'Task' conditions, as well as some addressing 'Technology', 'Human', and 'Organisational' conditions (columns in Fig. 2A, thus moving across the top row). If time is available, then safety managers will probably also want to evaluate these newly devised interventions on 'FACES' criteria (the third dimension, the 'z' axis, in Fig. 2B), to make sure they are highly rated and fit-for-purpose. In an ideal world, the safety management system should 'fill in the cube' to 'cover all bases' so that all potential active failures are addressed by a range of remedial safety interventions, which are all evaluated highly across a range of evaluation criteria.

However, a weakness of the original HFIX model is that its first dimension is based on frontline active failures at HFACS L1 (Fig. 2, '*y*' axis). The percentage of accidents associated with human error has remained relatively stable (Shappell et al., 2007), and 'routes to failure' can exist and interact across different categories before the consequential failure is observable (Li et al., 2008). To use HFACS L1 active failures as the sole basis for suggesting interventions is "like focusing on a fever without understanding the underlying illness causing it" (Li and Harris, 2013).

In addition, resilient systems require several breaches before an unsafe or unintended outcome occurs (Harris and Li, 2011). Analysts' evaluations of the viability of safety interventions can be driven by their beliefs of 'what went wrong' and 'what can be done about it' (Shappell and Wiegmann, 2007). If the 'what went wrong' is solely focused on active failures at level 1, then 'what can be done about it' in relation to latent conditions at the higher HFACS levels may be inappropriately discounted in the subsequent evaluations.

Therefore, the present research proposed a revision to the HFIX^3. The frontline-level errors and violations in the original HFIX^3 model were replaced by the five consolidated HFACS deficiency groups ('Environment', 'Task', 'Technology', 'Human', or 'Organisational') (Table 2; Fig. 3). Thus, the second objective of the present study was to determine whether the participants' tendency to attribute causal factors into HFACS categories within the 'Environment', 'Task', 'Technology', 'Human', or 'Organisational' groups were significant predictors of how the same participants evaluated HFIX interventions of different approach types (coincidentally also 'Environment', 'Task', 'Technology',

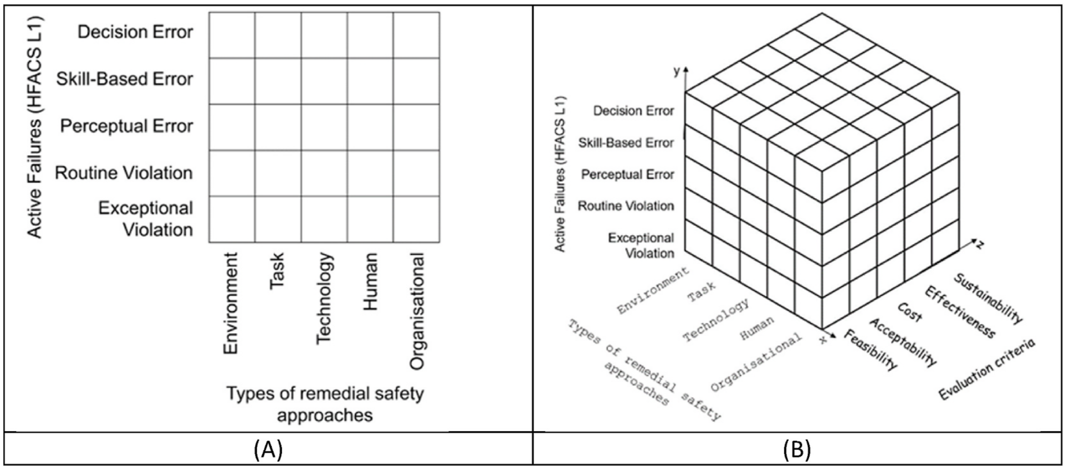

Fig. 2. The original Human Factors Intervention Matrix (HFIX) (A) and $HFIX^3$ (B), pitting active failures at HFACS level 1 ('y' axis) against intervention approaches ('x' axis) and evaluative criteria ('z' axis) (adapted from Shappell and Wiegmann, 2009a).

Table 2
'FACES' intervention rating criteria within the HFIX3 model.

Rating Criteria (low 1 – high 5)	Description (Shappell and Wiegmann, 2009a)
Feasibility	Can the change be implemented relatively easily or quickly?
Acceptability	Will those being impacted by the intervention readily accept the change?
Cost-Benefit	Does the benefit of the intervention outweigh the costs?
Effectiveness	How effective will the intervention be at eliminating the problem or reduces its consequences?
Sustainability	How well will the intervention last over time?

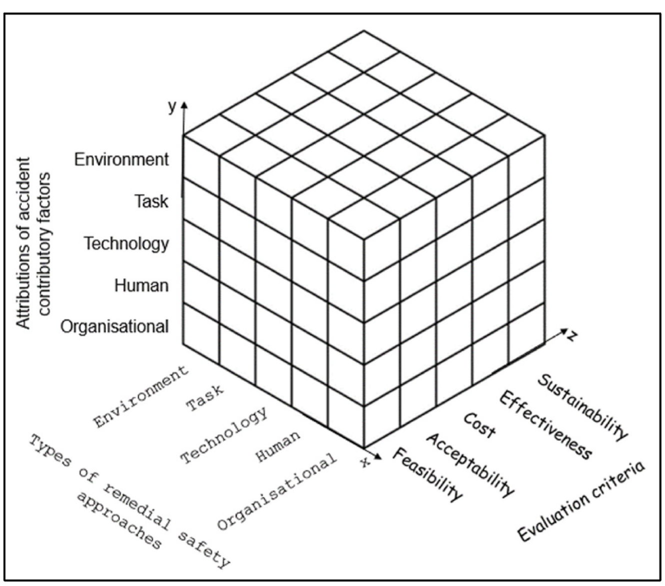

Fig. 3. Adapted '$HFIX^3$' framework with the frequency of attribution of contributory factors ('y' axis) pitted against remedial safety approach types ('x' axis) and evaluation criteria ('z' axis).

'Human', or 'Organisational') under the criteria of 'Feasibility', 'Acceptability', 'Cost-Benefit', 'Effectiveness', and 'Sustainability' (Table 2).

Based on the stated objectives, the research question for the present research was therefore:

Can safety analysts' utilisation of HFACS categories within 'Environment', 'Task', 'Technology', 'Human', or 'Organisational' groups predict their evaluative ratings of various types of HFIX interventions (coincidentally also 'Environment', 'Task', 'Technology', 'Human', or 'Organisational' types), on the evaluative criteria of 'Feasibility', 'Acceptability', 'Cost-Benefit', 'Effectiveness', and 'Sustainability'?

2. Method

2.1. Participants

Participants were aviation safety professionals recruited by convenience sampling. Aviation professionals attending professional development courses in one of two post-graduate institutions, either in Australia or the U.K., and the academics presenting these courses, were invited to participate. To ensure reliability, only those who were trained or experienced in using HFACS as part of their professional or academic experience were included.

2.2. Research design

A survey hosted on the Microsoft Forms platform was used for data collection. Prospective participants were sent an email which contained an anonymous hyperlink to the survey. On opening the hyperlink, the participants were shown an information page which described the tasks, research purpose, ethics and data handling protocols, participant rights, and a consent form. Participants who provided their consent in a dedicated checkbox were then redirected to the main survey. Ethics approval was provided by the University Ethics Committee (CURES, 20576/2023), and data collection was carried out in May 2024.

The first part of the survey consisted of an HFACS coding exercise which used the TransAsia Airways Flight GE235 accident as a case study. The accident involved an ATR72 aircraft which lost control and subsequently impacted terrain 3 nm East of Songshan Airport on February 4, 2015 (Aviation Safety Council, 2016). Participants were asked to read a short synopsis of the accident, and then the $n = 22$ contributory factors listed in the official accident report were presented as survey items. A dropdown list containing the 19 HFACS categories were placed alongside each item, and participants were asked to select the HFACS category which, in their opinion, was the most representative of the corresponding contributing factor item.

The second part of the survey was an evaluative rating exercise using the revised $HFIX^3$, which was based on the $n = 20$ safety recommendations put forward by the official investigation report. Each safety recommendation or remedial action published in the report was presented as survey items. Participants were asked to rate each item on five HFIX evaluative criteria of 'Feasibility', 'Acceptability', 'Cost-Benefit', 'Effectiveness', and 'Sustainability' ('FACES') on five-point Likert-scales from low (1) to high (5).

2.3. Coding framework

The intent of the present research was to examine whether the participants' tendencies to attribute causal factors into HFACS categories falling within one of five deficiency groups can predict how they subsequently rated five different types of HFIX intervention approaches. The goal was not to carry out a 'textbook' HFACS categorisation exercise for the case study. The GE235 incident was purely used as a specimen case study for the participants to perform a HFACS and HFIX coding exercise. There was no need for the analysts to achieve a consensus, and thus unlike conventional HFACS and HFIX exercises conducted with a strict accident or incident analysis focus (e.g., Kaptan et al., 2021a; Li et al., 2008), the emphasis was not on finding which specific causal factors in the case study were associated with which specific HFACS categories. The emphasis was on individual analysts' subjective differences in how they used or attributed factors to certain HFACS categories, when given the exact same list of causal factors. This was then compared with the individual analysts' subjective ratings of five coincident types of HFIX interventions.

2.3.1. Independent and dependent variables

The flowchart in Fig. 4 summarises the steps of the methodology and how the variables were derived in order to answer the research question.

To derive the independent variables, participants' frequencies of attribution of causal factors into HFACS categories within each deficiency group ('Environment', 'Task', 'Technology', 'Human', or 'Organisational') were compounded. In the present methodology, the attribution of causal factors into HFACS categories were based on the participants' own, qualitative opinions. To illustrate, the 'Resource Management', 'Organisational Climate', and 'Organisational Process' HFACS categories consolidate into the 'Organisational' deficiency group (Table 1). If a participant picked the 'Resource Management' category once, and the 'Organisational Climate' category twice, then the consolidated 'Organisational' deficiency group as an independent variable received a count of 3. Hence, the independent variables form the '*y*' (vertical) axis in the adapted HFIX^3 (Fig. 3).

The dependent variables were derived from safety recommendations published in the official accident report of the GE235 accident (Aviation Safety Council, 2016) through a two-step process. In the first step, the n = 20 GE235 safety recommendations were tagged by a group of five subject matter experts into one of five approach types ('Environment', 'Task', 'Technology', 'Human', or 'Organisational', forming the '*x*' axis of the adapted HFIX cube). This was conducted with reference to the types of remedial actions by HFIX approach in the original HFIX framework (Shappell and Wiegmann, 2009b, Table 3). In the second step, survey participants were asked to evaluate the n = 20 safety recommendations on the 'FACES' criteria. These criteria were rated on a scale of 1 (low) to 5 (high), with ratings on the high end more desirable.

The participants' rating scores for all safety recommendations within each approach type ('Environment', 'Task', 'Technology', 'Human', or 'Organisational') were averaged to the mean. To correct for cultural response bias, where certain participants may be culturally disposed to choosing extreme or central ratings, and to account for non-linear relationships in the rating scale (i.e., 'Moderately Feasible' may not necessarily be twice as feasible as 'Low Feasibility'), the evaluation rating scores were transformed for each participant and for each criterion. The means were transformed into rank order format from highest rated (5) to lowest rated (1) amongst 'Feasibility', 'Acceptability', 'Cost-Benefit', 'Effectiveness', and 'Sustainability' criteria, with mean ranks assigned to ties. The resulting ranked order score was used for statistical analysis and to create the final '*z*' axis in the adapted HFIX^3 (Fig. 3).

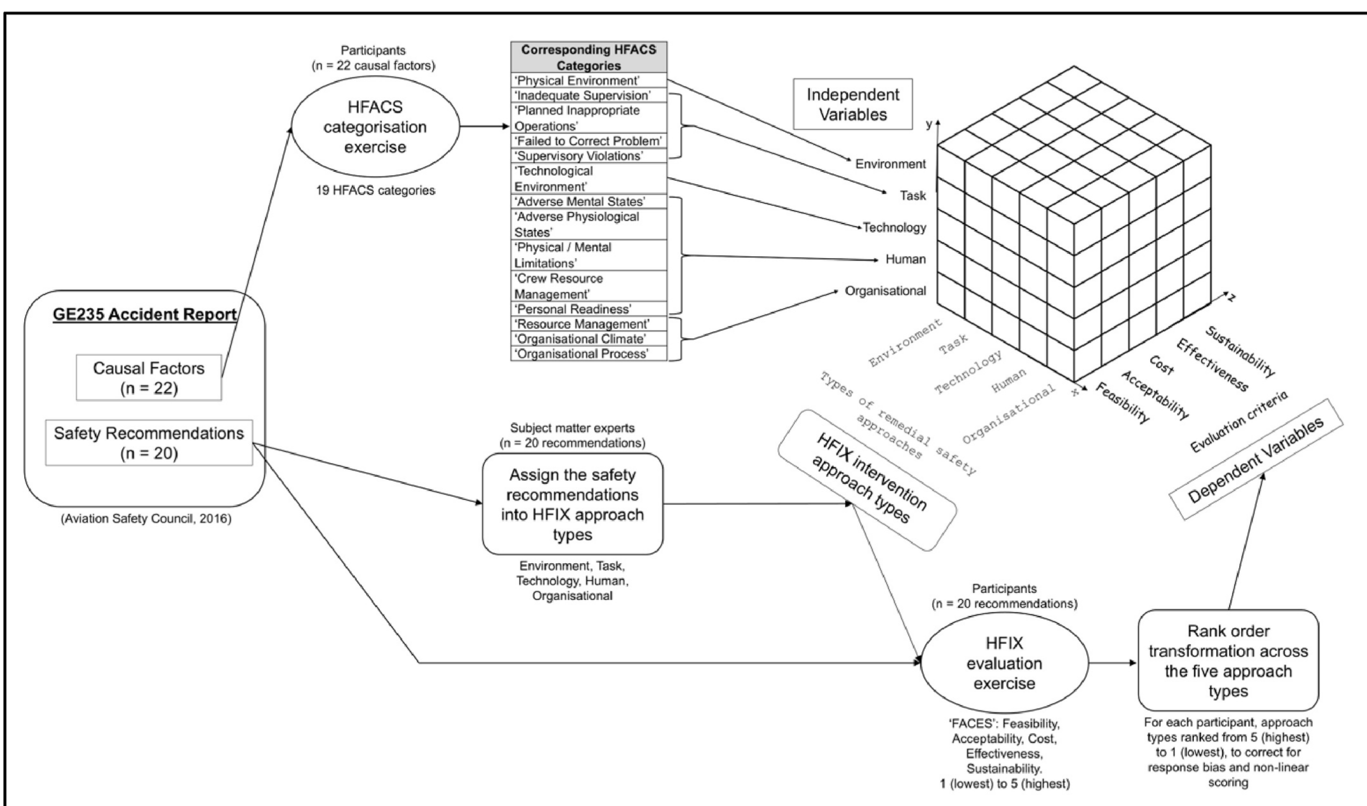

Fig. 4. Flowchart of the study methodology.

Table 3
Examples of remedial actions by HFIX approach.

HFIX Approaches	Examples of Remedial Actions
Environment	• Modifications to the operational or ambient environment, such as heat, vibration, lighting.
Task	• Amending, reviewing, developing, and validating procedures, manuals, checklists, and other instructions or guidance.
Technology	• Design and manufacturing changes including the modification, replacement, removal, or repair of parts and equipment. • Maintenance inspections, damage detection, and recommended safety checks.
Human	• Reviewing, developing, and implementing training programs. • Training of personnel to handle emergencies.
Organisational	• Human resource management review on the adequacy and skills of employees and the need for additional personnel. • Issuance, modification, or review of policies, rules, and regulations. • Improvements in disseminating, storing, and publishing information and reporting activities. • Conducting research and study to review processes and validate methodologies.

3. Results

3.1. Sample characteristics

N = 11 participants participated in the HFACS exercise and the evaluation of remedial safety interventions using HFIX criteria. The participants either had a professional background in Safety Management (n = 7), were in a supervisory or executive-level role within air crew or engineering professions (n = 2), had post-graduate level education in aviation management (n = 1), or was cross-qualified in more than one field (n = 1). The frequency of participants attributing contributory factors in the GE235 accident into particular latent condition groups are presented in Table 4.

3.2. Statistical analysis

Data analyses were performed using SPSS (version 29). Model fit statistics were tested by the log-likelihood test comparing the null and fitted models, and tests for the proportional odds assumption were carried out using the Test of Parallel Lines. These tests were successful across the board. Given these results, ordinal regression analyses were performed to assess how the participants' frequency of attributing contributory factors into HFACS categories within one of five groups of 'Environment', 'Task', 'Technology', 'Human', or 'Organisational' factors ('y' axis), can influence their subjective ratings of respective HFIX intervention approach types ('x' axis) based on the five evaluative criteria of 'Feasibility', 'Acceptability', 'Cost-Benefit', 'Effectiveness', and 'Sustainability' ('z' axis).

Table 4
Frequency of attribution of GE235 contributory factors across five HFIX deficiency types.

HFIX deficiency type	Corresponding HFACS categories	Frequency	% of Total
Task	'Inadequate Supervision' 'Planned Inappropriate Operations' 'Failed to Correct Problem' 'Supervisory Violations'	68	37.16 %
Organisational	'Resource Management' 'Organisational Climate' 'Organisational Process'	59	32.24 %
Technology	'Technological Environment'	26	14.21 %
Human	'Adverse Mental States' 'Adverse Physiological States' 'Physical/Mental Limitations' 'Crew Resource Management' 'Personal Readiness'	26	14.21 %
Environment	'Physical Environment'	4	2.19 %

3.3. Findings

The results showed that the frequency of attribution of accident contributory factors into certain HFACS categories noticeably influenced the subjective evaluative ratings of different types of safety interventions, with significant results presented in Fig. 5. The rows represent the five groups of HFACS deficiencies. The columns represent HFIX intervention approach types. Where the investigators' tendency to attribute accident contributory factors to a certain HFACS deficiency group was significantly associated with how they rated certain types of HFIX interventions, this information was presented in the appropriate cell.

To illustrate: In the present study, all participants were presented with an identical list of 22 contributory factors (drawn from the GE235 accident report) and they were asked to categorise these 22 factors using HFACS, using their own opinion. Some participants to a greater extent attributed these factors to 'Task'-type HFACS conditions. Hence, we enter Fig. 5 from the second row. Looking horizontally across, we can see that this greater attribution to 'Task'-type HFACS conditions was significantly associated with how these participants evaluated HFIX interventions on the 'Task'' and 'Human' columns. Within each cell, negative ordinal regression outputs represent negative predictive relationships (where an increase of one variable predicts the decrease of the corresponding variable), and positive outputs represent positive relationships (where the increase of one variable predicts a corresponding increase in the associated variable). Thus, based on this example, what it means is that accident investigators who liked to attribute incident causal factors to 'Task'-type HFACS conditions were likely to rate 'Task' interventions as less feasible and 'Human' interventions as more feasible.

Overall, differences were detected in four of the five types of remedial safety approaches, specifically the 'Task', 'Technology', 'Human', and 'Organisational' types. The participants' subjective evaluation of

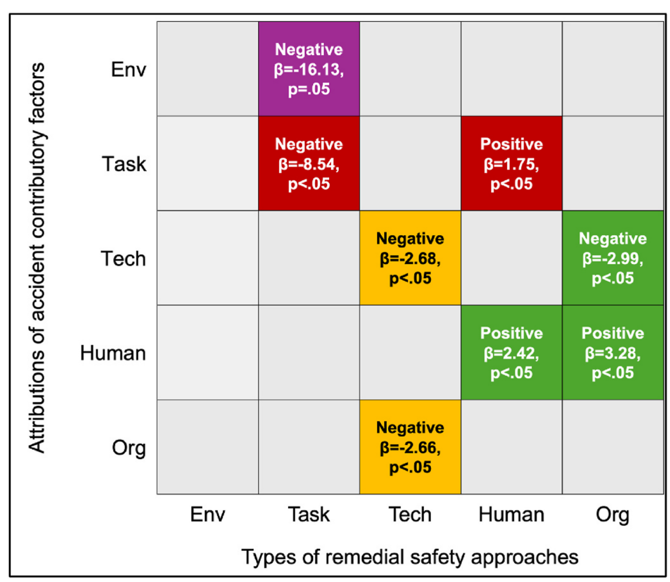

Fig. 5. The frequency of attribution of contributory factors into HFACS categories within one of five groups (rows) against the evaluated viability of corresponding remedial approach types (columns). Highlighted cells indicate significant predictive effects on 'Feasibility' (red), 'Acceptability' (yellow), 'Cost' (green), and 'Sustainability' (purple) ratings. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

safety intervention approach types on the criteria of 'Feasibility', 'Acceptability', 'Cost-Benefit', and 'Sustainability' scores were also found to be predictable based on the participants' patterns of attribution of accident factors into HFACS deficiency groups.

3.3.1. Feasibility

Feasibility refers to the ability for a safety intervention to be easily or quickly implemented (Shappell and Wiegmann, 2009a). On a scale of 1 (lowest) to 5 (highest), a score of 1 represents that the participants thought the intervention will be challenging to implement. On the contrary, a score of 5 represents that the participants considered that the intervention can be carried out within a short timeframe and with little effort.

In the present results, the frequency of attribution of contributory factors to 'Task' type HFACS categories was found to have a statistically significant predictive effect on evaluative ratings on the feasibility of 'Task' type intervention approaches ($\beta = -8.54$, 95 % CI = −16.87 to −0.22, $p < .05$) and on the feasibility of 'Human' type interventions ($\beta = 1.75$, 95 % CI = 0.04–3.45, $p < .05$; Fig. 5). Participants who attributed more contributory factors to the 'Task' categories within HFACS (i.e., inadequate supervision, planned inappropriate operations, failed to correct known problem, and supervisory violations) considered 'Task' type interventions to be less feasible, but 'Human' type interventions to be more feasible.

3.3.2. Acceptability

The 'Acceptability' scale evaluates whether the raters thought the proposed intervention will be readily accepted by the target workforce (Shappell and Wiegmann, 2009a). A score of 1 (lowest) represents that the participants considered that it is unlikely to be well accepted, and hence will likely be treated with disdain, by the workforce. A score of 5 (highest) represents that the workforce is likely to accept and consent to the changes.

The results suggest that participants who attributed more causal factors into 'Technology' deficiencies tended to consider 'Technology' type HFIX interventions to be less acceptable ($\beta = -2.68$, 95 % CI = −5.22 to −0.14, $p < .05$). Similarly, participants who attributed more causal factors into 'Organisational' category HFACS deficiencies in the accident analysis phase were likely to give 'Technology' changes lower acceptability ratings ($\beta = -2.66$, CI 95 % = −5.22 to −0.14, $p < .05$; Fig. 5).

3.3.3. Cost-benefit

'Cost-benefit' refers to the participants' judgement of whether the benefit of the proposed intervention is likely to outweigh the cost of implementing it (Shappell and Wiegmann, 2009a). A low score of 1 represents that the participants thought the safety intervention will have a high cost but create very little benefit to system safety outcomes. On the other hand, a high score of 5 represents an intervention that can be cheaply and easily implemented yet provides substantial benefits.

Evaluative ratings related to cost-benefit were found to be predictable by the participants' frequency of attributing contributory factors to HFACS categories within the 'Human' group. Those who made more attributions to 'Human' deficiencies when analysing the causal factors of the case study were found to rate subsequent remedial interventions based on 'Human' ($\beta = 2.42$, CI 95 % = 0.27–4.58, $p < .05$) and 'Organisational' ($\beta = 3.28$, CI 95 % = 0.05–6.52, $p < .05$) approaches as having greater cost-benefit. Contrarily, participants who attributed more causal factors to HFACS categories within the 'Technology' group were found to rate 'Organisational' interventions as less cost-beneficial ($\beta = -2.99$, 95 % CI = −5.81 to −0.17, $p < .05$; Fig. 5).

3.3.4. Sustainability

The 'Sustainability' scale evaluates whether the participants considered the intervention to have a lasting, sustainable impact. A low score (1) represents that the intervention is considered to only to work in the short-term, whereas a high score (5) represents that the raters thought the change will bring longer-term, lasting impacts. The long-term viability of safety recommendations is important because accident analyses have often revealed that accidents often repeat the same sequence of events which played out many times previously, in spite of systemic interventions (Shappell and Wiegmann, 2009a).

In the present results, participants' frequency of attributing accident contributory factors to HFACS categories within the 'Environment' group was found to be a significant predictor of subjective ratings on the sustainability of 'Task' type intervention approaches ($\beta = -16.13$, 95 % CI = −32.22 to −0.03, $p = .05$; Fig. 5). Participants who attributed more contributory factors to 'Environment' deficiencies were found to rate 'Task' type interventions as less sustainable.

4. Discussion

The research question was positively answered by the present results. Attribution patterns to HFACS categories across five deficiency groups were valid predictors of evaluative ratings of various types of HFIX intervention approaches. Specifically, the findings suggest that frequencies of attributing causal factors into one of five groups predicted the 'Feasibility', 'Acceptability', 'Cost-Benefit', and 'Sustainability' of 'Task', 'Technology', 'Human', and 'Organisational' intervention approaches. Conditions where the evaluative ratings of HFIX intervention approaches can be predicted by the analysts' frequencies of attributing causal factors to HFACS deficiency groups are presented in Fig. 6.

4.1. Considering the 'relevance paradox' and 'routes to failure'

As the HFACS framework was designed on the basis of the Swiss Cheese model, previous research has widely argued that there can be multiple 'routes to failure' connecting the holes of the Swiss Cheese. In the present study, associations between same-type attributions and interventions (e.g., 'Task' deficiencies and 'Task' interventions) on the evaluative criteria of feasibility and acceptability showcases the need to consider how latent conditions are interlinked in the 'relevance paradox' and 'routes to failure' concepts.

Negative predictive relationships were detected between 'Task' deficiencies and 'Task' interventions, as well as between 'Technology' deficiencies and 'Technology' interventions. Participants who attributed more factors to 'Task' type conditions considered 'Task' type interventions to be less feasible, and more frequent attribution of causal factors to 'Technology' categories predicted lower acceptability ratings of 'Technology' interventions. These observations correspond with previous studies which argued that same-type or direct interventions (e.g., improve CRM practices to fix CRM deficiencies) will have limited effect unless changes are made elsewhere in the 'routes to failure' to support the primary changes (e.g., changing organisational processes to provide CRM training facilities) (Li et al., 2008).

In contrast, a positive predictive relationship was found between attributions to 'Task' deficiencies and the feasibility rating of 'Human' interventions. Participants who attributed more causal factors to 'Task' deficiencies rated 'Human' interventions as more feasible. The positive predictive relationship can possibly be explained by the 'relevance paradox'. Previous research has found 'Task' and 'Human' conditions to dynamically coexist, and that interventions to accommodate one type of deficiency will dynamically alter the potential of innovations related to other dimensions (Wiegmann and Rantanen, 2003). This may be because 'Task' deficiencies cover situations such as failure to provide proper training or excessive tasking. These situations may be perceived as being more relevantly addressed via 'Human' interventions (e.g., personnel selection, incentives, training, teamwork, communication) rather than through 'Task' interventions (e.g., ordering or timing of events, procedures, standardization) (Shappell and Wiegmann, 2009a).

What this means in practice is that when safety analysts want to propose safety recommendations or remedial safety actions, they should

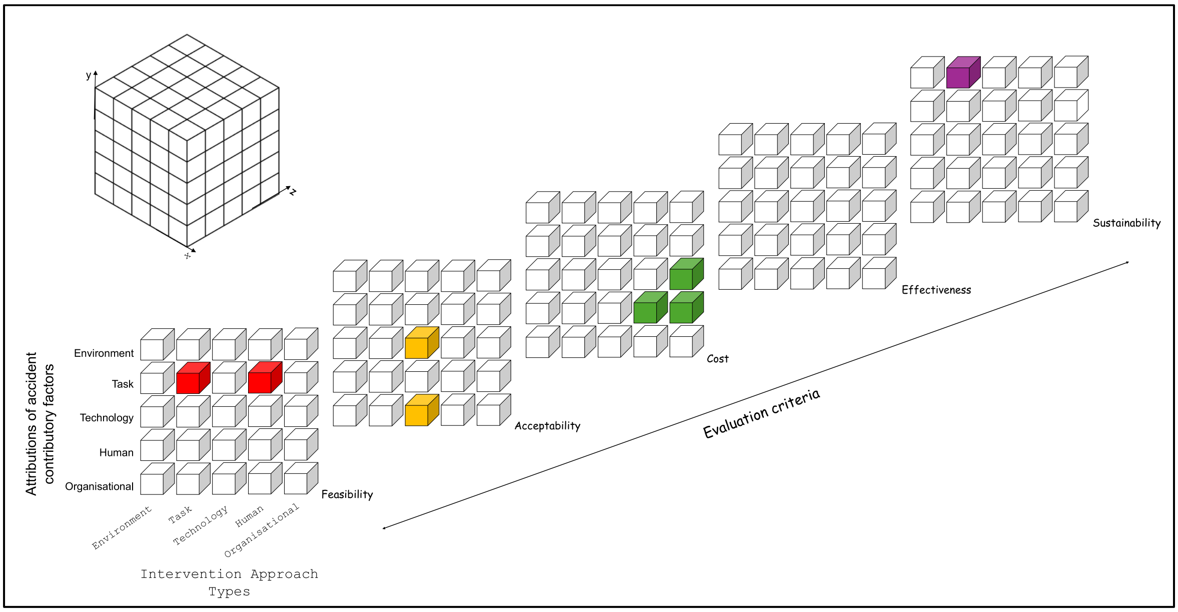

Fig. 6. The revised HFIX[3] presented in 'expanded' 3D cube format. Highlighted cells indicate significant predictive effects between attributions of contributory factors and the evaluative ratings for the respective evaluation criteria layer across five types of intervention approaches.

consider the target user groups' perception of 'what went wrong' in the 'relevance paradox' concept. Firstly, the results suggest that if the target users tended to consider the faults as originating from 'Task' or 'Technology' conditions, then direct interventions using 'Task' or 'Technology' type safety remedies should be de-emphasised as they are likely to be considered as less feasible and/or acceptable. Secondly, the results also serve as a reminder that alternative 'routes to failure' should be considered in safety management systems. For example, rather than directly addressing 'Task' conditions with 'Task' interventions, the implementation of remedial safety actions falling under the 'Human' approach may provide a more feasible fix.

4.2. Improving cost-benefit by integrating interventions across levels

It was notable to find that the frequency of attributions to 'Human' categories simultaneously predicted higher cost-benefit ratings for both 'Organisational' and 'Human' interventions. 'Organisational' and 'Human' interventions exist at different levels within an organisational hierarchy. 'Human' intervention approaches address preconditions of unsafe acts (e.g., improving mental and physiological conditions of human parties, at HFACS L2), whereas 'Organisational' interventions address higher-level organisational changes (e.g., budgeting, policies, and procedures at HFACS L4) (Shappell and Wiegmann, 2009a). Thus, the findings substantiate previous research which argued that resilient systems require several breaches in the lead up to an unintended outcome (Harris and Li, 2011), and provides further support for the many-to-one mapping of causal 'routes to failure' (Li et al., 2008).

In a review of commercial airline incident reports between 2009 and 2011, researchers have discovered that 'Organisational' and 'Human' intervention approaches respectively made up 41.1 % and 35.2 % of remedial safety actions proposed in response to human error conditions (Chen et al., 2013). On the one hand, the finding of such a high proportion of interventions falling within these two categories gives some confidence to the cost-benefit of safety actions proposed by previous incident investigations. On the other hand, as the high cost-benefit ratings of both 'Organisational' and 'Human' interventions are concurrently associated with the same 'Human' deficiencies, the present findings also showcase the previous knowledge that improvements to the human conditions are unlikely to be successful unless they are supported appropriately by changes at the higher organisational levels (Reason, 1990).

Additionally, the present results also discovered a negative predictive relationship between attributions towards 'Technology' categories and analysts' ratings of the cost-benefit of 'Organisational' interventions. By examining the conditions within 'Technology' deficiencies and 'Organisational' interventions, it is once again possible to come up with an explanation for this finding. 'Technological' deficiencies cover factors such as equipment design and checklist layout faults, interface characteristics, and automation (Wiegmann and Shappell, 2003). 'Organisational' interventions cover changes to company policy and procedures; revisions to training programmes; and changes to quality assurance processes (Shappell and Wiegmann, 2009a). It is likely that the participants considered 'Organisational' fixes to be less cost-beneficial because revisions to policies and training programmes will be remain constrained by what the technological hardware provides.

In practice, what the results suggest is that the suggestion of remedial safety actions should ideally cover different organisational levels and the interactions amongst these levels need to be considered. If the goal is to solely address 'Human' deficiencies in a cost-beneficial manner, both 'Human' and 'Organisational' interventions are viable options, but it will be more ideal if both types of interventions can be applied concurrently as human conditions may be constrained by organisational factors. However, if the goal is to address both 'Human' and 'Technology' deficiencies, then 'Organisational' interventions may be less ideal on the cost-benefit criterion. This leaves 'Human' interventions as the last viable option, meaning that greater consideration should be placed on addressing 'Human' latent conditions at lower levels of the HFACS hierarchy.

4.3. Technology – organisational influences showcase external influences

On the linkage between 'Technology' and 'Organisational' factors, it was noteworthy to find that whilst a higher frequency of attributions to 'Technology' conditions predicted lower cost-benefit ratings of 'Organisational' interventions, this relationship was paired with a predictive relationship in the opposite direction. A greater number of attributions made to HFACS categories within the 'Organisational' group predicted lower acceptability ratings for 'Technology' interventions.

Although it must be emphasised that the two evaluative criteria were respectively on cost-benefit and acceptability, and thus must not be directly compared, the two-way linkage between 'Technology' and 'Organisational' factors supports previous research on mutually interactive influences amongst system and external factors. According to Morley and Harris' (2006) review of human factors influences in high reliability organisations, interventions directed at systemic safety cultures are unlikely to be effective if the actions of workers are constrained by concerns (e.g., regulations and expectations by society and regulators) and influences (e.g., equipment availability as a result of wider economic conditions) originating from external factors.

Within the present research, it is plausible that both 'Technology' and 'Organisational' factors functioned as mutually influential external factors. A review of the case study material used for this analysis (GE235 safety recommendations: Aviation Safety Council, 2016) finds that activities within 'Technology' and 'Organisational' intervention approach types were largely impacted by external influences, such as manufacturer or external auditors' guidance. 'Technology' interventions included working with engine and aircraft manufacturers to rectify or review hardware changes and functions. 'Organisational' interventions included activities such as incorporating manufacturer guidelines into the company procedures, changes to external oversight, audit, and evaluation processes.

This presents a plausible explanation for the present prediction of lower cost-benefit and acceptability ratings. 'Organisational' interventions will not be cost-beneficial unless they are supported with a reduction of external 'Technology' deficiencies. Similarly, and in the opposite direction, 'Technology' interventions will not be acceptable unless they are supported with corresponding external improvements to 'Organisational' causal factors. The findings therefore provide safety analysts with a reminder to consider confounding external factors when proposing remedial safety actions. Ideally, safety management systems should ensure that future interventions will not be constrained by factors external to and outside the control of the immediate system.

4.4. Shared contexts between deficiencies and intervention approaches

In the present findings, higher frequency of attributions made by analysts to 'Environment' HFACS categories negatively predicted the sustainability ratings of 'Task' interventions. Following the 'relevance paradox' concept, this finding may be interpreted as being due to insufficient relevance between Environment' deficiencies (i.e., weather, terrain, cockpit lighting and vibration, etc.) and 'Task' interventions (addressing the ordering or timing of events, procedures, and/or standardization). However, for practical applications, rather than accepting this observation, a closer look into the contexts behind 'Environment' deficiencies provides a clue for how safety management practitioners can fix this negative predictive relationship.

In previous research, it was established that 'Environment' deficiencies (i.e., weather, terrain, cockpit lighting and vibration, etc.) are strongly associated and are likely to coexist with perceptual errors (Li et al., 2008; Wiegmann and Shappell, 2003). Whilst direct relevance between 'Environment' factors and 'Task' remedies may be weak, one solution may be to ensure future safety actions addressing 'Task' factors are routed through the prevention of perceptual errors. For example, standard procedures can be varied to ensure that the timing of tasks and events take into account and attempt to reduce the possibility of visual illusions occurring as part of the workflow. By taking an extra step within the 'routes to failure', negative associations amongst categories may be avoided.

4.5. Revising the HFIX to find practical interventions

There was notably a lack of significant findings on the 'Effectiveness' rating scale (Fig. 6). 'Effectiveness' refers to how effective will the intervention be at eliminating the problem or reduces its consequences, with a score of (5) being the most effective and (1) the least.

On the one hand, this is possibly a limitation related to the present research as the n = 20 safety recommendations utilised in the case study may have limited representativeness for the 'Effectiveness' scale. On the other hand, the finding may actually suggest that the 'Effectiveness' scale may be inapplicable within the 'FACES' dimension of HFIX^3. Previous research on the HFIX^3 similarly found the 'Effectiveness' scale to be unable to significantly distinguish amongst different intervention methods (Chan and Li, 2023). This would suggest that, in practice, the 'FACES' dimension may be reduced to 'FACS'. By reducing the system size, the reliability of the model as well as the ease of use for the HFIX^3 model may be improved.

Also, given that the HFIX^3 model provides three different dimensions, a practical alternative is to adopt a different perspective. One option is to enter the model from a 'transverse' direction, plotting the causal conditions ('y' axis) against the evaluation criteria ('z' axis), to determine what approaches are best for the situation ('x' axis) (Fig. 7). For occurrence investigation and safety management functions this should answer questions like: "If you want a 'feasible' fix for 'task' conditions, then what 'approach type' will be a good (or bad) idea?".

To illustrate, when looking for a *'feasible'* fix for *'task'* deficiencies, the focus should on 'Human' remedial approaches (as it has a positive predictive relation between attribution to 'Task' conditions and the 'Feasibility' rating). 'Task'-based remedies (which had negative relations between its 'Feasibility' rating and the frequency of attributions to 'Task' conditions) will be comparatively less desirable (Fig. 7).

Similarly, in cases where contributory factors are frequently attributed to 'Human' deficiencies, analysts looking for a cost-effective approach should focus on 'Organisational' or 'Human' fixes. In this case, although both options are likely to be associated with greater cost-effectiveness, 'Organisational' fixes ($\beta = 3.28$) are probably a slightly better choice than 'Human' interventions ($\beta = 2.42$; Fig. 7).

4.6. Future practical applications and theoretical limitations

The original HFIX^3 matrix was designed as a confirmatory tool, used by safety managers to verify that they have 'covered all bases' by ensuring that safety actions have 'filled in' all the cells. The modified HFIX^3 matrix, as presented in the current research (Fig. 3), improves the model and transforms it into a predictive tool.

Firstly, the present methodology using five deficiency groups ('Environment', 'Task', 'Technology', 'Human', or 'Organisational') as opposed to the five categories of frontline active failures (HFACS L1) as the entry point to HFIX represents an improvement to the HFIX framework. According to previous studies, the reduction in options is likely to improve the inter-rater reliability of HFACS analyses. Also, as latent factors at higher systemic levels are now included in the creation of safety interventions, the revised model should help to identify predictive relationships linking different 'routes to failure' within the Swiss Cheese. These relations can inform the incorporation of human factors interventions into wider safety management activities crossing different organisational levels.

Secondly, the finding of predictive relations between analysts' attribution of causal factors and their evaluative rating of relevant interventions provides the basis for safety managers to predictively select more highly rated remedial safety actions based on how previous deficiencies are attributed. The three-dimensional cuboidal nature of the modified HFIX^3 matrix also offers different ways to interpret independent and dependent variables, depending on the desired use-case. In conjunction with a reduction in evaluation criteria, such as by possibly eliminating the 'Effectiveness' criterion, the present findings may assist to reduce the complexity of future investigation and safety management processes.

However, a limitation of the present study relates to how the safety recommendations were evaluated by the analysts in the methodology. The present research relied solely on safety recommendations extracted from one case study. Although the mitigating effect of intervention

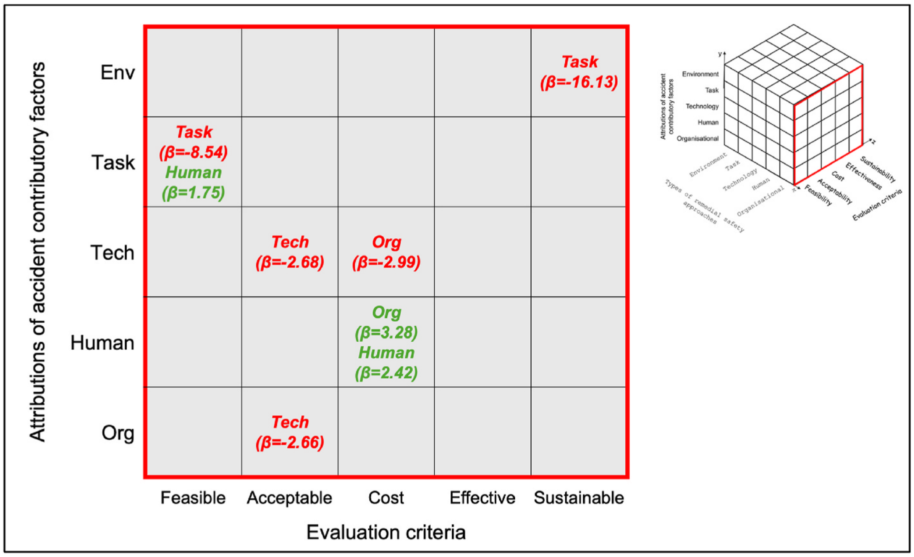

Fig. 7. The frequency of attribution of contributory factors ('y' axis) against five evaluation criteria ('z' axis) in HFIX^3. The polarity of β-values indicates positive (+) or negative (−) relations between attributive frequency and evaluative rating scores on relevant safety approach types ('x') axis.

strategies were known to be moderated by the immediate operational context and hence a large scale analysis using multiple case studies may not be desirable (Chen and Yu, 2018), in future research it may be beneficial to incorporate more extensive factors, perhaps within a restricted, operator-specific safety database.

In addition, when the safety recommendations were evaluated on the criteria of 'Feasibility', 'Acceptability', 'Cost-Benefit', 'Effectiveness', and 'Sustainability', they were assessed independently. Unlike in methods such as AcciMaps and STAMP where control actions linking different deficiencies and interventions can be mapped, the revised HFIX^3 matrix does not consider how certain interventions may influence the viability of other interventions in the second order and beyond. For example, a highly feasible 'Task' intervention may have secondary impacts on the effectiveness of an unrelated 'Human' intervention. Yet, this was not captured in the current methodology. Thus, an opportunity for future research may be to modify or adjust the rating scales according to each operator's conditions, or to use more extensive statistical methods to incorporate secondary changes.

5. Conclusion

Taxonomic frameworks, such as the HFACS and HFIX, have been used by accident investigators to categorise causal factors leading up to occurrences and to suggest consequential remedial actions on a systemic basis. However, previous research has found subjective differences in how causal factors were attributed. If the attribution of 'what went wrong' differed between analysts, then 'what can be done about it' and how these remedial safety interventions are evaluated by the target users are brought into question. The present research examined whether the participants' tendencies to attribute causal factors into certain HFACS categories within one of five Environment', 'Task', 'Technology', 'Human', or 'Organisational' deficiency groups were predictive of their ratings of subsequent remedial safety actions on the five criteria of ('Feasibility', 'Acceptability', 'Cost-Benefit', 'Effectiveness', and 'Sustainability'). It was discovered that ratings of 'Feasibility' were determined by the frequency of attributions to 'Task' categories, ratings of 'Acceptability' were determined by attributions to 'Technology' and 'Organisational' conditions, the 'Cost-Benefit' rating was influenced by how often faults were caused by 'Human' and 'Technology' conditions, and the 'Sustainability' rating was predicted by attributions to 'Environment' factors. Practical recommendations are to consider the 'relevance paradox' and 'routes to failure' when designing interventions, investigate cultural or language contexts when selecting remedial safety actions, and to take into account a wider range of external influences which may impact the success of each intervention. Rectifying deficiencies using same-type interventions were considered to less feasible and less acceptable unless they are supported by changes within other categories in the many-to-one mapping of 'routes to failure'. A closer look at the contextual background of case study deficiencies and corresponding intervention recommendations, especially in the contexts of the target user or operator, should be considered to improve the validity and reliability of future human factors intervention approaches.

CRediT authorship contribution statement

Wesley Tsz-Kin Chan: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Wen-Chin Li:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Richard Yeun:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **Thomas Wang:** Writing – review & editing, Validation, Investigation.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

For the purposes of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Accepted Author Manuscript version arising from this submission.

Data availability

The data associated with this article has been deposited in the Cranfield University Online Research Data Repository (https://doi.

org/10.57996/cran.ceres-2629).

References

Aviation Safety Council, 2016. Aviation Occurrence Report: TransAsia Airways Flight GE235 (*Report Number: ASC-AOR-16-06-001)*. Taipei.
Aydin, M., Uğurlu, Ö., Boran, M., 2022. Assessment of human error contribution to maritime pilot transfer operation under HFACS-PV and SLIM approach. Ocean Eng. 266, 112830.
Baysari, M.T., McIntosh, A.S., Wilson, J.R., 2008. Understanding the human factors contribution to railway accidents and incidents in Australia. Accid. Anal. Prev. 40 (5), 1750–1757.
Chan, W.T.-K., Li, W.-C., 2022. Training for future investigators: understanding cultural effects on standardisation and international cooperation. ISASI Forum - Air Safety Through Investigation 55 (3), 8–15.
Chan, W.T.-K., Li, W.-C., 2023. A Comparative Evaluation of Human Factors Intervention Approaches in Aviation Safety Management, pp. 36–45.
Chen, J.-C., Lin, S.-C., Li, W.-C., 2014. Utilization of Human Factors Intervention Matrix (HFIX) to develop aviation safety management strategy. Proceedings of the 18th World Multi-Conference Syst. Cybern. Informatics, 2014, pp. 50–55.
Chen, J.-C., Yu, V.F., 2018. Relationship between human error intervention strategies and unsafe acts: the role of strategy implementability. J. Air Transport. Manag. 69, 112–122.
Chen, J.C., Chi, C.F., Li, W.C., 2013. The analysis of safety recommendation and human error prevention strategies in flight operations. Lect. Notes Comput. Sci. 8020, 75–84.
Ergai, A., Cohen, T., Sharp, J., Wiegmann, D., Gramopadhye, A., Shappell, S., 2016. Assessment of the human factors analysis and classification system (HFACS): intra-rater and inter-rater reliability. Saf. Sci. 82, 393–398.
Harris, D., Li, W.-C., 2011. An extension of the human factors analysis and classification system for use in open systems. Theor. Issues Ergon. Sci. 12 (2), 108–128.
ICAO, 2020. Annex 13 to the Convention on International Civil Aviation - Aircraft Accident and Incident Investigation, twelfth ed. Montreal, Quebec.
Kaptan, M., Sarialioglu, S., Ugurlu, O., Wang, J., 2021a. The evolution of the HFACS method used in analysis of marine accidents: a review. Int. J. Ind. Ergon. 86, 103225.
Kaptan, M., Uğurlu, Ö., Wang, J., 2021b. The effect of nonconformities encountered in the use of technology on the occurrence of collision, contact and grounding accidents. Reliab. Eng. Syst. Saf. 215, 107886.
Leveson, N., 2004. A new accident model for engineering safer systems. Saf. Sci. 42 (4), 237–270.
Lew, V., 2022. The Utilization and Validation of the Human Factors Intervention Matrix and the Companion Assessment Tool FACES in the Development of Novel Interventions. Embry-Riddle Aeronautical University.
Li, W.-C., Harris, D., 2013. Identifying training deficiencies in military pilots by applying the human factors analysis and classification system. Int. J. Occup. Saf. Ergon. 19 (1), 3–18.
Li, W.-C., Harris, D., Yu, C.-S., 2008. Routes to failure: analysis of 41 civil aviation accidents from the Republic of China using the human factors analysis and classification system. Accid. Anal. Prev. 40 (2), 426–434.
Li, W.-C., Young, H.-T., Wang, T., Harris, D., 2007. International cooperation and challenges: understanding cross-cultural issues. ISASI Forum - Air Safety Through Investigation 40 (4), 16–21.
Morley, F.J.J., Harris, D., 2006. Ripples in a pond: an open system model of the evolution of safety culture. Int. J. Occup. Saf. Ergon. 12 (1), 3–15.
Olsen, N., Williamson, A., 2017. Application of classification principles to improve the reliability of incident classification systems: a test case using HFACS-ADF. Appl. Ergon. 63, 31–40.
Patterson, J.M., Shappell, S.A., 2010. Operator error and system deficiencies: analysis of 508 mining incidents and accidents from Queensland, Australia using HFACS. Accid. Anal. Prev. 42 (4), 1379–1385.
Reason, J., 1990. Human Error.
Reinach, S., Viale, A., 2006. Application of a human error framework to conduct train accident/incident investigations. Accid. Anal. Prev. 38 (2), 396–406.
Salmon, P.M., Cornelissen, M., Trotter, M.J., 2012. Systems-based accident analysis methods: a comparison of Accimap, HFACS, and STAMP. Saf. Sci. 50 (4), 1158–1170.
Shappell, S., Detwiler, C., Holcomb, K., Hackworth, C., Boquet, A., Wiegmann, D.A., 2007. Human error and commercial aviation accidents: an analysis using the human factors analysis and classification system. Hum. Factors 49 (2), 227–242.
Shappell, S., Wiegmann, D., 2007. Developing a methodology for assessing safety programs targeting human error in aviation. Proceedings of the Human Factors and Ergonomics Society 51 (2), 90–92.
Shappell, S., Wiegmann, D., 2009a. A methodology for assessing safety programs targeting human error in aviation. Int. J. Aviat. Psychol. 19 (3), 252–269.
Shappell, S., Wiegmann, D., 2009b. Closing the loop on the system safety process: the human factors intervention matrix (HFIX). ISASI 2009 Proceedings 62–67.
Shieh, J.-I., Wu, H.-H., Huang, K.-K., 2010. A DEMATEL method in identifying key success factors of hospital service quality. Knowl. Base Syst. 23 (3), 277–282.
Stanton, N.A., Salmon, P.M., Rafferty, L.A., Walker, G.H., Baber, C., Jenkins, D.P., 2017. Human Factors Methods. CRC Press.
Svedung, I., Rasmussen, J., 2002. Graphic representation of accidentscenarios: mapping system structure and the causation of accidents. Saf. Sci. 40 (5), 397–417.
Ugurlu, O., Yıldırım, U., Yuksekyıldız, E., Nisancı, R., Kose, E., 2021. Investigation of oil tanker accidents by using GIS. International Journal of Maritime Engineering 157 (A2).
Wiegmann, D.A., Rantanen, E.M., 2003. Defining the Relationship between Human Error Classes and Technology Intervention Strategies (Final Technical Report AH FD-03-1S/NASA-02-1). Hampton, Virginia.
Wiegmann, D.A., Shappell, S.A., 2003. A Human Error Approach to Aviation Accident Analysis. Routledge, New York.
Wiegmann, D.A., Shappell, S.A., 2001. Human error perspectives in aviation. Int. J. Aviat. Psychol. 11 (4), 341–357.
Williams, P.R., 2010. Some cultural considerations for investigators. Australian and New Zealand Societies of Air Safety Investigators, Regional Air Safety Seminar. Australian and New Zealand Societies of Air Safety Investigators, Canberra, ACT.

Wesley Tsz-Kin Chan MSc, ATP, PhD Candidate of Safety and Human Factors in Aviation, Cranfield University, United Kingdom, MSc Human Factors in Aviation, Coventry University, United Kingdom

Wen-Chin Li PhD, C.ErgHF, Senior Lecturer, Safety and Accident Investigation Center, Cranfield University, United Kingdom, PhD in Aviation Human Factors, College of Aeronautics, Cranfield University, United Kingdom

Richard Yeun PhD, MBus, MAvM, MSc, Senior Lecturer & Aviation Program Manager, School of Engineering, RMIT University, Australia, PhD in Safety Management, Griffith University, Queensland, Australia

Thomas Wang, Aviation Safety Investigator, Taiwan Transportation Safety Board, Taiwan, Master of Flight Safety and Operations, Embry-Riddle Aeronautical University, U.S.A