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# Using expert perspectives to explore factors affecting choice of methods in safety analysis.

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## Abstract

Many methods have been developed to understand and improve system safety. Previous research has indicated that a 'research-practice gap' exists in use of methods, where systemic methods are not adopted in practice. This study extends this research, by using interviews and focus groups with 29 safety experts to investigate their choice and use of different error and accident analysis methods. This study supports previous conclusions on the research-practice gap in different analysis approaches taken by researchers and practitioners, and provides new insights in understanding experts' familiarity and willingness to consider safety II approaches to safety analysis, including their interpretations of the principles of emergence and resonance. The key findings were that participants, both with and without prior experience of using FRAM (Functional Resonance Analysis Method, Hollnagel, 2012), used various strategies to identify how performance variabilities may resonate through the system to produce unwanted outcomes. They recognised the value of the safety II perspective in providing detailed recommendations for improving system safety, although some did not understand the underlying concepts, or described FRAM as time consuming and complex to use. There is a need to enhance the practical applicability of emerging methods, which provide further avenues of research.

**Keywords:** Accident analysis, Systems approach, Research-practice gap, Human error identification methods, FRAM

## 1. Introduction

There are many ways to study safety in high risk industries, ranging from retrospective investigation of accidents and their underlying causes, through to prospective, systemic analyses of risk and safety in various complex settings. Analysts use a variety of methods, all of which have different strengths and limitations (Sklet, 2004) and may be compromised by conflicting goals from organisations, including business priorities, productivity, cost efficiency and time pressure which are barriers to an effective safety culture (Provan et al, 2017). It is important to understand users' choice of methods and identify how these can be implemented effectively in practice. The current study focuses on sub-sets of methods that are typically termed error and accident analysis, to establish the scope for consultations with safety experts.

### 1.1. Error and accident analysis methods

There have been several reviews of the history and development of error and accident analysis methods (e.g. Saleh et al., 2010; Katsakiori et al., 2009; Ryan, 2015). Methods commonly used include predictive risk assessment methods such as FMEA (Failure Mode Effects Analysis, United States Military, 1949) and HAZOP (Hazard and Operability Analysis) workshops (Lawley, 1974), human error quantification methods such as HEART (Human Error Assessment and Reduction Technique, Williams, 1986) and THERP (Technique for Human Error Rate Prediction, Swain & Guttmann, 1983) and 'psychologically-based methods' which contain detailed error taxonomies with the ability to model cognitive aspects of performance (Kirwan, 1998), such as TRACEr (Technique for the Retrospective and predictive Analysis of Cognitive Error, Shorrock & Kirwan, 2002) and HFACS (Human Factors Analysis and Classification system, Wiegmann & Shappell, 2003). Systemic methods include STAMP (Systems Theoretical Accident Modelling and Processes model, Leveson, 2004), the Accimap approach (Rasmussen, 1997), and FRAM (Functional Resonance Analysis Method, Hollnagel, 2012).

Studies have compared different methods (e.g. Salmon et al., 2012; Benner, 1985; Katsakiori et al., 2009) and developed criteria to evaluate these (e.g. Kirwan, 1998; Shorrock & Kirwan, 2002), including the ability of the method to: discriminate and classify a comprehensive range of human errors (comprehensiveness), predict human errors (predictive accuracy), capture the circumstances in which an event occurs (contextual validity), and generate effective error reduction measures (usefulness). Usability of the method, including the resources and training required, has also been considered (Shorrock & Kirwan, 2002).

Whereas many of the traditional methods may offer benefits in terms of usability, they may not represent the complexity of human performance or the context of work in which it takes place (e.g. Kirwan; 2006; Yousefi et al., 2018; Patriarca et al. 2018). Systemic methods that consider accidents as being caused by dynamic and complex system behaviour aim to understand emergent behaviour, interactions and relationships between different components of the system (Salmon et al., 2010; Underwood & Waterson, 2013).

### 1.2. The Safety II perspective

As a result of developments in understanding safety, increasing emphasis has been placed on understanding the context in which human performance occurs. This includes understanding how operators actually carry out work ('work as done'), rather than as it should be carried out ('work-as-imagined') and how everyday variabilities in performance and adjustments contribute towards both success and failure (Hollnagel, 2014). This understanding of normal work is the basis of the safety II perspective and views safety as increasing the number of things that go right (Hollnagel, 2014).

FRAM is one example of an emerging systemic method, based on the resilience engineering approach or the "safety II" perspective (Hollnagel, 2004). The underyling principles of FRAM include 'the principle of emergence' (Hollnagel, 2012), where outcomes or incidents are explained by unexpected combinations of performance variabilities, present only at a specific time. The 'principle of resonance' explains that performance variabilities, which may be undetectable or 'subliminal', can interact resulting in disproportionately large consequences (Hollnagel, 2012).

FRAM can be used both retrospectively (analysis of past incidents or accidents) and prospectively (identifying hypothetical accident scenarios for risk management). The method has been used in a range of different domains, including aviation, healthcare, maritime and railway (Patriarca et al., 2020). Several researchers have identified advantages related to FRAM. For example, Belmonte et al. (2011), Patriarca & Bergstrom (2017) and Kaya et al. (2019) described FRAM as offering a dynamic representation of systems, allowing the identification of novel and complex incident and accident scenarios when used prospectively.

It is useful to know more about how FRAM is used in practice, and its relative strengths in comparison with other methods. In a review of the application of FRAM, Patriarca et al. (2020) found that FRAM has been progressively evolved by several researchers for modelling complex dynamic socio-technical systems, providing some practical solutions for improving system safety. For example, FRAM has been applied in the healthcare domain since 2012 to identify differences between 'work as imagined' and 'work as done', providing input to the redesign of clinical processes and procedures (e.g. McNab et al., 2018; Ross et al., 2018). According to several researchers however, a 'research-practice gap' may exist where systemic methods are not widely used in practice (e.g. Okstad et al., 2012; Read et al., 2013; Lundberg et al., 2010). Underwood and Waterson (2013) carried out interviews with safety experts from a variety of industries to understand their awareness and usage of systemic methods and identify barriers contributing to the 'research-practice' gap. They found that practitioners often face workload demands and consider systemic methods time consuming to use and require a lot of training (Waterson et al., 2015). Steele & Paries (2006) reported that practitioners prefer to use a method that is simple to use, with clear guidance to aid analysis.

The research-practice gap may be more evident with safety II methods. FRAM has been described as 'resource intensive' to use, particularly for more complex systems which involves modelling complex graphical representations of interactions and couplings between human organisational and technical functions (e.g. Patriarca et al., 2020). In particular, there are no 'stop rules' regarding the level of detail required when conducting analysis using FRAM. Some 'trade-offs' between certain criteria are inevitable, such that comprehensive approaches can be perceived to have lower levels of usability and require more resources of time and expertise, which may force some to choose a simpler approach .

Practitioners may be less familiar with FRAM for a variety of reasons including; costs associated with training to use methods, lack of communication between practitioners and researchers, and organisations dictating the choice of methods to be used (Underwood & Waterson, 2013). Practitioners can feel that researchers' interests do not align with their own and that research provides little value for industry (Reid, 2016). They may also rely on older methods as they are unaware of the reliability, validity or cost effectiveness of emerging methods and have limited accessibility to journal articles where these may be discussed (Reid, 2016). Addressing the research-practice gap is important to avoid missing opportunities to use the best available methods to understand accident causation and safety improvements in increasingly more complex industrial situations and settings (Goode et al., 2019; Ryan, 2020; Chung & Shorrock; 2011).

Provan et al (2017) suggested that the contrast between safety II literature and traditional safety management can cause confusion, particularly as there is little guidance on how to apply safety II concepts in practical contexts. These concepts could include 'guided adaptability' (making variations in normal performance safe), adapting to complexities (coping with foreseen and unforeseen demands, involving trade offs and sacrifice judgements on safety vs production), and implementing a safe course of action (Provan, 2020). Little is known of how safety professionals practically integrate these safety II concepts into their work. Steele and Paries (2006) suggested that theories and models based on the resilience engineering approach should be tailored for industry use, and processes should be developed to apply these in practice. This means that guidance should be made available, particularly for those who are less familiar with the underpinning research (Waterson et al., 2015).

It is important to understand how safety methods, including safety II concepts, are perceived by researchers, practitioners and those in other safety roles. This study aimed to extend previous research (Underwood & Waterson, 2013; Waterson et al., 2015), by using interviews and focus groups with safety experts to investigate their choice and use of different error and accident analysis methods, including their familiarity and willingness to consider new approaches to safety analysis

## 2. Method

Semi-structured interviews and focus groups were carried out with safety experts who had experience in using error and accident analysis methods in consultancy work, research, safety management or incident investigation. This qualitative approach allowed insights to be gained regarding factors affecting choice of current methods, based on discussion of real-life accounts and subjective interpretations offered by participants (Landridge & Hagger Johnson, 2009).

### 2.1. Participants

29 participants in total were involved in the study (11 were interviewed and 18 participated in focus groups). Participants recruited for the focus groups did not participate in the interview study. The sample consisted of 10 Human Factors practitioners, 4 Human Factors researchers, 3 incident investigators and 12 safety management specialists (table 1). The practitioners and industry specialists had experience of working in at least one of four industries, including rail, aviation, oil and gas, and nuclear power, for an average of 18 years (ranging from 1 year to 26 years) They were recruited through contacting Human Factors consultancies, and Human Factors teams within various universities and organisations. Judgement sampling was used, based on participants' likely knowledge and experience of using error and accident analysis methods.

**Table 1. Participants recruited in interviews and focus groups**

| | **Individual interviews** | **Focus group 1 (no or little experience of using FRAM)** | **Focus group 2 (experience in using FRAM)** |
|---|---|---|---|
| **Human Factors practitioners** | 5 | 5 | 0 |
| **Human Factors researchers** | 4 | 0 | 0 |
| **Incident investigators** | 0 | 0 | 3 |
| **Safety management specialists** | 2 | 0 | 10 |

The Human Factors researchers mainly worked within academic institutions, including universities, with research experience on the occurrence of human errors in incidents and the development of human error and accident analysis methods. The Human Factors practitioners were either employed within industry or were academic consultants, providing support to projects in a range of different industries, using methods to carry out risk and safety analyses, and support business cases. Incident investigators, and those who worked within safety management, were employed by a European agency, having a remit to improve safety within the rail industry.

### 2.2. Procedure

### 2.2.1. Interviews

Five of the eleven interviewees identified themselves as practitioners, four as researchers, and two as safety management specialists. Participants were asked a series of open-ended questions (table 1) to identify factors affecting their use of methods and collect relevant examples where appropriate. Twelve evaluation criteria from Shorrock & Kirwan (2002) (listed in table 2) were presented to participants as prompts, to aid the discussion and comparison of features of error and accident analysis methods. Participants were also asked to identify recommendations for improving these methods. These were in-depth interviews lasting between 60-180 minutes.

**Table 2. Interview questions**

| | |
|---|---|
| **Use of methods** | What is your job position, and which industry do you work in?<br>Which error or accident analysis methods do you have experience in using?<br>How do you decide which methods to use?<br>What features would your ideal method have? |
| **Evaluation of methods** | What are the strengths and limitations of these methods? (using evaluation criteria from Shorrock and Kirwan (2002) as prompts: Comprehensiveness, Structure and consistency, Life cycle stage applicability, Predictive accuracy, Theoretical validity, Contextual validity, Flexibility, Usefulness, Training requirement, Resource usage, Usability and Auditability).<br>What recommendations could you suggest to improve these methods? |

### 2.2.2. Focus groups

Two focus groups were carried out, separately to the interviews (section 2.2.1), to investigate how participants compared and evaluated safety I and safety II perspectives. A short presentation explained the application of safety I and II concepts during safety analyses. One focus group was carried out with five Human Factors practitioners (who had no or little prior experience in using FRAM) and one with 13 safety management specialists and incident investigators (who had prior knowledge or experience in using FRAM).

Participants then worked through a series of exercises in smaller groups to consider how safety I and II concepts could be applied in an example railway scenario, where safety processes are applied to protect maintenance staff who are working on the operational railway line. This example related to a process where railway lines are blocked to enable maintenance staff to carry out work. This involves a signaller who is responsible for authorising movements of trains through railway signalling, a site based person (Controller of Site Safety, COSS) who sets up safe systems of work for people to work on the track, and a handsignaller who provides additional protection and instruction to train drivers who may be approaching a place of maintenance work.

Participants were asked to consider safety I concepts such as opportunities for human errors, performance shaping factors and associated recommendations for improving system safety. Guidewords from an error classification tool GEM-R (Generic Error Modelling System- Rail) adapted from GEMS (Reason, 1990) by Network Rail in Great Britain, were used to identify and classify errors and violations in rail incidents, according to the intention, cognitive process and influencing factors of the act.

Two of Hollnagel's principles from the safety II perspective were then explored for their use in error and incident investigation. Participants were asked to read extracts explaining Hollnagel's principles of emergence and resonance (see table 3), and then identify potential instantiations of resonance, considering how potential performance variabilities for individual functions (or work processes) may resonate, and affect the variability of other functions. Participants were encouraged to use 'performance variability probes' for guidance (Hollnagel, 2012). These include timing (too early, on time, too late and omission) and precision (imprecise, acceptable and precise), to reflect how outputs of functions within FRAM can differ. Finally, participants were asked questions relating to the practical applicability of the safety I and safety II perspectives (table 3).

**Table 3. Focus group questions**

| | |
|---|---|
| **Evaluation of 'safety I' and 'safety II' perspectives** | How have you used the safety II approach, and what do you think of this perspective?<br>Which aspects of safety I and II do you consider important and less important for improving system safety?<br>Do the safety I and safety II approaches offer anything different compared to what you currently do today? If not, why not? |
| **Practical application/ recommendations** | How can the safety II perpsective can be translated into practice, and what are the associated benefits and limitations of doing so?<br>What can be done to improve its practical applicability? |

| | |
|---|---|
| **Identifying potential instantiations of resonance** | Please read the following definitions of the principles of emergence and resonance (Hollnagel, 2012):<br>**The Principle of Emergence**<br>"The variability of normal performance is rarely large enough to be the cause of an accident in itself or even to constitute a malfunction. But the variability from multiple functions may combine in unexpected ways, leading to consequences that are disproportionally large, hence produce a non-linear effect. Both failures and normal performance are emergent rather than resultant phenomena, because neither can be attributed to or explained only by referring to the (mal)functions of specific components or parts".<br>**The Principle of Functional Resonance**<br>"The variability of a number of functions may every now and then resonate, i.e., reinforce each other and thereby cause the variability of one function to be unusually high. The consequences may spread through tight couplings rather than via identifiable and enumerable cause-effect links, e.g., as described by the Small World Phenomenon. This can be described as a resonance of the normal variability of functions, hence as functional resonance. The resonance analogy emphasises that this is a dynamic phenomenon, hence not attributable to a simple combination of causal links".<br>Referring to the above definitions, as well as Hollnagel's (2012) performance variability probes (reflecting how outputs of functions may differ in terms of timing and precision), consider how performance variabilities may resonate through the system to produce unwanted outcomes (i.e. instantiations of resonance). |

## 2.3. Data analysis

Interviews and focus groups were audio recorded, transcribed and analysed using inductive thematic analysis, to provide a rich description and interpretation of participants' responses (Braun & Clarke, 2006). Thematic analysis was conducted across all data sets (interviews and focus groups), to examine and compare the perspectives of all research participants recruited in the study (Braun & Clarke, 2006). Initial ideas were formed regarding overarching themes and patterns, and quotes were organised using preliminary codes. As more understanding was gained of the data, codes were continually developed and refined, and then organised into broader themes and subthemes. At varying stages of the analyses, emerging codes and themes were reviewed and confirmed by two researchers, any revisions based upon their perspectives of the data. Validity of findings were supported when a common interpretation of the data was agreed. After refining the themes, data within these were analysed, looking for similarities and differences in participants' responses, and searching for common threads across the data sets (Bowen, 2006), with the aim of providing important insights to address the research question.

## 3. Results

From the analysis of the transcriptions, three higher-order themes were created (see table 4). Responses from the interviews related to the choice of different methods (theme 1), and from the focus groups related to the value of the safety II perspective (theme 2). Responses from participants both within the interviews and focus groups contributed to theme 2 (relating to the strengths and limitations of FRAM) and theme 3 (recommendations for enhancing the practical applicability of safety II methods).

Participants provided valuable insights regarding their use of error and accident analysis methods, including their familiarity and willingness to consider new approaches to safety analysis. They identified strengths and limitations for all methods, and a range of recommendations were identified to bridge the 'research-practice' gap.

**Table 4 . Summary of themes identified from interviews and focus groups**

| | **Theme name** | **Section** | **Summary of the main findings** |
|---|---|---|---|
| **1** | **Choice of methods** | **3.1.** | Participants identified different strengths and limitations of methods. There is no one 'perfect' approach. However, researchers prefer comprehensive, systemic methods. Incident investigators and safety management specialists recognise the value of a method that is comprehensive and practically applicable, yet still has structure and guidance to aid analyses. Practitioners prefer a method that is easy to use, contains taxonomies for guidance, and where analysts are encouraged to quantify human errors. However, they questioned the theoretical validity of HEQ methods. |
| | Factors affecting choice of methods | 3.1.1. | |
| | • Usability and comprehensiveness | 3.1.1.1. | |
| | • Structure and consistency | 3.1.1.2. | |
| | • Quantifying human errors | 3.1.1.3. | |
| **2** | **The value of the safety II perspective** | **3.2.** | Participants with and without prior knowledge of using FRAM (including practitioners) used various strategies to identify potential instantiations of resonance. They recognised the value of safety II in considering normal performance variabilities in incidents, and their varying effects on subsequent or 'downstream' functions, as they resonate through dependencies between functions. FRAM therefore encourages analysts to view the system as being more 'interconnected'.<br>However, these participants described FRAM to be time consuming and complex to use. Participants identified benefits of using FRAM alongside other methods, as safety I and II were seen as complementary not contradictory approaches, bridging the gap between 'research' and 'practice'. |
| | Participants' interpretations of the principles of emergence and resonance | 3.2.1 | |
| | Potential instantiations of resonance identified by participants | 3.2.1.1. | |
| | Difficulties in identifying potential instantiations of resonance | 3.2.1.2. | |
| | Strengths and limitations of FRAM | 3.2.2. | |
| **3** | **Recommendations for future development and application of methods** | **3.3.** | Participants identified benefits of using more than one method within a toolkit, including supplementary guidance. Other recommendations include enhancing the practical applicability of the safety II perspective by |
| | Using more than one method | 3.3.1. | |

| | | | |
|---|---|---|---|
| | Guidance to aid analysts | 3.3.2. | including examples, guidance and relevant training. |
| | Recommendations for enhancing the practical applicability of safety II | 3.3.3. | |

## 3.1. Theme 1: Choice of methods

Participants had experience in using a range of methods (see table A.1 in appendix), including descriptive, systemic approaches and structured, analytic approaches. Incident investigators and safety management specialists required methods that are comprehensive and considers organisational factors, yet structured and practically applicable. They used taxonomic methods to retrospectively analyse incident reports, such as GEM-R and HFACS. A range of prospective methods were also used by Human Factors practitioners and risk teams to predict potential human errors or incidents, such as event and fault trees and RARA (Railway Action Reliability Assessment), (RSSB, 2012). Human Factors researchers described the importance of using a comprehensive method that considers interactions and relationships between different components of the system, and therefore used systemic methods including FRAM, which were not widely used by the practitioners (see Appendix A- Theme 1 for additional responses from participants) .

Every participant identified strengths and limitations of methods they had experience in using. These were collated for each method, and summarised in table 5, where bold font indicates points mentioned by two or more participants.

**Table 5. Summary of the strengths and limitations of methods, identified by participants from the interviews.**

| **Method category** | **Method** | **Strengths** | **Limitations** |
|---|---|---|---|
| **Predictive risk assessment methods** | FMEA, HAZOP/ HAZID | Detects hidden failure modes (i.e. those with a low likelihood but high consequence), straightforward, easy, vigorous, considers observable errors | **Depends on the expertise of people in the room (x3), can be time consuming (x2),** can sometimes focus on the wrong things, people sometimes make things up as they go along, very linear (often does not consider interactions between influences), subjective as some errors are not reportable |
| **HEQ tools** | HEART, THERP | High consistency**,** lots of different Error Producing Conditions (EPCs) to consider, easy to use, flexible | **Can manipulate to get any number you want (x2), people focus too much on the final Human Error Probability (HEP) (x4), the final HEP is simplified (x2), and is based on guess-work (x2), it does not take into account different conditions (x3)** and interactions between EPCs, has little empirical basis |
| **Taxonomic methods** | GEM-R | Based on high levels of academic and industry knowledge, a consistent way of classifying human errors | Classifications can go too far, in terms of defining and redefining categories. Depends on the quality of incident reports- there is often not enough information in reports to distinguish between human error types |
|  | HFACS | Taxonomy provides guidance | **Taxonomy can be constraining, forces you to 'tick a box' (x2)** |
|  | TRACEr | Good for highly cognitive tasks, detailed guidewords, good academic tool, high construct validity and comprehensive | **Difficult to use (x2) , many error mechanisms are not reportable (x2), low levels of reliability (x2),** engineers may find it difficult to postulate predictive IEM (Internal Error Mechanism) categories. |

| | | | |
|---|---|---|---|
| | SHERPA | HSE specified for doing safety cases, linked to other tools to provide quantification (such as ‘Human Factors workbench’) | Does not consider cognitive errors in much depth |
| **Systemic models** | Accimaps | **Good way of understanding an accident (x2),** shows you the ‘**big picture’ (x2)** | Linear: unlike FRAM, there is less detail regarding interactions between different influences, no taxonomy for guidance, high on resource usage |
| | STAMP | Provides some guidance for the user, thorough, encourages you to look at everything within the system | Hard to use, more geared towards the research community rather than for practical use, high on resource usage (detailed information is required for analysis), low on usability |
| | FRAM | **Looks at whole picture, including interactions and dependencies between functions, considers complexities of the system (x3), enables the identification of systemic mitigation measures (x2),** generic (can be used for any system), shifts away from the ‘blame’ culture | **Can be time consuming to use (x2), probes are very complex (x2), lack of understanding of terminology (x2), practical guidance and examples are required (x 2)** |

### 3.1.1. Factors affecting choice of methods

#### 3.1.1.1. Usability and comprehensiveness

Participants' use of methods were reflected by different job requirements and time available for analysis. Four practitioners reported they would choose a method that is easy to use, due to limited time they have for analyses:

> "I've got a job to do, and I've got to do it very quickly. I'm under pressure with not many resources … Usability would be very important"

Three practitioners described the trade- off between usability and comprehensiveness:

> "you've got this trade off…between simplicity and ease of use, and depth and thoroughness of the analysis. Striking a balance is very tricky".

Systemic approaches were described by both researchers and practitioners as being comprehensive, as they consider the context in which human errors occur including the role of organisational factors :

> "They encourage you to look at everything…one of the strengths is their thoroughness" .

However, comprehensive systemic methods, and methods with detailed cognitive error categories, such as TRACEr and HAZOP, were also reported as having lower levels of usability and requiring more resources such as time and expertise:

> "The simpler, TRACEr-lite version with fewer human error categories is less time consuming to use"

> "The detailed cognitive errors in HAZOP workshops are rarely examined because they offer too fine a level of detail"

#### 3.1.1.2. Structure and consistency

Practitioners also recognised advantages of using methods which contain taxomomies for guidance. One participant described GEM-R as containing comprehensive taxonomies which aids analysts in classifying human errors. They contrasted this with the Accimap approach, where there is more reliance on the user. HAZOP was described as being high on structure and consistency, referring to guidewords to elicit consideration of potential human errors or risks. In contrast, HEART was described as being low on structure and consistency by two practitioners:

> "it covers a lot of things but it's generic…that means the consistency can be difficult".

They suggested that, since Generic Task Types (GTTS) described in HEART are not domain-specific, applications and interpretations of these may differ in different industries, which may reduce consistent analyses between different users. However training users would enhance consistency.

#### 3.1.1.3. Quantifying human errors

Practitioners generally said that they are encouraged to use human error quantification methods, as business or safety cases are often supported by numbers:

> "it has to be (*quantified)* because management are not interested in anything that's qualitative. They want hard numbers, and they want to know whether it's feasible".

Seven practitioners and safety management experts, however, identified limitations in quantifying human errors. They considered the theoretical validity of HEQ methods, arguing that they may not sufficiently acknowledge human performance, often having little empirical basis. Similarly, Swain (1990) described how these methods are not based on a sound theoretical background or model regarding human behaviour. Participants also questioned the reliability of Human Error Probability (HEP) data generated from HEQ methods, stating they can include elements of 'guess work', or are 'easily manipulated'. Participants also suggested that analysts may place too much emphasis on the final HEP (see French et al., 2011), and individual differences between operators, such as their subjective goals, intentions and expectations may not be captured (see Rasmussen, 1983).

## 3.2. Theme 2 : The value of the safety II perspective

### 3.2.1. Participants' interpretations of the principles of emergence and resonance

The study identified participants' understanding of 'emergence' and 'resonance'. Human Factors practitioners, with little prior experience of using FRAM, discussed the safety II perspective demonstrates how outcomes may result from unexpected combinations of performance variabilities, which cannot be traced back to the micro-level behaviour of components, and are therefore non-linear in nature:

> "emerging characteristics are the things you can't predict".
>
> "the emergent properties of the system are non-linear, it's not always possible to identify the causes"

Hollnagel (2012) described emergent outcomes as non-linear as dependencies develop as a result of a specific situation, rather than from predetermined cause-effect links (Hollnagel, 2012). This differs from the traditional view of 'resultant outcomes', which can be traced back to a root cause and therefore causal in nature (Hollnagel, 2014).

Participants from all groups noted that FRAM demonstrates how variabilities introduced by different operators may combine and produce disproportionately large consequences , resulting in resonance (Hollnagel, 2012):

> "slightly bad performance by several people produces really bad performance by the whole system".

One safety management expert, with prior experience of using FRAM, explained that the method demonstrates how incidents develop over time, highlighting the importance of considering the situation and conditions as a whole. He defined resonance as:

> “triggering a process orientated view of thinking. Most actions, errors, decisions have impact not only on the following steps in the process chain, but indirectly also to steps which are within certain distance”.

A Human Factors practitioner, with little prior experience of using FRAM, referred to Hollnagel’s (2012) probes when defining resonance:

> “ you characterise the variabilities by timings as either too early, too late…the question is how would any of those states for any of the functions impact on another?”.

Hollnagel (2012) described that ‘upstream-downstream couplings’ may result, where performance variabilities can have varying effects on subsequent or ‘downstream’ functions, as they resonate through dependencies between the different functions resulting in unwanted consequences.

#### 3.2.1.1. Potential instantiations of resonance identified by participants

In rail-engineering contexts relating to line blockages, participants identified six complex instantiations of resonance, both by those with and without prior experience of using FRAM (see table A.2 in appendix for a further description of these). These instantiations refered to dependencies between two or more processes, which are not immediately adjacent to each other in a list of sequential processes. They demonstrated how the same outcome can result from different variabilities in outputs of upstream (previous) functions, which have varying consequences on downstream (or subsequent) functions. For example, ‘*a line blockage being granted in an incorrect location’* can be the result of i) incorrect details of the line blockage being requested, ii) signaller failing to apply a reminder appliance in the correct location (a visual reminder to prevent a signaller accidentally signalling a train into a line block) iii) confirming incorrect details of line blockage request, iv) failing to check for sufficient margin (or sufficient minimum distance) between trains before granting a line blockage

When identifying these instantantions, some practitioners used the term ‘knock-on effect’ to describe how variable outputs in upstream functions can affect the variability of downstream functions within FRAM :

> “too late would have a knock on effect on subsequent tasks”.
>
> “we’re looking for something that happens at point 3 that might not have an immediate knock-on effect on point 4 and 5 but could have an effect on point 9. Variability at one end of a system, such as incorrect information regarding a line block, can affect variability at the other end of the system, where a line blockage is granted in a shortened area”.

Safety management specialists and incident investigators with prior experience or knowledge of using FRAM used similar terminology to those less familiar with the method. For example, they used terms such as ‘propogate’:

> “I can see an error here, propagating to here, and how it was not covered, or how the mistake was not corrected”.

One practitioner who had experience in using FRAM in air traffic control, described how the consequences of variabilities may ‘spread’ through the system and affect downstream functions. One participant clarified:

> “*(do you mean)* trying to find this function higher in the list that affects the function later down in the list?”.

In response, the practitioner pointed to the list of processes and stated:

> “so rather from just going from there to there, or going through processes in a sequential order, you want to go from there to there, where variability resonates through unexpected dependencies”.

As described by Hollnagel and Goteman (2004), FRAM does not explain accidents as a sequential or ordered sequence of functions. There are numerous couplings or dependencies between different functions, where different occurrences and propogations of variabilities may result in different outcomes. Therefore, variabilities do not always resonate through predetermined cause-effect links, but through more complex dependencies between functions as they develop in a specific situation (Hollnagel, 2012).

#### 3.2.1.2. Difficulties in identifying potential instantiations of resonance

Table 6 summarises the number of participants, within the focus groups, who demonstrated an understanding of safety II concepts. As shown in the table, most participants understood the principles of emergence and resonance, and applied these principles to identify complex potential instantiations of resonance. However, some Human Factors practitioners, with little or no experience of using FRAM, demonstrated difficulties in understanding these concepts. They did not consider multiple non-linear interconnections and dependencies within the system when identifying instantations of resonance.

**Table 6.** Differences in response patterns in understanding safety II concepts, between participants with vs those without prior knowledge of using FRAM.

| **Understanding of safety II concepts demonstrated** | **Total number of participants** | **Number of participants with prior experience of using FRAM** | **Number of participants with little or no prior experience of using FRAM** |
|---|---|---|---|
| Understanding the principles of emergence and resonance | 14 | 11 | 3 |
| Identified complex instantiations of resonance | 12 | 10 | 2 |
| Used terms such as ‘knock on effect’ and ‘propagate’ to explain understanding of emergence or resonance | 6 | 3 | 3 |
| **Difficulties in understanding safety II concepts** | | | |
| Lack of understanding of definitions of emergence and resonance | 2 | 0 | 2 |
| Difficulties in identifying potential instantiations of resonance | 3 | 0 | 3 |
| No consideration of more complex, non-linear relationships between functions, only dependencies that were sequential in nature | 3 | 0 | 3 |

These Human Factors practitioners reported that a lack of supporting guidance contributed to their difficulties in understanding safety II concepts:

> “There is a lack of explanations dedicated to definitions and criteria”,
>
> “resonance is a metaphor that doesn’t really speak to me... I don’t know what resonance is, there is no practical guidance”.

Perhaps due to the lack of familiarity with the underlying concepts of FRAM, these participants explained that dependencies were sequential in nature, but did not consider more complex, non-linear relationships between functions:

> “pretty much everything is dependent on the previous step…it’s largely a sequential process”.

Dependencies were assumed if one process could be only carried out if another was completed:

> “I would consider the consequences of the previous one *(work process)* not happening and how this would affect other work processes within the system”.

> "of each step that we went through, we thought can this step only happen if the previous steps already happened".

Although some outcomes can be interpreted as a linear consequence of other events (Patriarca et al., 2017), FRAM considers that variabilities may also resonate through non-linear, more complex dependencies between functions (Hollnagel, 2012).

### 3.2.2. Strengths and limitations of FRAM

Within the interviews and focus groups, participants with varying experiences of using FRAM identified different strengths and limitations of this method (table 7). In particular, they recognised the value of FRAM in being comprehensive, which is important in identifying detailed recommendations for system safety. However, limitations were raised regarding its practical applicability, including by those who had experience in using FRAM, with additional features of FRAM recommended such as consideration of organisationl factors and an integrated human error quantitative element.

**Table 7.** Differences in response patterns in identifying strengths and limitations of FRAM, between participants with vs those without prior knowledge of using FRAM.

| **Strengths of FRAM** | **Total number of participants** | **Number of participants with prior experience of using FRAM** | **Number of participants with little or no prior experience of using FRAM** |
|---|---|---|---|
| Recognised the value of safety II in considering performance variabilities, including interactions and dependencies between functions | **Total = 13**<br>Interviews = 3<br>Focus groups = 10 | 8 | 5 |
| FRAM aids analysts to identify more detailed recommendations for improving system safety | **Total =8**<br>Interviews =2<br>Focus groups= 6 | 5 | 3 |
| Shifts the focus away from the 'blame culture', as everyday performance and adjustments by operators throughout the system can contribute towards both success and failure | **Total = 3**<br>Interviews =1<br>Focus groups= 2 | 2 | 1 |
| High on both theoretical and contextual validity, as FRAM considers human performance and captures the circumstances in which events occur. | **Total =1**<br>Interviews = 0<br>Focus groups= 1 | 0 | 1 |

| | | | |
|---|---|---|---|
| High on life stage applicability, as the method can be used throughout the formative and summative phases of system design lifecycle. | **Total =1**<br>Interviews =1<br>Focus groups= 0 | 1 | 0 |
| **Limitations of FRAM** | | **Number of participants with prior experience of using FRAM** | **Number of participants with no or little prior experience of using FRAM** |
| Difficulties in the practical application of FRAM, including lack of explanation of definitions and a lack of practical examples to aid analysis | **Total = 9**<br>Interviews =2<br>Focus groups= 7 | 5 | 4 |
| Time consuming and complex to use. FRAM models can also get very detailed, with many possible instantiations | **Total =8**<br>Interviews =2<br>Focus groups= 6 | 5 | 3 |
| FRAM should have a better way of quantifying human errors, to support business or safety cases | **Total =4**<br>Interviews =0<br>Focus groups= 4 | 1 | 3 |
| Safety II perspective should have a better way of considering organisational factors, with supplementary guidance | **Total = 3**<br>Interviews = 0<br>Focus groups= 3 | 3 | 0 |
| Not knowing what level of detailed analysis is required, therefore further training is required | **Total = 3**<br>Interviews =0<br>Focus groups= 3 | 0 | 3 |

During attendance at the focus group, practitioners with limited prior experience in using FRAM recognised the value of safety II in considering performance variabilities in incidents:

> “variable performance are not normally taken under consideration, they fall under the line of what is considered ‘normal’. So that’s the additional value of safety II”.

They noted that FRAM encourages analysts to view the system as interactive:

> “rather than looking at the immediate consequences of failures, identifying instantiations enables analysts to looks at the little steps that might occur before that happens. In other

> words, understanding how incidents develop and occur over time".

One practitioner described FRAM as being high on both theoretical and contextual validity, as the method considers human performance and captures the circumstances in which events occur:

> "FRAM offers the ability to classify a comprehensive range of situations. It's got everything".

One researcher rated FRAM high on life stage applicability, as the method can be used throughout the formative and summative phases of system design lifecycle:

> "you could use it as part of a design process to get people talking, to verify, to show an inter-related process"

Two incident investigators described how FRAM shifts the focus away from the 'blame culture', as everyday performance and adjustments by operators throughout the system can contribute towards both success and failure:

> "There is a lot of positive action out of the safety I approach, but one that is not good is the blame culture. There is a real need to move out of this blame culture…to improve an inquisitive culture".

> "you can't attribute an accident to one person, there's variability in other parts of the system too"

Overall, eight participants (from all groups) believed FRAM aids analysts to identify more detailed recommendations for improving  system safety, ensuring adverse outcomes are prevented before the occur:

> "this method offers a new mind set, enabling you to proactively detect performance variability, before it has serious consequences. That's where you can learn."

> "considering dependencies between functions makes it easier to spot where it can fail..it should improve your response to make the system safe".

Participants also identified a number of limitations associated with using FRAM, relating to its practical applicability, being time-consuming and complex to use, and lack of a human error quantification element:

### Practical applicability and need for examples

Even those with prior experience of using FRAM identified difficulties in the practical application of the method, describing a lack of explanation of definitions, and not knowing what level of detailed analysis is required:

> "In the exercise I was really confused, because I didn't know how far to go."

> "what is missing for me is to have more explanation about terminology …. its difficult to understand the terminology of some definitions, and to do the exercise".

Some participants with, and without, prior experience of using FRAM, including practitioners and a safety management expert, questioned the practical applicability of this method:

> "FRAM is a new, creative concept … for me it's not fully worked out in practice. It encourages you to think afresh about a subject, but it's main weakness is a lack of practical guidance on how to use this"
>
> "There is too much variation in how to answer…the outcome is too vague for practical use".

One Human Factors practitioner, with limited prior experience of using FRAM, explained that theoretical methods may not necessarily be practically applicable, noting that one must consider the purpose of use:

> "you want something that's academically sound…*(or)*..practically applicable. This is a common problem with newly suggested techniques…it may be a reflection on academia and its focus on novelty and generating papers rather than practical results".

In response to this, one practitioner added:

> "To some extent you need to be positive and encouraging about a new idea, otherwise new technqiues will never get the chance to work".

### Time consuming and complex

Eight participants, including those with prior experience of using FRAM, described FRAM as being time consuming and complex to use:

> "All probes can be applied to all functions- so makes it very complex"
>
> "identifying individual work processes and potential resonance might be too much for a single person or team to get to grips with and analysis can become very detailed"

In particular, they described that constructing detailed FRAM diagrams is time consuming and requires experience. One practitioner described using FRAM in air traffic control, and although identifying resonance makes it "very powerful", encouraging the analyst to consider how variabilities in performance may affect downstream functions, he found:

> "it was extremely complex and it took a long time to understand the system, proper descriptions of tasks and dependencies is crucial. FRAM can be time consuming as you need to have a very good task analysis, to understand real activities, not only 'work as imagined'".

Hollnagel (2012) described that analysis using FRAM involves understanding how work is actually carried out (i.e. 'work as done'), to identify functions and associated aspects within FRAM, and create graphical representations of instantiations of resonance.

These participants concluded that FRAM is more suitable for experienced analysts and researchers who have more time for analysis. This is consistent with the notion of the research-practice gap, where systemic methods are not adopted in practice (Underwood & Waterson, 2013, Lundberg et al., 2010).

### No Human Error Quantification element

Some practitioners expressed concerns that FRAM should have a better way of quantifying human errors, to support business or safety cases:

> "FRAM has no sort of risk element, you're not saying this is the most critical, this is the most likely to fail".
>
> "I haven't yet seen a satisfactory way of blending the two".
>
> "FRAM results in a better understanding of the soft human processes, engineering processes are better analysed using traditional techniques".

Some studies however have integratated a quantitative element with FRAM to facilitate risk assessments (e.g. Patricia et al. (2017); Hirose et al. (2016) , section 4.1).

## 3.3. Theme 3: Recommendations for future development and application of methods

### 3.3.1. Using more than one method

During the interviews, one researcher and one practitioner described the 'perfect' method as being "all-encompassing", and "ideally meets all criteria". However, four participants argued that 'perfect' methods do not exist . One example from a practitioner illustrates this:

> "my ideal method has elements of cognitive work analysis… is easy to use and reliable… gives us a systematic overview and provides us with this helicopter and microscope view of the system. That's a lot. You're going to end up with a method which is very chunky ..and (*you will be)* spending a huge amount of time doing all those activities".

Practitioners and safety management experts (seven in total) identified benefits of using more than one method:

> "we need to collect information from different parts of the system, using different methods, and then you get the full picture".
>
> "there's no need to re-invent the wheel. The practitioner should be given more freedom to pick and choose from the models".

Two practitioners suggested using multiple methods in the context of a 'supporting toolkit', for carrying out different levels of analysis:

> "from a relatively shallow depth, to a more thorough analysis when resources are available".

Practitioners and safety management experts suggested that safety I and safety II approaches should be used together, as part of a toolkit or "wider decision framework", describing it as a "two-ended approach":

> "I see FRAM as a tool that could be used as another tool in the arsenal, rather than one that is

> uniquely more powerful”
>
> “The mixed approach can be translated into practice by giving the sector some examples on how to use it in real cases. We need to create a structured risk assessment system that take into account the parameters of safety I and II”

### 3.3.2. Guidance to aid analysts

Four participants (practitioners, a researcher and an incident investigator) suggested that guidance is necessary to help the user choose from the different methods (Kirwan, 1998; Herrera & Woltjer, 2010), otherwise “you end up picking whichever one you know”. Integrated examples can guide the user:

> “for example, TRACEr would be better for highly cognitive tasks, barrier analysis would be better if you are focused on engineering barriers as opposed to human error”.

One participant stated that the guidance should be as neutral as possible:

> “the problem with if it forces you down a line…effectively you are not using the tool, the tool is using you”.

### 3.3.3. Recommendations for enhancing the practical applicability of safety II

Participants suggested a range of recommendations for increasing the practical applicability of the safety II approach, which include further practical guidance, training and practice, and considering safety I and safety II as complementary approaches:

- **Further practical guidance**

Nine participants, with and without prior experience of using FRAM, recommended integrating practical examples and guidance to enhance usability and understanding of definitions:

> “The concept is very theoretical. I think there is a need for more practical applications, examples and definitions of terms as well”

One incident investigator and two safety management specialists (with prior experience of using FRAM) recommended that the safety II perspective should have a better way of considering organisational factors, with supplementary guidance. One participant referred to prompts within FRAM, claiming they relate more to the actions of individual operators:

> “it’s very interesting, but it still remains at the individual level of analysis. I would like more focus on the organisational level”.
>
> “there is less focus on wider, regulatory factors, further practical guidance is required”.

- **Training and practice**

Participants stated that FRAM can be complex to use, particularly depending on how far you go with the analysis. However, three practitioners, with no prior experience of using FRAM, recognised the value of training analysts, to ‘bridge’ the gap between theory and practice:

> “It is also a matter of training and practice that reasonable depth of consideration and analysis is found”.

> “constructing detailed FRAM models is so complicated... you have to go through each step and understand what each line means, I would need more training”.

Three practitioners, with limited prior experience of using FRAM, suggested the method can be used as a common language for experts to consider how the system is interconnected, and identify recommendations for improving system safety:

> “FRAM can be used as a basis for discussion, as it can be used as a common language for people from different domains….if you had an engineer, Human Factors person, a systems designer and an operator coming up with some new process, you could start to think about how everything might fit together”

> “FRAM can be used as a design process to get people talking, to verify, to have a process to show an inter-related process”

- **Safety I and Safety II are complementary approaches**

13 participants (in all groups) believed that safety I and II are complementary, not contradictory approaches, and that they should be used in combination to address system safety:

> “Safety I and II should be considered as two aspects of the same matter. Two sides of the same medal”

> “I don’t see them as opposing views….a lot of the techniques and tools that have been used for years, within the safety I area, can be re-used, but just with a different mindset. They are still valuable tools”

However, accepting the safety II perspective requires a change in mindset:

> “First step is raising awareness….. If the majority of the users see the benefits of a new approach, such an approach will be successful”.

## 4. Discussion

This study has articulated the views of a diverse set of safety experts, including Human Factors researchers and practitioners. This adds important commentary and context to earlier work on the choice of safety methods and researcher / practitioner perspectives (Underwood & Waterson, 2013; Waterson et al., 2015). New insights include understanding experts’ familiarity and willingness to consider safety II approaches to safety analysis, including their interpretations of the principles of emergence and resonance, and recommendations for future development and application of methods. It is clear from the current interview and focus group study that there is an appreciation of the value of systemic methods that are thorough and comprehensive in coverage, though a trade-off with ease of use is recognised. For example, methods such as STAMP and FRAM were described as being comprehensive, but extensive and time-consuming to use. This may result in a research-practice gap, where systemic methods are not widely used in practice (Okstad et al., 2012; Read et al., 2013; Lundberg et al., 2010). There is, however, a willingness to consider use of new methods, but it is clearly important that any such use is integrated with existing safety and investigation practices. There is also an openness to change with regards to how concepts such as error or variability are considered within industry, with a desire to move in the direction of a no blame culture.

Many strengths and weaknesses of existing methods are explained by experts who have experience in using error and accident analysis methods. Their accounts reflect understanding of the different methods available, and the difficulties that are experienced in applying these. It is clear that there are different needs for people in different roles. For example, choice of methods by practitioners may be influenced by their job demands and time constraints. They often have multiple priorities alongside safety, including business performance, and are under pressure to complete work quickly (Underwood & Waterson, 2013, Wilson et al., 2009; Shorrock & Williams, 2016; Ryan, 2020). Whereas, Human Factors researchers may prefer comprehensive systemic methods, as they tend to have more time for analysis.

Nevertheless, there are also similiarites between the reports from practitioners and researchers regarding desired features of methods (table 8); it is generally preferred that a method has sufficient guidance to aid analysis but does not require extensive resource usage and training requirements. Using detailed cognitive error taxonomies can be limited by time constraints (section 3.1.1.1) and analysis can become too unwieldy due to the number of errors categorised (O'Hare, 2000).

**Table 8. Desired features of error and accident analysis methods**

| | **Practitioners** | |
|---|---|---|
| **Researchers** | ***Desired features*** | ***Less desired features*** |
| ***Desired features*** | Recognise the value of the safety II perspective in considering performance variabilities in incidents<br>Viewing the system as interactive<br>Supports identification of recommendations for improving system safety ('usefulness')<br>Can be integrated with other methods in a toolkit<br>Has sufficient guidance to aid analysts.<br>Consideration of organisational factors<br>Theoretical validity | Comprehensive<br>Provides depth and thoroughness of analysis |

| | | |
|---|---|---|
| ***Less desired features*** | Quick to use (usability)<br>Has taxonomies for guidance (structure and consistency)<br>Quantifies human errors | Requires extensive resources (e.g. resource usage and training requirements)<br>Complexity |

Some strong opinions were presented, such as the need for quantification in some sectors. Although practitioners and safety management experts questioned the extent to which Human Error Probability (HEP) data is reliable and sufficiently acknowledges human performance, they are generally encouraged to use human error quantification methods, as business or safety cases are often supported by numbers. Some practitioners expressed concern that FRAM should have a better way of quantifying human errors. There may be opportunities to develop quantification within the emerging Safety II methods (discussed further in section 4.1).

Overall, the accounts show a range of perspectives, both in terms of user confidence in application of the methods and the level of trust in outcomes arising from their application.

### 4.1. Using Safety II approaches in safety analysis

The participants reported a range of experience of applying Safety II principles and using FRAM. The descriptions from some participants demonstrated a good appreciation of important concepts such as resonance and emergence. In particular, practitioners with limited prior experience of using FRAM noted that it offers a 'new' mind set to looking at the system. In particular, the importance of considering multiple non-linear interconnections and dependencies within the system, and proactively detecting performance variability before it has serious consequences. These participants also valued the identification of how incidents develop and occur over time, viewing the system as holistic, which may move away from the blame culture (Hollnagel & Speziali, 2008). Adaptable and flexible human performance that is essential for working efficiently and, the corresponding potential for 'drift into failure', have been recognised previously (Rasmussen, 1997). Participants appreciated the value in FRAM as a method for capturing these concepts, and the ability to consider performance variabilities in a range of situations.

Nevertheless, some participants found it difficult to understand some definitions of the central concepts of FRAM and how these could be applied in practical contexts. This resulted in some participants experiencing difficulties in identifying potential instantiations of resonance. Participants also recommended that the safety II perspective should have a better way of considering organisational factors. However, Hollnagel (2012) described that within FRAM performance variability is determined by the work environment and wider organisational context. Eleven Common Performance Conditions (CPCs) are identified in FRAM, such as work conditions, availability of procedures and organisational quality, to identify potential variability in functions (Herrera & Woltjer, 2010). This emphasises the importance of appropriate communication of safety II concepts via practitioner-focused literature and accident analysis training (Steele & Paries, 2006).

Practitioners expressed concern that FRAM does not contain a human error quantification element (section 3.2.2.). Hollnagel (2014) explained that FRAM should focus on variability and representation of the dynamics of sociotechnical systems, rather than probability. However, there are examples where researchers have integrated a quantitative element with FRAM to facilitate risk assessments. With the aim of gaining more accurate human error probabilities (HEPs), FRAM has been integrated with Bayesian Networks (Bahoo Toroody et al., 2017), FMEA and MEHARI approaches (Mock et al., 2017) and STPA (System-Theoretic Process Analysis, Leveson, 2011) in the railway domain (Toda et al., 2018). However, quantifying variabilities or human errors depend on subjective expert judgement, linking their experience in processes with theoretical aspects of FRAM to specify quantitative values (Smith et al., 2017; Frost and Mo, 2014). Future research must explore the extent to which combined approaches contributes towards informed management decisions to enhance system safety (Yu, et al 2020).

### 4.2. Recommendations for enhancing the usability and practical applicability of emerging methods

The responses derived from safety experts in the current study reveal how the different safety approaches and methods are perceived by users, and is an important step towards the goal of supporting better application of safety methods (Underwood & Waterson, 2013; Shorrock & Williams, 2016; Dempsey, 2018). Participants provided several recommendations for the future development of methods, particularly relating to the use of methods in combination and the need for more guidance and training to facilitate more effective application of existing methods including FRAM. This may include integrating practical examples and guidance for those less familiar with Human Factors research (Waterson et al., 2015). A possible suggestion might also include experts in research and practice working together to create qualitative examples and case studies to assist in using FRAM , to demonstate how safety II concepts can be practically applied to improve system safety.

As some participants described FRAM as time-consuming and complex to use, 'stop rules' need to be considered, so that practitioners know how far to go with analysis. Whilst this may offer a more concise analysis procedure, that may be more practicable than a complete analysis, the guidance should acknowledge that this may also result in a reduction in the obtained level of detail acquired and subsequent limitation in the overall systemic vision. 'Comprehensiveness' and 'usability' are important methodological requirements (Shorrock & Kirwan, 2002), but there were some perceptions from participants that these are mutually exclusive. There is a need to bridge the gap between 'academically sound' and 'practically applicable' features of methods.

Many participants advocated that Safety I and Safety II should be seen as complementary approaches to safety, emphasising that methods should be used with a changed mind set in line with the safety II perspective. Hollnagel (2016) and Hollnagel, Wears and Braithwaite (2015) advised that safety I should not be replaced by the safety II perspective, rather both should be used in combination when thinking about system safety. This may involve the use of existing methods and techniques, in combination with new practices to consider what goes right, and to manage performance variability rather than constraining it. Collaboration between researchers and practitioners can explore how these complementary perspectives can be combined in practice, including how the safety II perspective can be tailored for industry use (Steele & Paries, 2006).

Participants from all groups recommended integrating multiple methods within a structured framework or toolkit, as part of a 'wider decision framework' (section 3.3.1). Similarly, some studies have suggested combining different approaches for more comprehensive accident analysis, such as STEP (Sequentially Timed Events Plotting, Hendrick & Benner, 1986) with FRAM (Herrera & Woltjer, 2010), or FRAM with CREAM and Fuzzy Logic (Hirose et al., 2016). Frameworks and supplementary guidance must be developed and tested, to ensure it can be understood and applied in different contexts (Waterson et al., 2015). This can take into account desired and less desired features of methods, ensuring the needs of different groups of safety experts are met (table 8). There is a requirement to bridge the gap between theory and practice, so the best available safety concepts and methods can be practically applied to understand accident causation and safety improvements in complex sociotechnical systems.

## Conclusion

The study brought together participants from different safety and Human Factors roles, adding important commentary and context to earlier work on the choice of safety methods. This study supports previous conclusions on the research-practice gap in different analysis approaches taken by researchers and practitioners. Findings provide new insights in understanding experts' familiarity and willingness to consider safety II approaches to safety analysis, including their interpretations of the principles of emergence and resonance. They key findings were that participants recognised the value of the safety II perspective in providing detailed recommendations for improving system safety, though some found difficulty in understanding concepts and applying this method in practice. Recommendations were discussed around the future development and better application of safety methods, including the wider application of FRAM, potentially in conjunction with traditional safety methods.

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## Appendix A. Additional responses from participants

### Theme 1

**Table A.1. Error and accident analysis methods used by participants**

| Categories of methods | Name of methods | Users |
|---|---|---|
| Predictive risk assessment methods | FMEA (United States Military, 1949) HAZOP workshops (Lawley, 1974) | Human Factors practitioners and safety experts within the rail and other industries |
| Human error quantification tools | HEART (Williams, 1986) | Human Factors practitioners within the oil and gas industry |
| | THERP (Swain & Guttmann, 1983) | Human Factors practitioners within the nuclear industry |
| | RARA (RSSB, 2012) | Used by risk teams in the rail industry |
| Taxonomic methods | TRACEr (Shorrock & Kirwan, 2002) | Not currently used in the rail industry, described as an 'academic' tool. One practitioner sometimes uses TRACEr-lite |
| | SHERPA (Embrey, 1986) | Human Factors practitioners within the oil and gas industry |
| | GEM-R (Network Rail, 2012) | Incident investigators in the rail industry |
| | HFACS (Wiegmann & Shappell, 2003) | Incident investigators in the aviation industry |
| Systemic methods | Accimaps , (Svedung & Rasmussen, 2002) STAMP ( Leveson, 2004) and FRAM (Hollnagel, 2004) | Human Factors researchers,<br>Incident investigators/ safety experts in the rail industry |

### Theme 1: Participant role/experience in safety analysis

Human Factors researchers described using systemic methods such as Accimaps, STAMP and FRAM, although acknowledging these are 'academic' methods not widely used by practitioners:

> "these are the most popular methods for systemic accident analysis, but they are not widely

> used throughout industry".
>
> "Accimaps are used to teach incident investigators, but they are very academic"
>
> "STAMP is being heavily worked on, in terms of prospective work it can do, to enhance its suitability as a predictive approach".

In terms of desired features of methods, two Human Factors researchers noted the importance of comprehensiveness, stating they have more time for analysis:

> "As a researcher I'd want it to be comprehensive. I can sacrifice it being a bit more complicated, because I've got time to get to grips with that. I'd like it to take a systems perspective. I wouldn't want it just to focus on human error".

One Human Factors researcher noted the importance of choosing a method that considers interactions and relationships between different components of the system:

> "*(it's important to)* look at the wider picture, I don't think the taxonomy should be the be all and end all. You need to consider how all components interact and fit together".

Incident investigators use a range of methods, including human error classification tools. One participant stated that HFACS is used in the aviation industry, and two practitioners explained that GEM-R is used by incident investigators for retrospectively analysing rail incidents. Safety management specialists also use predictive risk assessments, and systemic approaches including FRAM.

Incident investigators and safety management specialists identified additional requirements of a method. These included; being practically applicable, assisting in generating measures for reducing human errors and improving system safety, and avoiding apportionating of blame to humans at the 'sharp end' of the system:

> "the possibility to identify more systemic/ process oriented mitigation measures"
>
> "Something can be integrated into norms, methods, and established as good practice"
>
> "Something that considers cultural change, and open minds to variability, moving away from (the) guilty, even holding responsibilities"

They also recognised the value of a method that is comprehensive and considers a range of factors within the organisation, yet has structure and guidance to aid analyses:

> "Consideration of group or organisational factors"
>
> "There must be a structure to its actual use"
>
> "there should be practical examples and definitions of terms as well".

Practitioners used a range of prospective methods to predict human errors, including predictive risk assessment and HEQ methods. Within the rail industry, event and fault trees are used for predictive purposes, as well as quantification tool RARA (Railway Action Reliability Assessment), (RSSB, 2012). Two interviewees commented that FMEA is used in numerous industries to assess equipment failures and human-related processes.

**Theme 2.**

**Table A.2. Examples of instantiations of resonance identified in focus groups**

| **Upstream function (and step number)** | **Individual performance variability** | **Downstream function affected (and step number)** | **Output variability** | **Consequences** |
|---|---|---|---|---|
| Request line block (2) | Too late | Check there is sufficient margin (4) | Too late | Missed margin |
| Request line block (2) | Imprecise | Arrange for additional protection if necessary (5), place reminder appliance on protecting signal (6), authorise line blockage (7) | Imprecise | Protection in wrong location |
| Apply reminder appliance (6) | Omitted | All | Too early | Line blockage granted in incorrect location |
| Confirm details of line block request (3) | Too late | All | Too late | Not safety related, but in terms of delays |
| Confirm details of line block request (3) | Imprecise | Arrange for additional protection if necessary (5), place reminder appliance on protecting signal (6) | Imprecise | Line blockage granted in an incorrect location |
| Check there is sufficient margin (4) | Imprecise | All | Too early | Line blockage granted when train is in the section |

Instantiations included those where an upstream function providing a precondition to a downstream function was **imprecise** or carried out **too early,** resulting in a loss of accuracy in downstream functions. Preconditions must be completed before a function is carried out. For example, if <check there is sufficient margin> is imprecise, it is too early to perform subsequent functions, including <turn signals to danger>, <place reminder appliance> and <confirm additional protection is placed>. It is therefore too early for the track worker to enter the line blockage.

> "Number 2 requesting line blockage could be done imprecisely so the wrong information was given….So it could affect 6, placing reminder appliance on the signals"

Instantiations also included those where an upstream function was **omitted** or carried out **too late,** resulting in the delay of downstream functions. Processes must be carried out in a particular sequence, and preconditions must be completed before subsequent functions can be performed. For example, if <apply the reminder appliance> is omitted, it is too early to perform subsequent functions, resulting in a line blockage being granted in an incorrect location. Alternatively, if an upstream function is carried out too late, other functions are severly delayed resulting in a loss of time and delays in the system:

> "if something was done too late (*there would be)* delays in the system and everything would get done too late".

According to Macchi et al. (2009), variabilities in upstream functions, in terms of timing or precision can have varying effects on downstream functions, resulting in improper couplings among functions. For example, incorrect timing of the output from an upstream function may affect the time available for a downstream function to be performed, in turn impacting the timing or precision of its output. This may also occur if upstream functions, which serve as preconditions, are omitted or insufficiently checked (Hollnagel & Goteman, 2004).