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Evaluating Advancements in Accident Investigations Using a Novel Framework

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Safety is monitored by various proactive and reactive methods, including the investigation of adverse accidents and incidents, which are collectively known as safety investigations. In this study we demonstrate how accident and incident investigation reports can be useful to identify implicit safety views and accident investigation approaches. An analysis framework was developed based on contemporary safety literature. The framework incorporates aspects such as hindsight bias, judgemental approach, proximal or distal focus, and the application of systemic versus sequential accident causation models. The framework was piloted through the analysis of sixteen (16) accident investigation reports published by a Nuclear Power Plant (NPP). The comments of independent researchers lead to framework refinements that increased the inter-rater reliability substantially. The initial results were validated through interviews with the staff of the NPP. Afterwards, the framework was applied to 52 air accident reports published by the Dutch Safety Board (DSB) from 1999 to 2013. Frequency calculations revealed the extent of new safety thinking embracement from the DSB, and Fisher's Exact Test showed that none of the modern safety aspects has changed over time. The framework can be used to analyse accident investigation reports published by various organisations as means to identify implicit safety views and evolution of accident investigation practices over time. Further research will explore the reasons for potential gaps between theory and practice and contribute to minimizing such distance.

I. Introduction

Safety critical organisations such as the aviation and nuclear industries have been highly concerned about their safety performance. Safety performance is monitored by various proactive and reactive methods, including the investigation of adverse incidents and accidents, collectively known as safety investigations. Such investigations comprise opportunities for organisations to learn from events and introduce improvements in the form of safety recommendations. In this context, specific methods and tools are available to investigators for accomplishing their tasks. Most of the safety investigation methods stem from accident causation models. While accident causation models suggest illustrations of mechanisms that attempt to explain the accident, safety investigation methods provide guidelines for the analysis of the accident or incident (e.g., evidence collection, data analysis, synthesis of findings, development of remedial actions). Hence, safety investigation methods are

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based inevitably on an accident causation model, even the latter is not explicitly stated in investigation procedures and handbooks.

Over time, accident causation models have evolved from the root cause rationale to multiple cause analyses and, quite recently, to systemic approaches (Katsakiori, Sakellaropoulos, & Manatakis, 2009); the differences among these models are discussed in the literature review section below. In parallel, the view of how humans contribute to system failure has also shifted; for example, Dekker (2006) stated that human error must be seen as symptom of trouble deeper in the system and not a cause.

The new accident causation models and safety thinking are widely accepted in academic circles and have been continuously tested with positive results. Hence, it is of high interest to compare current practice with academic thinking and research. Under this concept, safety investigation reports (i.e. accident and incident investigation reports) may be seen as valuable sources of data for identifying the type of accident models followed and revealing implicit safety views of the publishing authorities.

This paper describes an analysis framework that can be applied to safety investigation reports in order to compare industrial practice with accident causation models and views on safety, as contemporary safety theorists and researchers have articulated. The framework was piloted through the analysis of sixteen (16) accident investigation reports of a Nuclear Power Plant (NPP) and the results were validated through interviews with NPP personnel. Afterwards, the framework was used to analyse 52 air accident reports published by the Dutch Safety Board (DSB) from 1999 to 2013.

II. Literature

A. Accident causation models

Literature review revealed that accident causation models fall in one of the three families analysed in the following sections: single root cause, epidemiological and systemic.

1. *Root cause*

Root cause models and methods assume that an accident factor, also called the root cause, triggers a sequence of events that lead to an accident or incident. These models assume a linear and deterministic relation between causes and effects. Following this rationale, users perceive that the removal of the root cause will prevent the recurrence of the accident or incident (Underwood & Waterson, 2013). A dominant paradigm in this family of models is the Domino model of Heinrich (1931). Although during an investigation multiple factors may have been identified as part of the chain of events, the root cause approach focuses on the last part of the chain regardless of the surrounding conditions. A major flaw of this model is that the investigator might choose arbitrary the relative importance of the “root’’ cause compared to other contributing factors.

2. *Epidemiological*

Epidemiological models and methods attribute accidents and incidents to the combination of latent and active failures in the system. Latent conditions (e.g., working environment, supervision and organizational culture) might affect negatively operators’ performance. When these latent conditions coincide with unsafe acts (i.e. errors and violations), accidents occur (Underwood & Waterson, 2013). The dominant paradigm in this family is the Swiss Cheese Model of Reason (1990). Epidemiological models and methods need an unsafe act to trigger accidents or incidents. This excludes the perspective that a system has drifted towards an unsafe state over time under conditions of “normal’’ work.

3. *Systemic*

Modern accident causation models and methods suggest that accidents and incidents occur due to the uncontrolled complex interactions among human, technical and environmental factors within a system at a specific point of time and space. Systemic models and methods originate from systems and resilience engineering concepts that intend to represent interrelationships and interdependencies of system components. As accidents and incidents occur due to uncontrolled interactions, the logic of simply removing the root cause seems ineffective. It is necessary to identify and address all safety deficiencies throughout the system, and to control them by enforcing safety constraints (Leveson, 2011; Underwood & Waterson, 2013). This accident model family includes the Systems Theoretic Analysis Model and Processes Model (STAMP) of Leveson (2004), the Functional Resonance Analysis method (FRAM) of Hollnagel (2004), and the Accimap model of Rasmussen (1997).

B. Characteristics of the recent view on safety

Literature research on recent views on safety resulted to the following distinct characteristics of modern safety thinking.

1. Human error perceived as symptom

Dekker (2006, p.1) stated: "Human error is a symptom of trouble deeper inside a system [not a cause of accidents and incidents]." This means that apart from the human error identified during an investigation, there must be sufficient explanation for the factors that influenced human performance. Premise is that human operators set out to avoid adverse effects, cases of terror and sabotage excluded.

2. Hindsight bias avoidance

Dekker (2006, p.14) argued: "Hindsight means being able to look back, from the outside, on a sequence of events that led to an outcome you already know about." One case of hindsight is the "hindsight bias", which refers to the phenomenon that under knowledge of the outcome we exaggerate the probability that we knew this was going to happen. To avoid hindsight bias during accident investigation, it is necessary to shift from the rationale of "what did the operator wrong" to the rationale "why made it sense for the operator to act the way he/she did" (Leveson, 2011). Another type of hindsight is the "outcome bias" that refers to the influence of outcome knowledge on our evaluation of decision quality as good or bad.

3. Shared responsibility

In the context of shared responsibility, there have been two concepts: the Individual Blame Logic (IBL) and the Organization Function Logic (OFL). Catino (2008, p.55) stated:

> "The starting point for the Individual Blame Logic (IBL) is the assumption that people make mistakes because they do not pay enough attention to the task they are doing. It, therefore, adopts a causal linear model leaving the organizational context mostly in the background. The efforts to find blame are as a result directed to people in the front line, and the result of the approach is the attribution of the blame. If the guilty person is found, he or she can be held responsible for the accident. In practice this may mean that the 'bad apple' will be removed or prosecuted."

In contrast to IBL, the OFL "[…] reconducts the causal factors of an event to the whole organization [shared responsibility]. It acknowledges that accidents are the result of mistakes made by individuals, but these mistakes, however are socially organized and systematically produced (Vaughan, 1996)." (Catino, 2008, p.55).

Therefore, an advocate of OFL, and subsequently of shared responsibility, will focus on both the proximal (sharp end) and the distal (blunt end) during accident and incident investigation. As Dekker (2006, p.20) explained:

- "At the sharp end (for example the train cab, the cockpit, the surgical operating table), people are in direct contact with the safety critical process."

- “The blunt end is the organization or set of organizations that supports and drives and shapes activities at the sharp end (for example the airline or hospital; equipment vendors and regulators).’’

4. Safety-II thinking

Safety-II thinking is fundamentally different from traditional approaches (i.e. Safety I) because the focus shifts from merely on failure to additionally explaining success. Hollnagel (2014, p.147) argued, “Things basically happen in the same way, regardless of the outcome. The purpose of an investigation is to understand how things usually go right as a basis for explaining how things occasionally go wrong.’’ Under this concept, a success analysis of safety barriers and daily operations under similar conditions in the past must be part of the accident investigation.

5. Control loop consideration

Accident investigators and analysts must explore if safety constraints have been designed and enforced, and if system controls and feedback mechanisms were adequate and operative. Leveson (2011, p.80-82) stated:

> “In systems theory [...] systems are viewed as hierarchical structures, where each level imposes constraints on the activity of the level beneath it – that is, constraints or lack of constraints at a higher level allow or control lower-level behaviour. Control processes operate between levels to control the processes at lower level in the hierarchy. These control processes enforce the safety constraints for which the control process is responsible. Accidents occur when these processes provide inadequate control and the safety constraints are violated in the behaviour of lower-level components.’’

6. Avoidance of folk models

Dekker & Hollnagel (2004) argued that accident investigators must sufficiently analyse complex human behaviour and avoid abstract statements that do not provide adequate explanation of human behaviour and limit the growth of human factors knowledge (e.g., “lack of situation awareness” and “complacency”). Dekker (2006) recognised the popularity of folk models and attributed it to the inherent oversimplification such models offer, which, however, is not helpful for getting a deeper understanding of events.

7. Non-counterfactual

According to Dekker (2006), counterfactual is an approach whereby an investigator lays out in detail what options the end-user did not consider in order to prevent failure. The retrospective nature of accident investigation usually leads to a persistent focus on the end-user, with the use of expressions such as “could” or “should”. These formulations point to courses of action that were not pursued and thus, counter the facts, and, consequently, do not support complete understanding of people’s actions and decisions.

8. Non-judgemental

On the scope of explaining failure, external observers tend to search for decisions, judgments and perceptions that deviate from what was expected according to operators’ experience, established norms, or subjective observers’ expectations. This judgmental inclination is a result of the possession of knowledge about the background, circumstances and outcome of the accident (Dekker, 2006). It is inevitable that during any accident, the human element may have played a role for doing or not doing something that was expected or not. The judgemental approach is the one that emphasises mostly on comparing the actions of the end user with what was expected instead of exploring the why’s and how’s.

III. Method

Based on the literature presented above, the researchers developed an analysis framework based on the accident causation models and the characteristics of the current views on safety. Initially, the reliability of the framework between two (2) researchers was assessed via a pilot analysis of three (3) reports published by a Nuclear Power Plant (NPP). The variance among raters was substantially decreased by improving the clarity of each topic's description. Afterwards, the analysis framework was applied on sixteen (16) accident investigation reports published by the specific NPP in 2013 and 2014. The results were validated through semi-structured interviews held with the NPP staff.

Following validation, 52 air accident reports of the Dutch Safety Board (DSB) were analysed with the framework; the analysis constituted part of a graduation thesis (Jong & Palali, 2015). The sample was divided into two (2) periods, 1999-2006 (26 reports) and 2007-2013 (26 reports), in order to assess if safety approaches have changed over time. The selection of periods was based on the fact that most of the literature addressed by the framework was published after 2004, and that accident reports are released 2 years in average after accident occurrence. The latter was confirmed by calculating the median value of such durations for the sample considered in the research.

Finally, the researchers calculated the frequency of each new safety view aspect for the whole sample and per period. Fisher's Exact Test was employed to explore potential differences in frequencies between the selected periods. The data were analysed with the PASW software package and the results of 2-sided tests were considered; the significance level foe the tests was set to 0,05.

A. Analysis framework

1. Accident causation models

In order to assess to what extent the accident investigation reports embedded modern causation models, the frequency of each model family found in the reports was computed (root cause, epidemiological and systemic models).

2. Characteristics of the current views on safety

The modern views on safety discussed in section II.B above were employed to determine to what extent the DSB encompasses them, as reflected in its accident investigation reports. The presence of each of the following safety views was assessed through corresponding questions:

- "Human error perceived as a symptom": Does the accident investigation provide explanation for factors that influenced human performance?
- "Hindsight bias avoidance": Does the accident investigation clarify why it made sense for the operator to act/decide the way he or she did? (This research included both "hindsight bias" and "outcome bias" and under the common heading "hindsight bias'').
- "Shared responsibility": Does the accident investigation equally focus on both the proximal and distal organisational levels?
- "Safety-II thinking": Does the accident investigation refer to success analysis of safety barriers and operations, in addition to the failures identified?
- "Control loop consideration": Is there a discussion about feedback loops in the system and sub-systems discussed in the accident investigation report?
- "Avoidance of folk models": Are abstract statements about human behaviour (e.g., "lack of situational awareness'', "complacency'', "boredom'') sufficiently explained?
- "Non-counterfactual": Does the accident investigation refer to explanation about what the humans did (not) before or during the accident in reference to standards and procedures? (e.g., he/she should or could have done).
- "Non-judgmental": Are the findings of the comparison between human performance and norms further explained?

B. Pilot analysis and inter-rater reliability

In order to ensure rigorousness of the analysis framework, a pilot analysis of three (3) NPP's accident investigation reports and a subsequent inter-rater reliability evaluation was conducted with the participation of a NPP's representative. Each of the reports was analysed independently by the NPP representative and a researcher. The inter-rater reliability was assessed through the percentage of absolute agreement between the NPP representative and the researcher.

The initial average score of inter-rater reliability was not satisfactory (63%). Taking into account the extremely low agreement on one accident investigation report, the research team reviewed the analysis framework in terms of completeness and comprehensiveness. Each finding that revealed high disagreement between the raters was thoroughly discussed and compared against the framework. Following the remarks made, the analysis framework was reworded in order to reflect the changes required for improving its clarity and ensuring higher consistency. Afterwards, the raters repeated the application of the analysis framework and the agreement score for all three (3) pilot reports was recalculated 81%, which was considered satisfactory (>75%).

The inter-rater reliability was again assessed though the application of the framework to eight (8) DSB's air accident reports, which were analysed by two researchers, who had not participated in the development of the framework and the analysis of the NPP's accident reports. The results were marginally satisfactory (75% agreement); discussions about the different ratings revealed that in some accident reports the raters did not identify clear cut-points for each safety view aspect. The rating in some cases was a result of each researcher's overall perception of the safety perspectives depicted in the accident reports. Also, human error related aspects (e.g., Human Error Seen as Symptom and Non-Judgmental attitude) did not apply to accident reports that had not addressed human performance issues. Therefore, the researchers decided to follow a case-by-case approach and exclude from calculations the cases where a new safety thinking aspect was not evident or applicable.

C. Validation

The results from the analysis of NPP's accident reports were validated through thirteen (13) semi-structured interviews with NPP personnel. The researchers had predetermined a list of questions, but also prompted interviewees to discuss any other topics considered as important. An interview guide was developed in order to group topics and tailor the questions to various participants' functions (heads of departments and production lines, safety management, human factors department etc.). The questions were based on the results of the accident investigation reports' analysis and the research of Rollenhagen, Westerlund, Lundberg, and Hollnagel (2010), who studied the context and habits of accident investigation practices of 108 investigators from different sectors.

IV. Results

A. Accident causation model

The results of the classification of the accident investigation reports, in terms of the accident causation model that was employed, revealed that the root-cause model was applied in 48.1% of the reports, 50% of the accident reports used an epidemiological model approach, and only 1 case (1.9%) employed a systemic model approach (**Figure 1**).

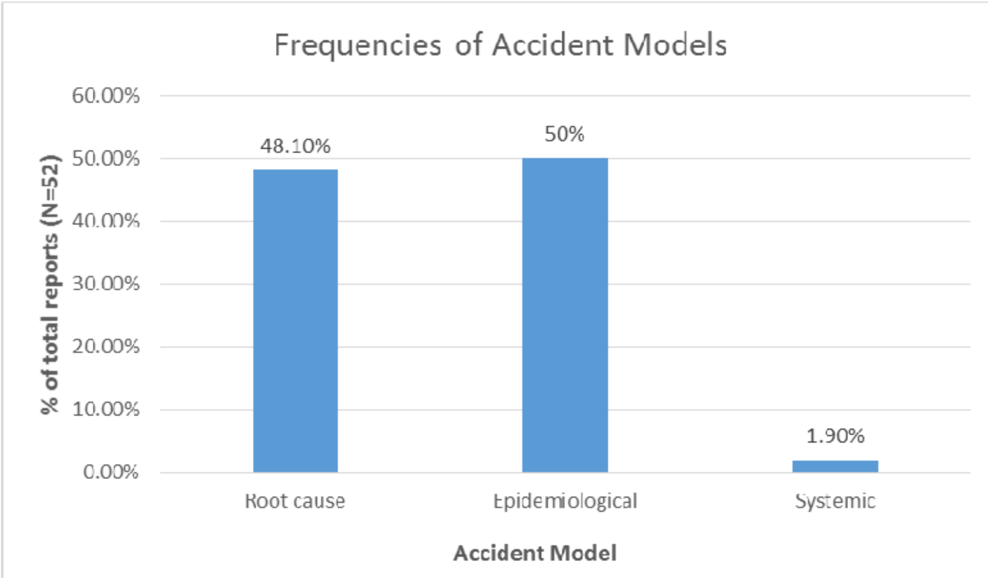

Figure 1: Frequencies (%) of the Accident Causation Models in Accident Reports

The Fisher's Exact Test results did not show significant difference of the accident model frequencies among the periods 1999-2006 and 2007-2013 (*p= 0.267*).

B. Characteristics of the current views on safety

The numbers of the reports that new safety thinking aspects could be assessed are presented per period in **Table 1.**

New Safety Thinking Aspects	**Period**		
	1999 - 2013	**1999 - 2006**	**2007 - 2013**
Folk Models Avoidance	47	24	23
Control Loop Consideration	50	24	26
Human Error as Symptom	36	17	19
Non-counterfactual	38	19	19
Non-judgmental	38	19	19
Shared Responsibility	41	22	19
Hindsight Bias Avoidance	35	17	18
Safety - II	50	25	25

Table 1: Number of Accident Reports Considered per Aspect

The frequencies of the characteristics of modern safety views in accident investigation reports regardless period are presented in **Figure 2**. The three characteristics mostly underrepresented were "Safety-II thinking", found in 14% of the reports, "Hindsight avoidance", identified in 45.7% of the reports, and "Shared responsibility" noticed in 53.7% of the reports.

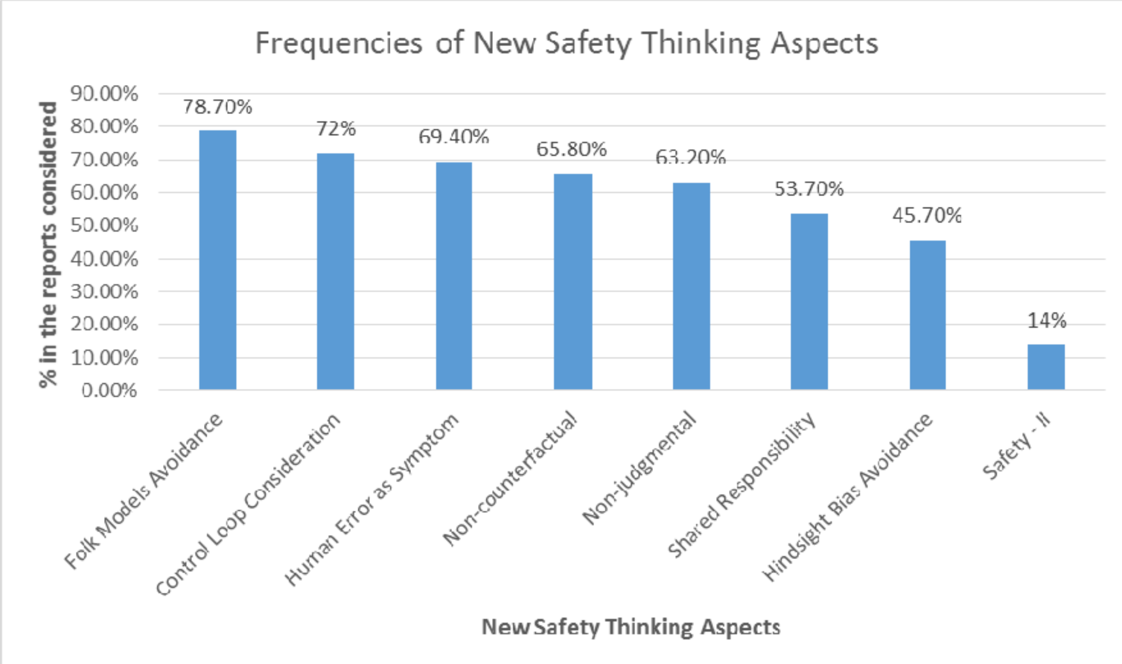

Figure 2: Frequencies (%) of the New Safety Aspects in Accident Reports

Fisher's Exact Tests did not show significant differences of the new safety views embracement between the two periods (**Table 2**).

New Safety Thinking Aspects	**1999 – 2006 (% of accident reports)**	**2007 – 2013 (% of accident reports)**	**Fisher's Exact Test (p value)**
Folk Models Avoidance	79.2%	78.3%	1.000
Control Loop Consideration	70.8%	73.1%	1.000
Human Error as Symptom	76.5%	63.2%	0.481
Non-counterfactual	68.4%	63.2%	1.000
Non-judgmental	63.2%	63.2%	1.000
Shared Responsibility	54.5%	52.6%	1.000
Hindsight Bias Avoidance	47.1%	44.4%	1.000
Safety - II	4%	24%	0.098

Table 2: Fisher's Exact Test results for the New Safety Thinking Aspects

V. Discussion

The pilot analysis of the NPP's accident investigation reports and the validation of the results through interviews confirmed the potential of the framework to identify the frequency of accident models types in use and reveal implicit safety views of the company. The refinement of the framework and the decision to exclude cases that new safety view aspects were not evident or applicable strengthened the reliability and validity of the results referred to the DSB accident reports analysis.

The results of the accident models in use revealed that the DSB has not adapted a systemic approach to investigation reports, and the frequencies between the root cause and epidemiological model cases have been almost evenly distributed over time. Although the first observation might be attributed to various factors (e.g., lack of awareness of the potential benefits of modern accident models, difficulties in their use, insufficient communication of new models, resistance to change), the high frequency of root cause models' use is not perceived as encouraging. Taking into account that epidemiological models have been vastly introduced since 1990 and embedded in safety documents and training, an increasing trend of such models' use over time was expected.

Regarding the implicit safety thinking, the medium to high frequencies (>50%) calculated for 6 out of 8 modern safety views implies that, in general, the DSB has been promoting a human-centred culture during accident investigations. However, it may be claimed that the emphasis on some of the modern safety thinking aspects will not fully unfold their collective potential to foster such culture. For example, although the perception of human error as symptom is a positive aspect, if this is not coupled with a shared responsibility approach, the latter may counteract the attempt to completely address the former.

The remarkable low presence of the Safety – II characteristic indicates a focus on failures and rare discussions about success. Although a holistic approach to Safety – II has been recently introduced in literature, the need to address successes as means to share positive lessons has been always a topic of modern management practice. However, the fact that Safety – II is more visible in the second period (2007 – 2013) might be indicative of an evolution towards considering success in addition to failure.

VI. Conclusions

The application of this analysis framework on a set of accident investigation reports provided evidence that it can be used to identify implicit safety views and assess the investigation approach followed. Taking into account the literature reviewed by the researchers, the analysis framework characteristics can be seen as mutually exclusive and collectively exhaustive. However, continuous monitoring of safety thinking evolution will ensure the future update of the framework by adding, removing or rephrasing characteristics.

At this stage, further research has been conducted by the Aviation Academy in order to:

- Develop a tool, which will accompany the framework and will provide guidance for its application.
- Apply the tool to accident investigation reports published by the Australian Transport Safety Board (ATSB).
- Apply statistics in order to assess relations among safety view aspects and evaluate effects of variables (e.g., time period, publishing authority) on these aspects.
- Explore further the validity of the results through interviews with the DSB and ATSB staff and discuss potential explanations.
- Discuss the results from interviews and statistics with safety researchers and thinkers.
- Extend the research to accident reports published by various authorities and industry sectors.

It is clarified that the current and future research on the specific topic does not aim to compare the traditional and modern approaches, or judge organizations and authorities for not following safety advancements. The main objective of the research is to introduce a consistent tool that will allow an assessment of the distance between new safety thinking and practice over time. The ultimate goal is to unveil the reasons of such distance, provide feedback to safety researchers and the industry, and, eventually, minimize the gap between theory and practice.

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