How could investigators use safety models to inform decisions on what to focus on?

Nektarios Karanikas, BSc, MSc, DProf, SFHEA, GradIOSH, PMP, CEng, MHFESA, FRAeS

ISASI member MO6544

School of Public Health & Social Work, Faculty of Health, Queensland University of Australia, Queensland, Australia.

Dr Nektarios Karanikas is Associate Professor in Health, Safety and Environment at the Queensland University of Technology (AU). Before starting his academic career, Nektarios worked for about 19 years as an officer at the Hellenic Air Force. There, he served in various positions related to maintenance, safety, and quality management, including accident investigations, and he was lecturer and instructor for safety and human factors courses. In addition to his academic qualifications, Nektarios holds professional engineering, human factors, project management, and safety management credentials and has been a member of various national and international associations.

1. The landscape

Consultation with or (in)direct exposure to specific Safety/Accident Models (SAMs) can guide thinking, define how a safety-related situation, challenge or event will be examined and how and what data will be collected. Typically, models comprise the input to methods for investigating safety incidents/accidents and designing safety management initiatives to identify and control safety hazards and risks. Although SAMs are general in purpose, rather than application-specific as methods, safety investigations methods still depend heavily on underlying accident models [1]. As such, models propose possible causality mechanisms (i.e., the possible "why" of events) and can drive the methods through which investigations are conducted (i.e., the necessary "how" to examine the possible "why").

Surprisingly, despite academia and industry focusing on a relatively limited number of SAMs, by 2016, in total, 161 such models were recorded [2]. Each SAM advocates a significantly or slightly different approach to safety, can reflect a mixture of various elements of social, engineering and management perspectives and/or meet the needs of a specific context or industry domain. Broadly, SAMs can be grouped into three categories [3]:

1. Sequential (cause-effect) models that focus on fixed linear/direct relationships between causes, ranging from end-users to equipment and management as well as event linkages in a timeline. Heinrich's Domino Model is one of the earliest linear models.

2. Epidemiological (multiple causes-effects) models approach safety events like disease epidemics, considering active errors and latent conditions along with their implications as an accumulative chain of events that, after an incubation period, produce multiplying effects. The Swiss Cheese Model (SCM) is one of the most popular models in this category.

3. Systemic (complex) models focus on two system properties, namely coupling and interactions. Coupling refers to the level of control as direct (tight) or indirect (loose), and interaction refers to the proximity amongst systemic actors and processes and their relevant control or feedback loops. Examples of models in this category are the AcciMap and System-Theoretic Accident Model & Processes (STAMP).

Notably, the benefits promised by contemporary systemic models and methods are not being widely tested in practice; they lack a track record within the industry, although concerns exist that using simple, non-systemic techniques could facilitate the attribution of liability without searching for deeper and wider causes [4]. Accordingly, it has been proposed to tailor SAMs to the needs of targeted users [5]; since there might be various stakeholders, the results of applications of models should serve a different range of needs and ways of understanding. Considering the diversity of SAMs and the research-practice gap outlined above, it has been recommended to develop hybrid models based on the ones that already exist instead of introducing more new SAMs [6]; however, no such large-scale attempt has been made to date.

2. Strengths and limitations of SAMs

Interestingly, over three decades ago, a study on 14 accident models used across 17 governmental agencies showed that the number of SAMs seemed unnecessarily diverse, and, based on the conflicts detected amongst the specific models, it was argued that all models could not be valid [7]. Indeed, newer studies on individual SAMs widely used in industry have identified a spectrum of strengths and limitations. For example, see [8] for STAMP, [9] for the Human Factors Analysis and Classification System (HFACS) based on the Swiss Cheese Model, and [10] for the Accimap model. Other comparative studies have confirmed that each SAM has something to offer over other models, but also brings its own limitations compared with other SAMs. For instance, see [11] for ATSB model vs Accimap vs STAMP, [12] for Events & Causal Factors (ECF) vs HFACS vs STAMP vs Accimap, [13] for STAMP vs Accimap and [14] for a comparison amongst eight SAMs.

Moreover, a review of studies on 63 sequential, epidemiological, and systemic SAMs and methods found over 63% of them had received little scrutiny from the scientific community and have not been applied often [15], with the review of the 37% more often used models indicating various advantages and disadvantages. Sequential ones were easy and fast to apply and offered clear illustrations but missed deeper structural causes related to socio-technical systems. Epidemiological methods required more time but revealed latent factors that could be controlled to reduce incidents. Systemic methods, despite being more detailed, necessitated considerable effort and costs that could not justify their use for regular business activities and safety investigations with limited casualties [16].

Some work on extended and hybrid SAMs includes the Systemic and Dynamic Sensitising Model of Safety and Systemic and Socio-Natural-Technical System [17], a combination of only two or a few models to meet the needs of a specific industry sector [18], customisations of particular SAMs to the context of particular industry domains [19] and extensions of specific models to capture missing elements based on empirical data from specific contexts [20]. Recently, the concept of a Standard Safety Model (STASAM v.0) was introduced [21] based on the review of four widely known SAMs and the combination of their strengths and mitigation of their limitations.

3. Study objectives and method

Typically, researchers use SAMs to analyse investigation reports retrospectively by distilling causal and contributory factors, indicating their relationships and interactions, presenting aggregated data from several reports, etc. to reveal trends and areas deserving more focus. Moreover, studies like the ones mentioned above about individual models and comparisons rely on the analysis of causal/contributing factors from published reports that are mapped against different SAMs to compare similarities/differences in representations, difficulties in using those models, etc. Thus, to date, the use of SAMs is limited to retrospectively using safety investigation reports, and, occasionally, (in)directly judging investigation teams for missing system elements from their investigations.

Nevertheless, the principal aim of air safety investigators is to analyse and understand systems to improve aviation safety by approaching each event as holistically as possible. Although receiving feedback retrospectively can help improve professional practice, safety investigators could be more interested in how they can proactively enhance the completeness and quality of investigations. As such, we have paid little attention to how we can use SAMs proactively, before and during investigations, to inform decisions about where and what matters to look at in a system.

Considering the above, in 2021, we commenced research by analysing the reports of two randomly chosen aviation events: an incident investigated by ATSB [22] and an accident investigated by AAIB [23]. We distilled information from the investigation reports about what the investigation team searched, regardless of whether this was found as causal/contributing to each event or not. We clarify that when the reports referred to various subsystems checked but not found causal/contributing to the events, we recorded the whole system as "searched" (e.g., the aircraft).

Then we used four models (SCM, AcciMap, STAMP and FRAM: Functional Resonance Analysis Model) to map this information. The mapping revealed what areas/elements from each model were searched by the investigators and the system areas suggested by these SAMs but not found in the reports. As we aimed to reveal the degree to which the system elements investigated satisfied "completeness" against the four models, the decreased granularity for "successfully" performed (sub)systems, as explained above, was not of concern. Nevertheless, the degree of detail aligned mostly with the investigators' practice, who did not refer with the same depth to "performing" systems and elements as with "underperforming" ones, with the latter having been more scrutinised.

Also, whereas all models suggest some form of relationships between (sub)systems/elements, we did not draw them from the reports, as it was outside the scope of our research to map causality mechanisms. Furthermore, the researchers had to decide the representation of processes for STAMP and functions for FRAM. As the reports did not explicitly adopt the particular models and were not written by adhering to their terminology about processes and functions, we mapped processes and functions related to distinct activities per person or organisation included in the reports.

The collection of the data from the investigation reports and their mapping against the four SAMs was performed iteratively through several inter-rater reliability sessions between the four researchers, namely Dr Oseghale Osezua Igene (United Kingdom), Ritu Sharma (Australia), Zenita Fosah (Cameroon) and the author of this technical paper. Collectively, the researchers have completed undergraduate and postgraduate studies in health & safety, including aviation safety, and had previous research and industry experience, including safety investigations in aviation. Sharma and Fosah had never analysed investigation reports or used the specific models during their academic studies or professional practice. As such, the composition of the team ensured, on the one hand, the necessary competency and skills for this research, and, on the other hand, the least possible bias in favour or against particular SAMs.

4. Results

In this technical paper, we report the findings of the analysis of the incident investigation report as the one for the accident has not yet been completed. The information distilled from the specific report resulted in 54 factors investigated (systems, subsystems, and elements), 23 of which were attributed by the investigation team as causal or contributory. Because SCM and AcciMap refer to system levels (higher level of abstraction) whereas STAMP and FRAM refer to more specific system elements (higher levels of detail), the analysis results are presented separately for each pair of models in Tables 1 & 2.

For facilitating the interpretation of the Tables, we note:

- SCM refers to four system levels: Unsafe acts of operators, Preconditions of unsafe acts, Unsafe supervision, and Organisational influences.

- AcciMap refers to seven system levels: Equipment and environment, Physical processes (including operator actions), Technical and operational management, Organisational management, Local area government, Regulatory bodies and associations, and Federal and State governments.
- STAMP revolves around processes and refers to respective controller(s) with a control algorithm (i.e., what, and how to be done) and dynamic process model (i.e., what is happening), control actions, actuators to transmit these actions, sensors/feedback mechanisms from the process, inputs to and outputs from the process and inputs from external controllers to the controller(s) of the process.
- FRAM focused on interrelated functions, each of which is characterised by its inputs and outputs, preconditions, resources, time constraints and control means.

Model	**System levels described in the model**	**System levels searched**	**System levels not searched**		**System levels searched but not mentioned in the model**	
			Levels	**Difference**	**Levels**	**Difference**
Swiss Cheese Model	4 system levels	3 system levels	1 system level (supervisory)	– 25%	2 levels (Regulators and agencies)	+ 50%
AcciMap	7 system levels	5 system levels	2 system levels (Federal/State and local governments)	– 29%	2 levels (international bodies and mental/physical states of individuals)	+ 29%

Table 1: Results from more abstract models

Model	**System elements described in the model**	**System elements searched**	**System elements not searched**		**System elements searched but not mentioned in the model**	
			Elements	**Difference**	**Elements**	**Difference**
FRAM	36 elements (6 elements per function * 6 functions)	24 elements	8 elements (various across the functions)	– 22%	Nil	0%
STAMP	120 elements (8 elements per process * 15 processes)	44 elements	76 elements (mainly dynamic process models, control actions, actuators and feedback channels)	– 63%	Nil	0%

Table 2: Results from more detailed models

As shown in Table 1, while investigators did not reportedly search for facts in the supervisory level according to a "complete" SCM and Federal/State and local government levels according to the "ideal" AcciMap, they investigated system levels that the SAMs above do not explicitly mention. SCM does not visibly address system levels above the organisation of interest, and AcciMap does not mention international associations as well as conditions of operators, all of which were included in the incident investigation report.

The results presented in Table 2, which regard the more granular SAMs, suggest that everything the investigators searched for could fit in what elements STAMP processes and FRAM functions include, leading to a 0% of system elements searched but not mentioned by the specific SAMs. On the other hand, the higher the model granularity, the more the elements not mentioned in the reports when compared with each model's "ideal" coverage. In the case of FRAM, we identified six functions, with 22% of their elements not found in the report. Regarding STAMP, which is more detailed than FRAM, we mapped 15 processes, with 63% of their respective elements not mentioned in the incident report.

5. Discussion and recommendations

During several investigation conferences and other events as well research [16], it has been acknowledged that organisational and regional policies, resources and cultures along with a lack of data do not always allow deeper and wider search across system levels and elements to identify possible causes and contributing factors. While sometimes the boundaries between the sharp and blunt ends of systems remain blurry, we must still consider personal responsibility despite any systemic factors. During an investigation, foresight and hindsight are complementary, with the latter comprising the inevitable starting point when an event occurs and the former providing the opportunity to understand each event's context better when evaluating human performance.

Considering the reality expressed above, the plurality of SAMs and the studies revealing each model's advantages and limitations, as outlined in sections 1 and 2 above, dogmatism of the practical superiority of any model can lead to isolation instead of a shared understanding. The boundaries between the various approaches underpinning each model are not strict, and context does not drive only the development of SAMs but also their adoption and application.

Moving beyond negative criticism about investigation choices and practices, especially when comparing them against popular models, the current study suggests another, allegedly more useful, way to use the various SAMs. Our premise is that consultation with one or more models can complement prior system knowledge and intuition from professional experience, stimulate discussions amongst investigation team members and help to make more deliberate decisions about what we should investigate or what we could presume as "true" and not necessitating investigation.

As such, considering the resource limitations during investigations and the diverse backgrounds and knowledge of investigators, our position is that a conceptual mapping before and during investigations, like the one we reported in this paper, would be highly supportive. When planning investigations and/or after data collection begins, teams/investigators could start with consulting a "simple" SAM to identify system areas of interest they might have missed. Then, depending on constraints and other factors, extend this mapping by using more detailed models.

Admittedly, the four SAMs used in our analysis are just a few of the many. Nonetheless, the aim of this study is not to recommend subscribing to any model but provide an example of how any SAM can be used to support decision-making during investigations. Furthermore, mappings like the one we performed in this research should/could not be something prescribed. We acknowledge that despite various SAMs exist, some of them having been adapted by investigation authorities and agencies in their original or further modified versions, investigators do not (always) start their tasks with a model in mind.

Nevertheless, models can help improve investigation practice despite the weaknesses they inevitably carry, if we use them with caution and consideration of the context. Although any author of advanced and complex model can justifiably claim its high validity, we must account for the skills and experience of investigators at all system levels. Despite some academic voices judging professional practice, we cannot, and should not, impose the use of complex models on persons that cannot even correctly apply the simpler ones.

Conditions might not allow the operationalisation of various literature suggestions, but scepticisms and practical challenges should not mean rejection of approaches. Under this premise, we believe that consultation with SAMs in the way presented in this paper can improve transparency in choices and approximations during investigations, which in turn, will help both the industry and academia to improve.

References

[1] P. Katsakiori, G. Sakellaropoulos and E. Manatakis, "Towards an evaluation of accident investigation methods in terms of their alignment with accident causation models," Safety Science, vol. 47, no. 7, p. 1007–1015, 2009.

[2] M. C. Everdij and H. P. Blom, "Safety Methods Database. Version 1.1," Netherlands Aerospace Centre NLR, Netherlands, 2016.

[3] S. Kaspers, N. Karanikas, A. C. Roelen, S. Piric and R. J. de Boer, "How Does Aviation Industry Measure Safety Performance? Current Practice and Limitations", International Journal of Aviation Management, 4(3), pp. 224-245, 2019.

[4] P. Underwood and P. Waterson, "Systemic accident analysis: Examining the gap between research and practice," Accident Analysis and Prevention, vol. 55, pp. 154-164, 2013.

[5] M. Lehto and G. Salvendy, "Models of accident causation and their application: review and reappraisal," Journal of Engineering and Technology Management, vol. 8, p. 173–205, 1991.

[6] P. Waterson, D. Jenkins, P. Salmon and P. Underwood, ""Remixing Rasmussen": The evolution of Accimaps within systemic accident analysis," Applied Ergonomics, vol. 59, p. 483–503, 2017.

[7] L. Benner, "Rating accident models and investigation methodologies," Journal of Safety Research, vol. 16, no. 3, p. 105–126, 1985.

[8] C. Johnson and C. Holloway, "The ESA/NASA SOHO mission interruption: using the STAMP accident analysis technique for a software related "mishap"," Software: Practice and Experience,, vol. 33, no. 12, p. 1177–1198, 2003.

[9] A. Ergai, T. Cohen, J. Sharp, D. Wiegmann, A. Gramopadhye and S. Shappell, "Assessment of the Human Factors Analysis and Classification System (HFACS): Intra-rater and inter-rater reliability," Safety Science, vol. 82(C), p. 393–398, 2016.

[10] P. Salmon, M. Cornelissen and M. Trotter, "Systems-based accident analysis methods: A comparison of Accimap, HFACS, and STAMP," Safety Science, vol. 50, no. 4, p. 1158–1170, 2012.

[11] P. Underwood and P. Waterson, "Systems thinking, the Swiss Cheese Model and accident analysis: A comparative systemic analysis of the Grayrigg train derailment using the ATSB, AcciMap and STAMP models," Accident Analysis and Prevention, vol. 68, p. 75–94, 2014.

[12] O. Igene and C. Johnson, "Analysis of medication dosing error related to Computerised Provider Order Entry system: A comparison of ECF, HFACS, STAMP and AcciMap approaches," Health Informatics Journal, 2019.

[13] G. A. Filho, G. Jun and P. Waterson, “Four studies, two methods, one accident – An examination of the reliability and validity of Accimap and STAMP for accident analysis,” Safety Science, vol. 113, p. 310–317, 2019.

[14] N. Stanton, “Models and Methods for Collision Analysis: A guide for policymakers and practitioners, Report to RAC Foundation,” University of Southampton, 2019.

[15] H. Wienen, F. Bukhsh, E. Vriezekolk and R. Wieringa, “Learning from Accidents: A Systematic Review of Accident Analysis Methods and Models,” International Journal of Information Systems for Crisis Response and Management, vol. 10, no. 3, p. 42–62, 2018.

[16] N. Karanikas, D. Chionis and A. Plioutsias, “Old” and “New” Safety Thinking: Perspectives of Aviation Safety Investigators, Safety Science, 125 (104632), pp. 1-17, 2020.

[17] J.-C. Le Coze, “New models for new times. An anti-dualist move,” Safety Science, vol. 59, pp. 200-218, 2013.

[18] M. Lower, J. Magott and J. Skorupski, “A System-Theoretic Accident Model and Process with Human Factors Analysis and Classification System taxonomy,” Safety Science, vol. 110, p. 393–410, 2018.

[19] L. Xue, J. Fan, M. Rausand and L. Zhang, “A safety barrier-based accident model for offshore drilling blowouts,” Journal of Loss Prevention in the Process Industries, vol. 26, no. 1, p. 164–171, 2013.

[20] T. Morineau, J. Flach, M. Le Courtois and P. Chapelain, “An extended version of the Rasmussen’s Dynamic Safety Model for measuring multitasking behaviors during medical emergency,” in International Symposium of Human Factors and Ergonomics in Healthcare, 2017.

[21] N. Karanikas and A. Roelen, “The concept towards a Standard Safety Model (STASAM v.0),” in 6th European STAMP Workshop & Conference, Amsterdam, 2019.

[22] ATSB. Runway incursion and take-off commenced on incorrect runway involving GIE Avions de Transport Régional ATR72, VH-VPJ, Canberra Airport, Australian Capital Territory, on 25 September 2019. Report AO-2019-055, Australian Transport Safety Bureau, Australia, 2020.

[23] AAIB. Report on the accident to Piper PA-46-310P Malibu, N264DB 22 nm north-north-west of Guernsey on 21 January 2019, AIRCRAFT ACCIDENT REPORT 1/2020, Air Accidents Investigation Branch, United Kingdom, 2020.