Accident Analysis Methods and Models — a Systematic Review

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ABSTRACT

After a risk has manifested itself and has led to an accident, valuable lessons can be learned that can be taken into account to reduce the risk of a similar accident occurring again. This calls for accident analysis methods. In the past 20 years a large number of accident analysis methods have been proposed and it is difficult to find the right method to apply in a specific circumstance. We conducted a review of the state of the art of accident analysis methods and models across domains. We classify the models using the well-known categorization into sequential, epidemiological and systemic methods. We find that these classes have their own characteristics in terms of speed of application versus pay-off. For optimum risk reduction, methods that take organizational issues into account can add valuable information to the risk management process in an organization.

Keywords

Accident Analysis, Incident Analysis, Telecommunications

INTRODUCTION

The research reported in this paper was motivated by the goal of defining a risk analysis method for telecommunication service failure. Failure of telecommunication services can both cause crises (*e. g.* loss of signaling along railroads) and aggravate crises due to the inability to effectively communicate during the crisis resolution stage. In previous research, we have defined the RASTER method for risk analysis of telecommunication service failure, which is now used by the Dutch telecommunications regulator (Vriezekolk *et al.*, 2011; Vriezekolk *et al.*, 2015). Our current research aims to strengthen risk analysis by including lessons learned from past accidents. As part of the LINC (learning from incidents) project started by the Dutch telecom regulator, we conducted a comprehensive literature review of accident analysis methods, that we report here.

Methods to investigate accidents have been proposed and investigated at least since the early 1970s, but the number of methods proposed has increased steeply since the late 1990s. Different methods have been proposed for different domains, and they may use different accident models. For quite a few methods, there is little published evidence that they have been used more than once or twice. On the other hand, a few methods are cited frequently, and some techniques, such as fault tree analysis, are widely used in practice. Some methods are easy to use but lead to a potentially incomplete analysis, while others are expensive to use while allowing more thorough analysis. This raises the question whether from all of the published methods, a generic method can be distilled, using the useful elements of all published methods, and whether we can provide guidelines for choosing an appropriate accident model depending on the context of the accident.

In this paper we present a systematic literature review of accident analysis methods published since the early 1970s across many domains. After a discussion of related work, we state our research questions, we introduce the three classes in which accident analysis methods are generally categorized, and describe some statistics of the corpus of literature we found. We provide qualitative analytics for the different classes of analysis models. We conclude with the answers to our research questions. We present a generic accident analysis method, that can be applied in a lightweight to heavyweight manner, depending on the context of the accident. We also provide generic accident models for two of the major classes of analysis methods: sequential and epidemiological. A full account of our literature review, including selection method, databases under investigation, the full corpus under consideration and an overview of all methods found has been reported in (Wienen *et al.*, 2017).[1]

Related work

For the purpose of this review, Accident Analysis is the analysis of an accident that has actually happened. The analysis is done with the benefit of hindsight and it works back from the actual event towards its causes and enablers. Note that there are accident analysis methods that are prospective — most notably methods used in the Nuclear Industry. These methods simulate extreme conditions inside a nuclear facility to estimate the impact of nuclear accidents (Eggen and Banal, 1976). These methods are out of scope for this review.

Risk analysis is the *a priori* assessment of what *can* go wrong and what its impact may be. Risk analysis therefore works with possible paths towards possible outcomes. Accident analysis and risk analysis are each other's complement, as a fully analyzed accident may give new insights that can be added to an already existing risk analysis.There have been other reviews of accident methods (*cf. e. g.* (Bosse and Mogles, 2013; Herrera and Woltjer, 2010; Mohammadfam *et al.*, 2014; Strömgren *et al.*, 2013; Underwood and Waterson, 2014; Wagenaar and Schrier, 1997)), but we found none that have the breadth of this review. They single out specific methods, sometimes describing the classes mentioned in this article, sometimes applying them to real world problems. But they do not give an overview of the breadth of the subject as comprehensively as our research. Note however, that for risk analysis, this type of research has been done before (*e.g.* (Tixier *et al.*, 2002)).

For the purpose of this article, we use the following definition of an accident:

An Accident is an undesired and unplanned event that results in a loss, damage or injury.

This term is generally used in the industry, but some fields (such as Medicine and Telecommunications) prefer to use the term *incident* for an accident as meant in this definition.

RESEARCH QUESTIONS

The questions we pose ourselves for this research are the following:

1) What is the state of the art in accident analysis methods?
    a) Which accident analysis methods are in use today?
    b) Which accident models are in use today?
    c) What are the comparative strengths and weaknesses of these methods?
2) Can we draw up a generic model encompassing all current accident methods and models?
    a) What are domain-specific entities, attributes and relationships in accident models?
    b) Can we formulate a generic analysis method and model

We chose to cast our net as wide as possible. That meant that the scope for this investigation covers domains as varied as nuclear industry, aviation, space flight, chemical industry, traffic, outdoor activities and emergency services. We did this with two aims: first, to learn as much from different domains as we could, and second to improve our chances of finding specific methods used for telecommunications.

We ended up selecting 216 articles. In those articles 63 methods were described. Of these methods, 23 were mentioned at least three times. This included PRISMA (Van der Schaaf, 1996) and HFACS (Shappell and Wiegmann, 1997), which are not analysis methods. The remaining 21 methods (henceforth the "Top 21") have been subjected to further, quantitative analysis. Due to the sheer number of methods found, we only discuss the Top 21.

RESULTS

Introduction

In order to provide some structure, we have divided the analysis methods into four categories. Three of these have been identified by Hollnagel (Hollnagel, 2002; Hollnagel and Goteman, 2004) and they form three classes of methods, based on the accident model that they employ. The fourth is a rest category ('Other').

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Sequential accident models describe the accident as the end point of a string of causes.

Epidemiological accident models describe the accident as the product of the interaction between a set of entities and actors, some of which may be visible, and others invisible. In effect it is a sequence of causes that are inhibited or enabled by environmental factors that also have a place in the model. This model is similar to models of how diseases develop, hence the name. Key factor in epidemiological types of analysis is the description of latent factors that contribute to the development of an unsafe act into an accident.

Systemic accident models describe the accident as the result of the interaction within a tightly coupled system and between a system and its context. Feedback loops may play an important role in these models.

Other These methods and models are either defined very superficially, rendering them impossible to categorize, or are not analysis methods *per se*.

Descriptive statistics

From Figure 1, we conclude that there is a clear distinction between the number 1 (STAMP) and the rest of the field. This is partially because it is a popular subject for theses: four Master's and six PhD theses. No other method has been the subject of so many academic theses.

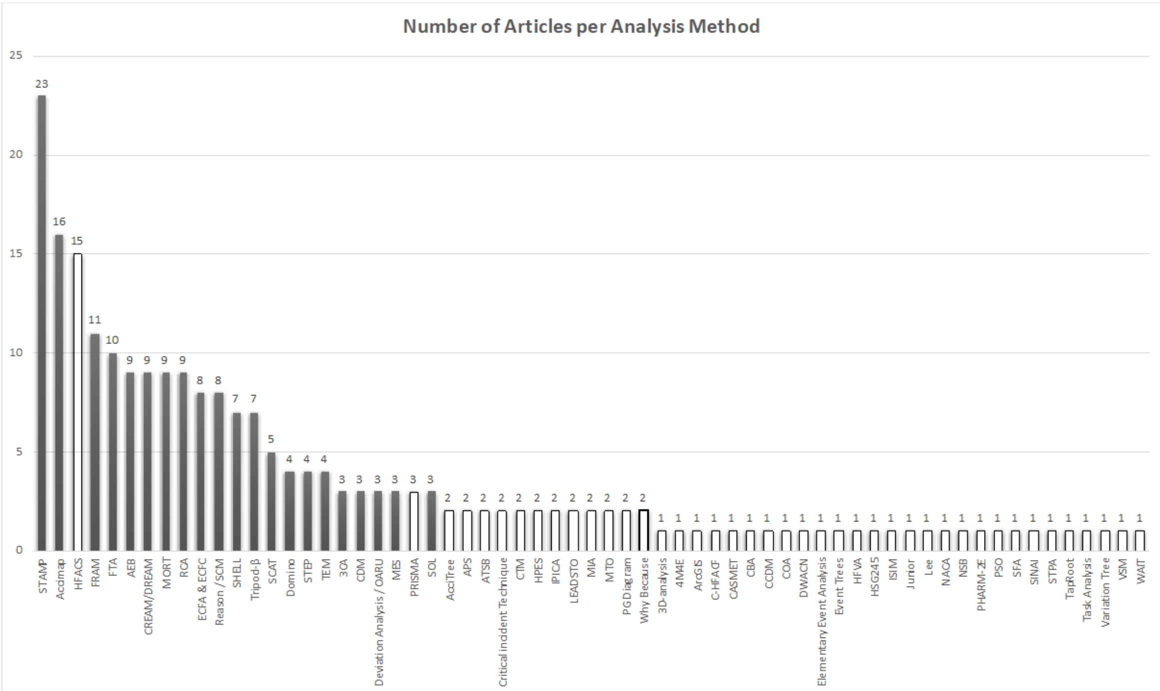

Figure 1. The number of times a method was mentioned in the articles researched. Note: only when actually defined, applied or used in a comparison — not mere mentions. The methods we discuss in this article are in black, the others in white

Domains in the corpus

Figure 2 shows that some domains mostly use methods that are more often discussed in the literature (*e.g.* mining, maritime), while others mostly use methods that we encountered only once or twice in the literature (*e.g.* medical and traffic). This may be due to the maturity of the practice of accident investigation in the former domains as compared to the latter domains. One counter example for this hypothesis is the low number of Top 21 methods for aviation accidents — a field for which we would expect some maturity. For nuclear accidents, the number of methods is zero, as we only found *a priori* analysis methods in this domain.

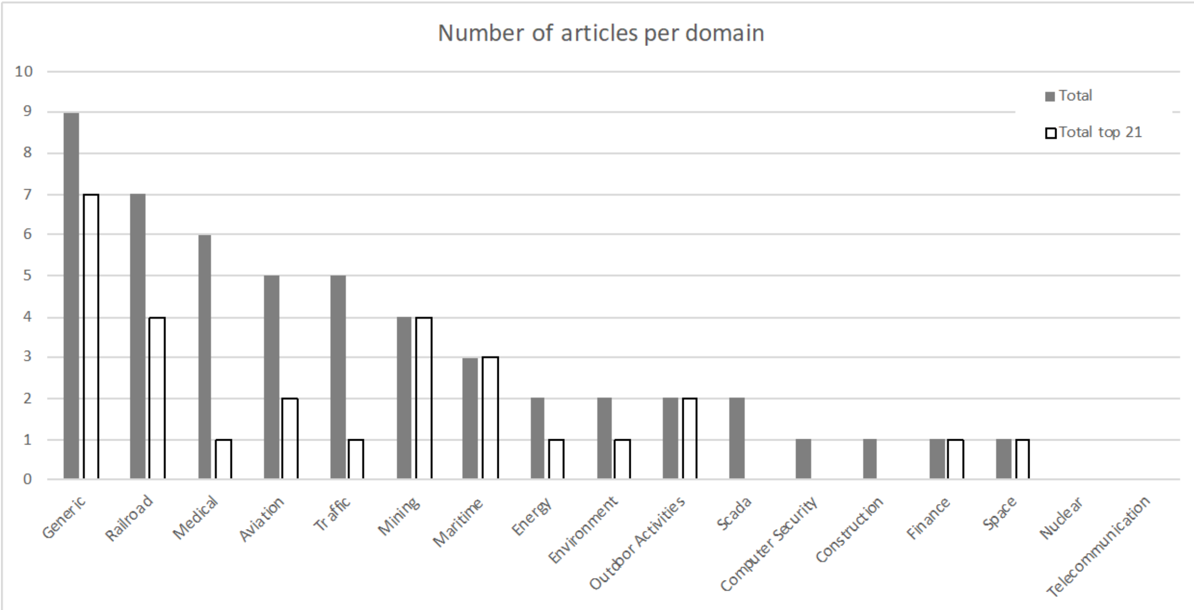

Figure 2. The number of analysis methods per domain. As can be seen from the graph, the number of more accepted methods (those that are in the top 21) differ strongly per domain.

Articles per class and per year

Figure 3 describes the distribution of articles in the corpus over time. This suggests that accident analysis methods are growing as a field of research. Note that the queries were executed in May, June and July 2015, hence the lower number of articles in 2015.

The general trend is that interest in accident methods is growing over time (*see* Figure 3), with the sequential methods starting early, followed by epidemiological and systemic, in that order. Furthermore, the interest in individual systemic methods is relatively high, with 33 articles about only 2 methods (on average 16.5), while that for individual epidemiological methods is lower, with 62 articles about 9 methods (on average 6.9). The average for individual sequential methods is comparable to the epidemiological (40 articles about 6 methods, averaging at 6.7). This is quite remarkable, as these methods have been around far longer (from 1941 for epidemiological models and from 1973 for sequential models) than the systemic (from 2004). This is indicative for the academic interest in the systemic accident models.

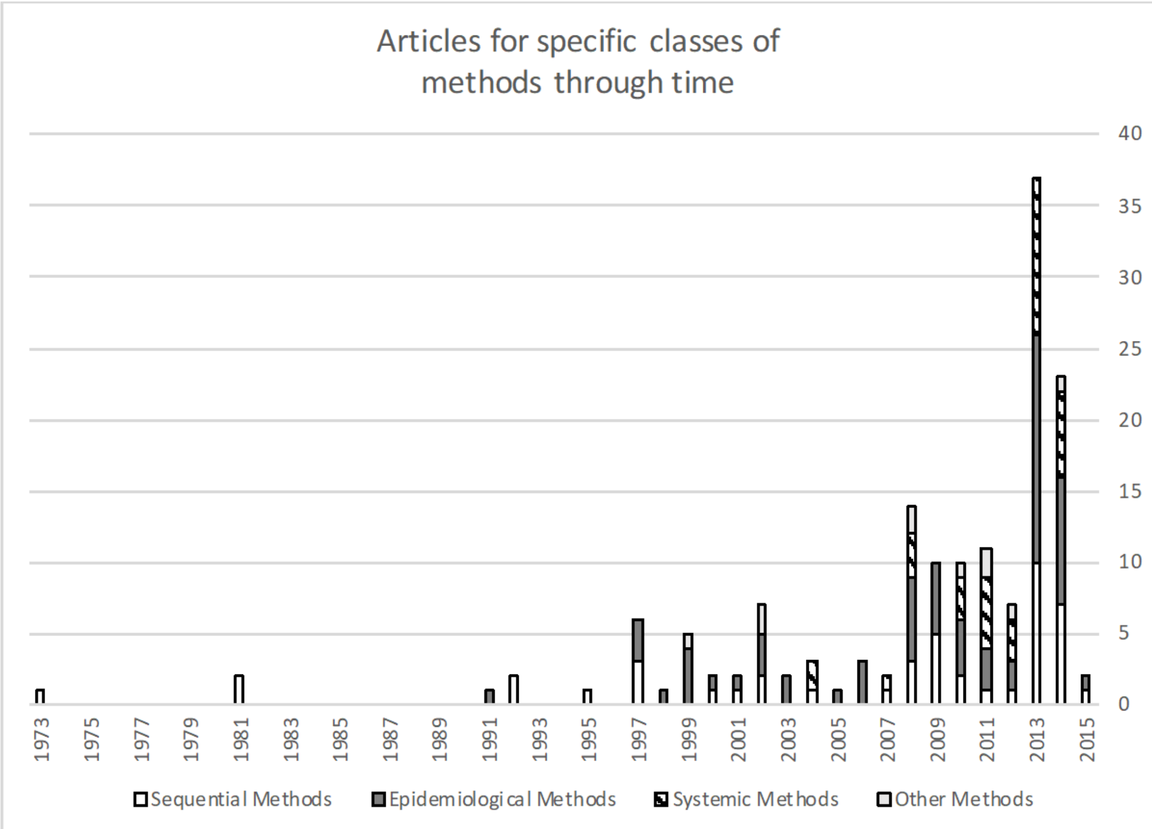

Figure 3. The number of articles per model class through the years. The median for sequential methods is 1992, for epidemiological methods is 2003 and for systemic methods is 2012

Qualitative Analysis

Table 1 shows that the top 21 contain representatives of all three classes along with a few other methods.

Table 1. Methods per Class

Class	Methods
Sequential	Deviation Analysis, ECFA/C, FTA, MES, MORT, RCA, STEP
Epidemiological	3CA, Accimap, AEB, CREAM, Domino Accident Model, Reason/SCM, SCT, SOL, TEM, Tripod-β
Systemic	FRAM, STAMP
Other	CDM, SHELL

Sequential Methods

Sequential methods describe sequences of *events*, connected through cause-consequence links. Events constitute the main entities of the models describing accidents in a sequential method. The accident itself is an event as well. Other methods use *conditions* that enable the event.

The term "sequential" refers to the cause-effect sequences that have actually led up to the undesirable event. A well-known sequential method, used both in accident analysis and in risk analysis, is the Fault Tree Analysis (FTA) method (figure 4.) Note that in contrast to the accident analysis method, in sequential *risk analysis* all possible causes that can lead to an undesirable effect are taken into account.

The most notable strength of the sequential methods is that they have been around for a long time, giving them time to mature. They are easily understood as they paint a picture of sequences of events leading up to the accident. As a result of this clarity, they can be persuasive when trying to convince management to allocate budget to preventing accidents from happening. One weakness is that these methods do not take the socio-technical context into account. They can only lead to improvements that are clear from the chain of events leading to the accident and the barriers preventing those. Please note that this is a weakness of the methods, and not of the models *per se*, as the models do provide means to model socio-technical factors.

We have created narratives for all sequential models that are used in the methods investigated, identifying entities and relations and we have combined these into the following narrative describing an overarching model:

> A sequential model can be represented by a causal network (with branches and merges, but without loops) of events and states leading up to an accident, which causes damage; branches may be AND or OR branches (and merges too), and edges can be inhibiting. A causal network does not contain feedback loops. Some events are failures, incidental factors, or deviations from a norm. Some are determining factors of the accident. Some are the result of unsafe acts or errors of people. So the network may include events in the social environment.

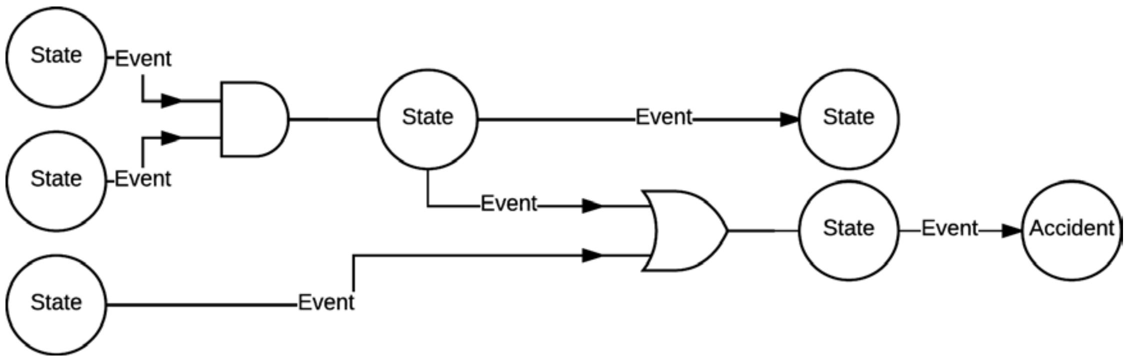

Figure 4. A sequential model for an otherwise unspecified accident. In contrast to a risk analysis this describes an actual series of events resulting in a past accident.

Epidemiological Methods

Epidemiological methods are also modeled around *events*, but they add a layer of *latent conditions* to the model. *Latent conditions* are conditions that are present in the system well before the onset of an accident (Hollnagel, 1999), but are not recognized as such by management before the actual accident occurs. *E. g.* bad maintenance may cause a sprinkler installation to stop functioning. This condition may be present for a long time, but will only be evident when a fire starts and the sprinkler installation malfunctions. Events are generally described as consequences of *actions* by *actors*. These actors are influenced by their *environment* (organizational goals, safety culture, pressure on scarce resources, more or less adequate management and legislation and so forth). Furthermore, some form of risk control is active through the use of *barriers* which may function more or less effectively due to similar environmental factors. One of the more prominent methods the AcciMap method (Rasmussen, 1997; Branford *et al.*, 2009).

The main benefit of this class of methods is that they not only take a serious look at the socio-technical context, but they also have attention for latent conditions present in the system. They can therefore uncover shortcomings in company culture, safety procedures, legislation et cetera that the sequential methods cannot. They will generally take more time to complete as the scope of the investigation is larger. And they may take more effort to convince management to accept the lessons learned as they will sometimes disclose managerial shortcomings. Furthermore, they can be more convoluted, as the context is harder to incorporate into comprehensive and clear pictures that paint the narrative of the accident.

The overarching narrative for Epidemiological models is (*see* Figure 5):

> Actions have (direct or indirect) consequences due to the behavioral variability always present in a socio-technical system. These consequences are events that can be critical. If there is no functioning barrier in place, a critical event has an accident as a result.
>
> In epidemiological methods, actions are triggered by tasks, orders, plans, production goals, and decisions on different system levels. Organizational influences, such as management and the allocation of resources (personnel and equipment), create local conditions that can trigger accidents. These local conditions can both be latent and overt threats.

Events can be characterized by time, location, action and actor.

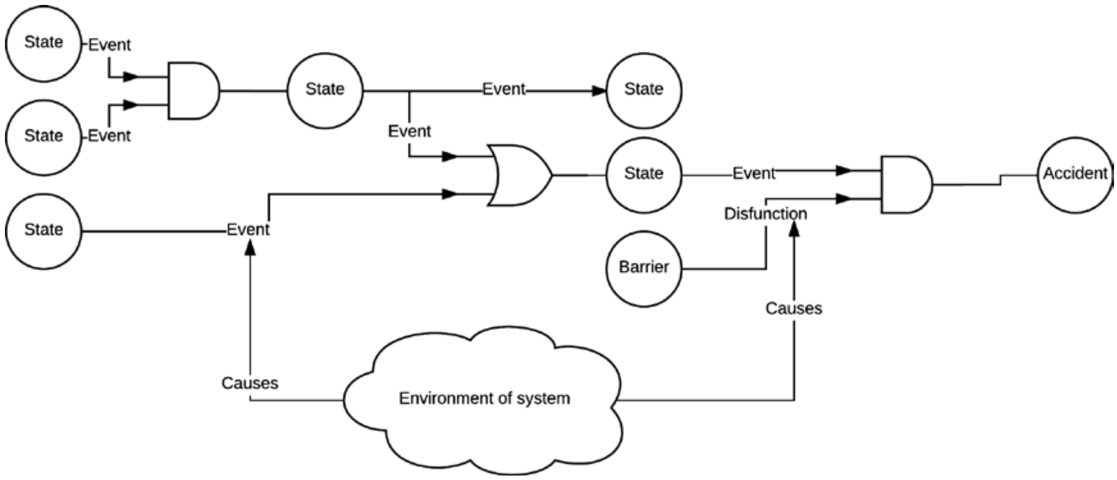

Figure 5. An epidemiological model for an otherwise unspecified accident

Systemic Methods

The two most quoted and well-known methods are STAMP by Nancy Leveson (Leveson, 2011) and FRAM by Eric Hollnagel (Hollnagel and Goteman, 2004; Hollnagel *et al.*, 2014). The systemic methods are characterized by strong links between the different components of the system that directly influence each other. This is mirrored by their ontologies. As FRAM and STAMP use a different paradigm for analyzing the environment, there is little correspondence between the main entities in the methods. STAMP uses a system-theoretical control cycle model, containing the process under control, sensors, actuators, controllers and conceptual models governing the decision taken to control the process. FRAM on the other hand only knows *functions* with several parameters that influence the output of the functions and with interactions between the functions leading to events. Due to the disparate descriptions of these two methods and the fact that we did not find any more systemic methods, we did not succeed in creating an overarching narrative.

The systemic methods take more effort to apply than the other classes of methods as they necessitate a deeper analysis of the regular processes and organization in order to either map them on system-theoretical feedback-control loops (STAMP) or functions (FRAM). This extra effort is in many cases not justifiable considering the benefits of such an analysis. Especially in situations where the consequences of incidents are relatively minor (no lethal victims, no major financial consequences), these methods are too heavy. The literature seems to support this, as the only applications of FRAM and STAMP are as part of the analysis (mostly as an academic exercise) of aviation accidents (Carvalho, 2011) and incidents (Herrera and Woltjer, 2010) and naval accidents (Herald of Free Enterprise (Praetorius *et al*., 2011)) for FRAM and Master's and PhD research projects for STAMP (Dong, 2012; Helferich, 2011; Kawakami, 2014; Li, 2013; Spencer, 2012).

Comparing the three models

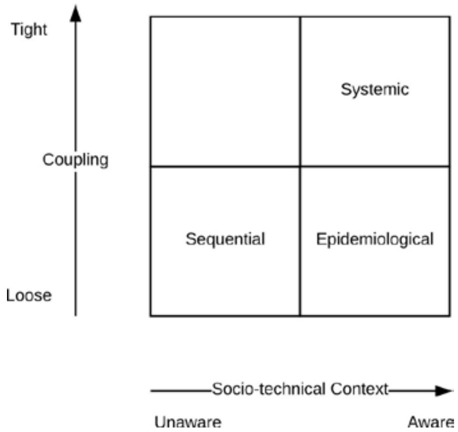

Figure 6. Comparing the three classes of models along two distinguishing axes

In figure 6, we compare the three methods and their underlying accident models. In the historical development of these methods (from the lower left quarter through the lower right quarter up to the upper right quarter), we see the following: the earliest, Sequential models only looked at the system itself, without taking the socio-technical context into account. The Epidemiological models added the socio-technical context. The Systemic models were developed for tightly linked systems and after the Epidemiological methods introduced the socio-technical context, the developers of the Systemic methods made the socio-technical context an integral part of their methods.

Generic Accident Analysis Method

The reviewed methods share a common approach, that we view as a generic, domain-independent accident analysis method, which contains two steps which the analyst can choose to skip, depending on the circumstances of the analysis:

1. Find all events that have a causal relationship with the accident.
2. Describe the history of the accident by linking these events.
3. Find all conditions that enabled these events, including events that lead to those conditions (only in Epidemiological and Systemic methods)
4. Identify components, feedback mechanisms and control mechanisms that played a role during the development of the accident (only in Systemic methods)
5. Identify at which points the accident could have been prevented and analyze if this can be generalized
6. Draw conclusions and propose improvement actions

DISCUSSIONS AND CONCLUSIONS

Answers to research questions

1a) Which incident analysis methods are in use today?

We have identified 63 methods for accident analysis in the corpus we researched. The methods and their frequencies are listed in Figure 1. Most methods that are mentioned only once or twice, but a few methods have a stronger presence in the literature.

1b) Which incident models are in use today?

The literature recognizes three different classes of analysis models: the Sequential, the Epidemiological, and the Systemic. They differ in if and how they include socio-technical context and in how they handle the internal links in the system under consideration. The most often quoted methods per model class are: FTA for the Sequential methods, AcciMap for the Epidemiological methods and STAMP for the Systemic methods.

1c) What are the comparative strengths and weaknesses of the methods?

The strengths and weaknesses are linked to the class of models the methods employ. Sequential methods have been around for a long time and have been able to mature. They paint a picture that is relatively easy to understand and can be quite persuasive. Their main weakness is that they do not take the socio-technical context into account.

The strength of the Epidemiological methods is that they *do* take the socio-context into account. They also give insights in latent conditions that have enabled the chain of events to unroll into an accident. Their weakness is that it takes more time to perform an analysis using an Epidemiological method, and it may be harder to present the results as the different visual methods are more complex than the average Sequential method.

Systemic methods are more appropriate for systems that have tight couplings where a change in one part of the system has a direct consequence in another part of the system that may be hard to predict. They are more appropriate for Perrow's 'normal accidents' (Perrow, 1984) and are basically in a class of their own. They are more expensive to execute as they take more time and resources.

2a) What are domain-specific entities, attributes and relationships in incident models?

We found that the individual models do not contain domain specific entities, attributes or relations. But we did find that the entities, attributes and relations are class specific. We did not find any methods that have been applied to telecommunications networks. Given the domain independence of the models, the different models should all be applicable to accidents in the Telecommunications domain.

2b) Can we formulate a generic analysis method and model?

We have been able to formulate generic accident models for two of the three classes of models (Sequential and Epidemiological). We have given graphical representations of these models as well. The Systemic models (notably FRAM and STAMP) differ in so many respects that formulating a generic accident model was not feasible.

Furthermore, we have been able to formulate a generic method for accident analysis. This method covered all three classes of models.

Conclusions

The research in accident analysis methods is growing, as evidenced by the number of articles per year (*cf.* Figure 3). Furthermore, the attention has shifted over time from sequential methods and epidemiological to systemic methods. Especially, the high volume of articles for the latter (even though it only involves two methods) is an indication of its relative popularity in academic circles.

We find that many of the methods (40 out of 63) are only mentioned once or twice in the corpus of literature we studied. This implies that those methods did not receive much scrutiny from the scientific community and have not been applied very often. The quality of these methods cannot be determined from the literature, but the absence of discussion is in stark contrast with the 13 most discussed and applied methods (starting from 7 times up to 23 for the method that was most discussed).

Furthermore, we see a clear distinction in the classifications between the groups: if we disregard the methods that we did not classify (due to too little information or no specific class), we find for the Top 21 methods that 10% falls outside the three main classes, while for the remaining 27 methods (40 minus 13 unclassifiable methods), 48% falls outside the three main classes. This may be an indication that the authors of many of the less mentioned methods are unfamiliar with the subject and were trying to re-invent the wheel. The great number of methods in the Sequential and Epidemiological classes may indicate an evolution of methods within those classes. We did not analyze this any further.

When balancing strengths and weaknesses of the different analysis methods, we are considering the classes instead of the individual methods. There is a difference between 1) methods that quickly resolve the incident and restart the interrupted service and 2) methods that from a service continuity point of view, make sure that a similar incident does not happen again. This will give us information about which class of methods to choose.

The Sequential methods paint very clear pictures that can assist in resolving incidents quickly after they developed. For troubleshooting purposes, these methods can be lightweight enough to quickly find the cause of an incident and repair the issue. However, these methods will miss deeper, structural causes, often present in the socio-technical system. Too few resources for maintenance or a broken safety culture will not be identified by these methods.

The Epidemiological methods however, although taking more time, will tend to find the latent factors that — after resolution — may strongly help reduce incidents of the type investigated in the future. We can even imagine that they may uncover a fundamental flaw in the organization the resolution of which can help prevent a larger class of incidents. The concept of barriers gives a clear reference point where to apply corrective measures, giving management a clear means to improve the safety of the system.

In many domains, from a business point of view, the Systemic methods are too expensive to use for the analysis of accidents and incidents: the costs would seldom outweigh the benefits and these methods are therefore not efficient enough for regular business activities and accidents or incidents with relatively light damage. Furthermore, safety is an emergent property in systemic methods. That makes it harder to formulate corrective measures that can be implemented by management.

To sum up, a sequential method may be appropriate during the resolution phase of an incident, while an epidemiological method is more fitting for a deeper analysis after the incident has been resolved in order to find latent factors that can be neutralized to prevent incidents from happening again. Systemic methods will not add enough value to this process to justify the considerable effort and consequently considerable costs.

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