

Accident Analysis Methods and Models — a Systematic Literature Review

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Abstract

As part of our co-operation with the Telecommunication Agency of the Netherlands, we want to formulate an accident analysis method and model for use in incidents in telecommunications that cause service unavailability. In order to not re-invent the wheel, we wanted to first get an overview of all existing accident analysis methods and models to see if we could find an overarching method and commonalities between models. Furthermore, we wanted to find any methods that had been applied to incidents in telecommunication networks or even been designed specifically for these incidents. In this article, we present a systematic literature review of incident and accident analysis methods across domains. We find that accident analysis methods have experienced a rise in attention over the last 15 years, leading to a plethora of methods. We discuss the three classes in which they are often categorized. We find that each class has its own advantages and disadvantages: an analysis using a sequential method may be easier to understand and communicate and quicker to execute, but may miss vital underlying causes that can later trigger new, similar accidents. An analysis using an epidemiological method takes more time, but it also finds underlying causes the resolution of which may prevent accidents from happening in the future. Systemic methods are appropriate for complex, tightly coupled systems and executing such a method takes a lot of time and resources, rendering it very expensive. This will often not be justified by the costs of the accident (especially in telecommunications networks) and it will therefore be too expensive to be employed in regular businesses.

We were not able to find any published definitions of structured methods specific to telecommunications, nor did we find any applications of structured methods specifically to telecommunications.

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1. Introduction

The European Telecommunication Agency ENISA (European Union Agency for Network and Information Security) publishes an annual report about significant outage incidents in the European electronic communications sector. The Telecommunications Agencies of the countries constituting the EU have to report their local significant outage incidents to ENISA. In the Netherlands, this is the responsibility of the Dutch Telecommunication Agency (*Agentschap Telecom*, AG). We have started a project in co-operation with AG (the LINC project – learning from incidents in telecommunications networks) in order to learn lessons from the incidents the telecommunication operators are obligated to report to AG. These lessons can help telecommunication operators to improve their operations and thereby prevent future incidents from happening. To facilitate this process, AG need to know which information to gather from the telecommunication operators. To determine this, we want to formulate an accident analysis method and model for use in incidents in telecommunications that cause service unavailability.

The purpose of this report is to find the state of the art in accident analysis methods as a starting point for formulating an analysis method that can be applied to incidents and accidents in telecommunication networks.

1.1. Accident analysis methods

In many domains (*e.g.* Aviation and Nuclear Energy), incident and accident analysis forms an integral part of safety and innovation. Many researchers have analyzed incidents and accidents to gain new insights into system errors and impact of these errors on the safety of stakeholders. Sometimes the researchers used a rigorous framework to analyze these incidents, and sometimes they did so without such a framework.

Having such a framework in place makes it easier to compare different incidents and accidents and to draw conclusions about common elements in those models. More generally, in order to draw lessons learned from incident and accident analyses across domains, we review the state of the art of incident and accident analysis methods. Our goal is to find commonalities across these methods, which should support drawing lessons learned across different domains. In addition, our goal is to identify strengths and weaknesses in the reviewed methods, in order to define a new method based on the strong elements of the existing methods. The first application domain for this new method would be telecommunications, as this is the domain we are primarily focused on as part of our current research, but it should be generic enough to be applicable to all domains and useful for all practitioners of incident and accident analysis.

1.2. Definitions

So what constitutes an incident and what constitutes an accident? The literature uses multiple definitions for these terms, while the telecommunications sector uses their own. Generally, the difference between the two is that an incident is a deviation from the standard that does not lead to losses, while an accident is an incident that causes loss or harm. Incidents are often defined as a near-accident. The term *near misses* is also employed for incidents.

1.2.1. Accidents

Here are some examples of definitions of the concept of accident:

Leveson an undesired and unplanned event that results in a loss (including loss of human life or injury, property damage, environmental pollution, and so on). [145, p. 467]
Harms-Ringdahl an event that causes unintentional damage or injury. [83, p. 13]
DOE Workbook Conducting Accident Investigations an unwanted transfer of energy or an environmental condition which, due to the absence or failure of barriers or controls, produces injury to persons, damage to property, or reduction in process output. [260, p A-1]
Doytchev an undesired event or sequence of events causing injury, ill-health or property damage [54]

From these definitions, it follows that an accident must at least be undesirable. The authors all agree on the fact that an accident causes damage. This damage ranges from damage to property, reduction of production, to injury and death. Note that the definition given by the DOE makes explicit use of entities of the model they use. That definition is therefore specific to their model and not as generic (or model agnostic) as the other three. Leveson adds the idea that an accident must be unplanned. The other definitions do not include this extra criterion. We feel that this unexpected aspect is a valuable addition: a loss that is planned, is not accidental, even though it may be undesirable. In the remainder of this report we use a slightly more general version of Leveson's definition of the concept of an accident:

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

1.2.2. Incidents

Here are some examples of the concept of an *incident*:

Leveson an action that 'involves no loss (or only minor loss) but with potential for loss under different circumstance' [21]
Harms-Ringdahl (or near-accident) is an event that almost causes unintentional damage or injury. [83, p. 36]
DOE Workbook Conducting Accident Investigations no definition available
Doytchev an unplanned, undesired event that hinders completion of a task and may cause injury or other damage [54]
Fukuda an event that has the possibility to cause an accident but does not fortunately in actuality, or a slight abnormal event without a substantial obstacle or damage [66]

Three out of these four definitions state that incidents do no or only minimal harm, but they could have caused greater losses if the circumstances were different. Doytchev does not limit the harm that can be caused by an incident, but ties an incident to a specific task that cannot be completed due to the incident. This seems to be very specific to a model containing tasks and we feel this is too restrictive. In the remainder of this report, we will use the following definition of an incident:

An Incident is an undesired and unplanned event that did not result or only minimally resulted in a loss, damage or injury, due to favorable circumstances. Were the circumstances different, it could have developed into an accident.

As an aside, we noted that in medicine, an incident does involve harm - as evidenced by the following definitions:

Critical Incident An incident resulting in serious harm (loss of life, limb, or vital organ) to the patient, or the significant risk thereof [63]
Clinical Incident any event or circumstance which has actually, or could potentially, lead to unintended and/or unnecessary mental or physical harm to a patient. [57]
Medication Incident Any preventable event that may cause or lead to inappropriate medication use or patient harm while the medication is in the control of the healthcare professional, patient, or consumer [63]

The incidents in medicine would be covered by our definition of an accident, as (serious) harm is the result of a medical incident. We have not observed the use of the term *accident* in telecommunications. This has been confirmed by the Telecom Operators we have discussed our findings with. They use the term *incident* even if the situation causes grave financial and

reputational harm. Also in cases in which people may actually have been harmed (*e. g.* in the case of unreachability of emergency services due to unavailability of telecommunication networks), the term *incident* is used.

In the remainder of this report, we will only consider accidents. Although incidents are interesting as well, the data we have overwhelmingly contain accident data. Furthermore, we will adhere to the terminology used in the literature. This means that we will use the term accidents even though it is common practice within telecommunications to use the term incidents to refer to events that fall under our definition of accident.

1.2.3. Damage

The concept of **damage** plays a central part in distinguishing incidents from accidents. It should be noted that damage is a localized concept: although there may be no damage in the system under consideration itself, there may be substantial damage in the environment in which the system operates. In this case, whether a critical event constitutes an incident or an accident depends on where you place the boundaries of the system. *E. g.*, if telecommunications service unavailability is avoided by containing the potentially fatal consequences of an event, this constitutes an incident, even if this means that the containment itself may have financial consequences (and thus damages) for the telecommunication operator.

1.2.4. Methods and Models

For the purpose of this report, we use the following definitions of methods and models:

Method A sequence of steps to achieve a result

Model A conceptual structure by which an incident is modeled

An accident analysis method that is based on a sequential accident model will be called a sequential (accident analysis) method. Similar definitions apply to epidemiological and systemic accident analysis methods.

1.2.5. Entities of the models

Although the different models feature a host of entities, three are central to many of the models and of the generic models. They are: events, actions, conditions and barriers. Most models do not provide definitions for these concepts and this implies that not all models use the concepts interchangeably. This does not seem to pose any problems, as the concepts are largely used in the same manner, but room for ambiguity remains. We did not perform a thorough analysis of the use of the concepts for definition purposes, but for our work, we feel that they should be defined explicitly. Our definitions are modeled after system theoretical concepts.

Event A change of state in the system that is important enough to give it a name.

Action The fact or process of doing something, typically to achieve an aim [194]

Condition A state of the world that enables a certain class of state changes.

Barrier A state of the world that inhibits a certain class of state changes.

1.2.6. Modeling Narrative

In the descriptions of the different methods in appendix A.3 we use the term **modeling narrative**. A modeling narrative is a short story that takes the different entities of a model and places them in context. This clarifies the relations between the entities.

1.3. Structure of this report

Chapter 1 introduces the subject to the reader. In chapter 2 (Research Method) we describe the scope of our research and how we found the methods that are the subject of the rest of the report. In chapter 3 (Results) we present the results of our literature review, both quantitatively (3.2) and qualitatively (3.3). We then return to our research questions and answer them in chapter 4 (Discussions and Conclusions). In that chapter we also discuss possibilities for future research.

2. Research Method

This section lists the research questions and how we intended to and did answer them. It describes the criteria for selecting the relevant bibliographic databases, the selection of possibly relevant articles, and the pruning method to get to the final list of articles under consideration.

2.1. Research Questions

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

1. What is the state of the art in incident and accident analysis methods?
 - a) Which incident analysis methods are in use today?
 - b) Which incident 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 incident methods and models?
 - a) What are domain-specific entities, attributes, and relationships in incident models?
 - b) Can we formulate a generic analysis method and model?

2.2. Approach

We have chosen to cast our net as wide as possible. That means that the scope for this investigation covers domains as varied as nuclear industry, aviation, space flight, chemical industry, traffic, telecommunications, outdoor activities and emergency services.

The approach for answering the research questions is as follows:

- We start by defining our inclusion and exclusion criteria for the literature databases and the articles to be used
- We then define the query we use to interrogate the different databases at our disposal
- We select the databases and query them
- We then select the articles that are pertinent to our research (see 2.3)

This will provide us with a set of articles that we can subject to the following two top level research questions:

1. Which method was used in this article?
2. Which model was used in this article?

We then will compare the identified models and methods and try to extract:

1. A generic model in order to answer Research Question 2
2. A specific model per domain in order to answer Research Question 2a
3. A generic method in order to answer Research Question 2b

With this approach, we will be able to maximize our chances of finding commonalities among methods across domains, draw lessons learned from this, identify strength and weaknesses, and be able to define a generic incident analysis method and model that can be easily adapted to the telecommunications domain in the future.

2.3. Strategy and execution

2.3.1. Overview of the selection process

Our systematic review started with the selection of data from 108 databases and ended with 63 identified analysis methods. This section describes the selection process. An overview of the process is drawn in figure 2.3.1.

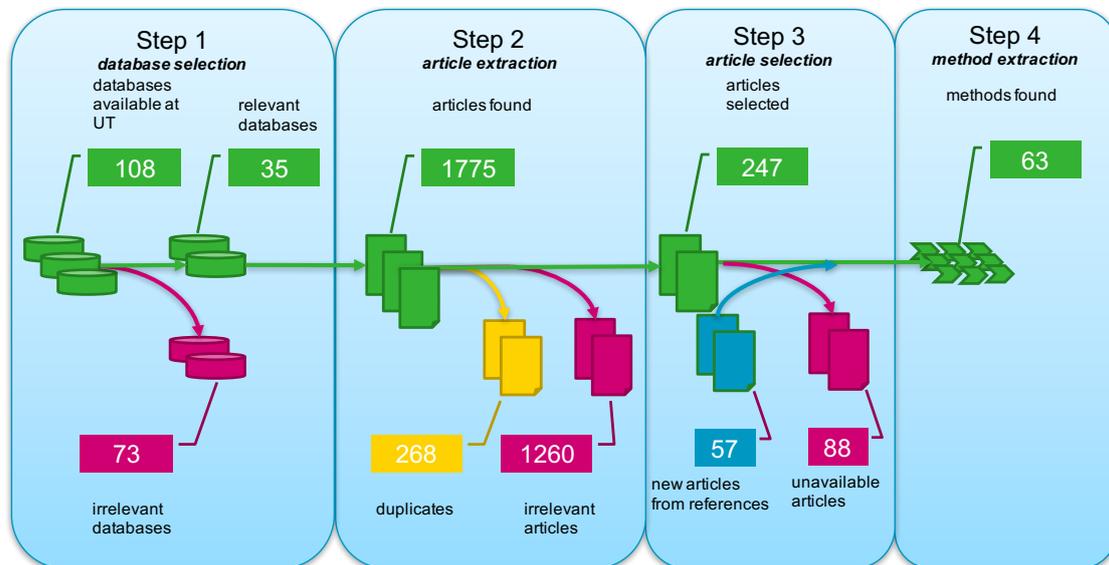


Figure 2.3.1.: From 108 databases to 63 methods

2.3.2. Step 1: Database selection

One much used guideline in computer science for systematic literature reviews was written by Kitchenham and Charters [128]. In the guideline, they state that

The aim of a systematic review is to find as many primary studies relating to the research question as possible using an unbiased search strategy.

This calls for a sound strategy that will help us reach this goal. This section describes the strategy along with the results of each step.

We will query all bibliographic databases that meet our database inclusion criteria using search strings for “*incident analysis method*” or “*incident analysis methods*” or “*accident analysis method*” or “*accident analysis methods*”. The database inclusion criteria are:

- include** only databases that are pertinent to our research (this excludes *e.g.* the Astrophysics Data System)
- include** only databases that have articles (this excludes *e.g.* the Eurostat database, containing numerical and factual data)
- include** only databases that allow search on phrases (our search queries sometimes yield hundreds of thousands of results due to the database selecting all articles that contain just one of the words in our phrases)

After we have selected the databases we will query them using the search phrase ‘*Accident Analysis Method*’ OR ‘*Accident Analysis Methods*’ OR ‘*Incident Analysis Method*’ OR ‘*Incident Analysis Methods*’. The results of the database selection and the queries are listed in table A.1.1 in the appendix.

The University of Twente has access to 108 databases, of which we queried 35. The other 73 database were excluded based on the three criteria listed above:

1. Not pertinent to our research: 24
2. Not containing articles: 44
3. No phrase search: 5

2.3.3. Step 2: Article selection based on title and abstract

In the remainder of this article we will refer to any text referred to by a bibliographic database that was found as an article. That means that the word *article* not only implies Journal Articles, but also Theses, Technical Reports and so on. In some rare cases it even means Slide Packs.

Articles that are selected for inclusion will have to comply with the following criteria:

include only articles describing Incident or Accident Analysis Methods (i.e. a systematic approach to in/accident analysis) or an application of such a method to a case

include only articles written in English

include only articles available through the databases queried

include only articles that perform analyses using a clear and defined analysis method (either in the article itself, or in one of the references) — no analyses on an ad hoc basis

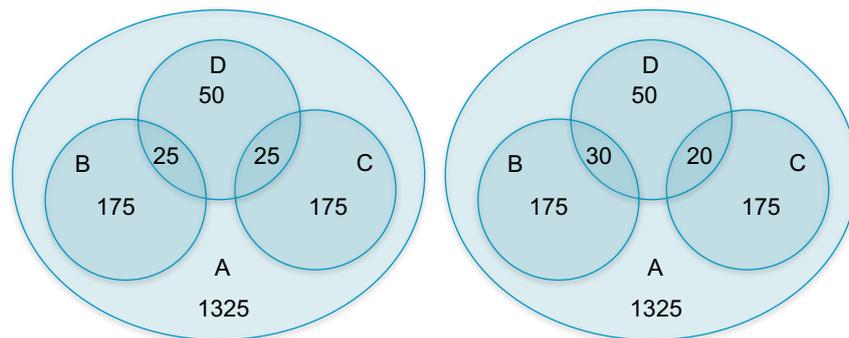
include only articles that actually have analyses of incidents or accidents or that define a method for analysis of incidents or accidents

After the first selection, we found 1775 articles. Reading all these articles was not possible in the time available to us. So we decided to perform the first selection based on the title and abstract, and if this did not yield enough information (*e. g.* because the abstract was not available) a quick scan of the text of the article. We decided to err on the side of caution and to include articles that we could not obviously exclude. After this first, coarse selection, we read the selected articles, discarding articles that on second pass did not meet the inclusion criteria.

The remainder of this section describes the process by which we assessed the quality of the selection process.

To ensure objectivity while keeping the extra work to an acceptable minimum, we have picked several articles that would be categorised by multiple reviewers according to the following setup:

- One assessor [*A*] will assess all papers
- 20 disjoint clusters of 20 articles each will be created that will be divided between two assessors [*B* and *C*]
- 10 of those clusters will be extended with 5 more articles, and the bottom 10 will be assessed by a fourth assessor [*D*]



(a) Venn diagram of intended distribution (b) Venn diagram of actual distribution

Figure 2.3.2.: Venn diagrams of distribution. Note the numbers pertain only to the set in the diagram to which they belong. *E. g.*, assessor *A* has read all 1775 documents, 1325 of which were assessed only by him

The Venn diagram in Figure 2.3.2a clarifies the approach. This way, 50 articles will be assessed by three assessors (25 by *A*, *B*, & *D* and 25 by *A*, *C*, & *D* ; 400 articles will be assessed by two authors (175 by *A*&*B*, 175 by *A*&*C* and 50 by *A*&*D*); the starting point of the clusters was

Table 2.3.1.: Agreement on assessment of inclusion criteria

reviewer combination	# agreements	# differences	% agreement
<i>A</i> and <i>B</i>	162	38	81%
<i>A</i> and <i>C</i>	150	50	75%
<i>A</i> and <i>D</i>	80	20	80%
<i>B</i> and <i>D</i>	19	1	95%
<i>C</i> and <i>D</i>	21	9	70%

determined by randomly picking numbers between 1 and 1775 using <https://random.org>; if a cluster overlapped an earlier picked cluster, the number was discarded and a new number was picked.

Ultimately, due to a mistake in assigning the articles to assessors *B* and *C*, the numbers changed a little as can be seen in figure 2.3.2b.

After allocating the 450 articles to reviewers, we individually selected all articles fulfilling the criteria we defined above based on the titles and abstracts (if available) of those articles. We created a tool to facilitate this process and to consistently register results. After this exercise, reviewer *A* found 268 to be duplicates of other articles, 1276 to be irrelevant and 231 to be relevant, based on the title and abstract. The reviewers *B*, *C*, and *D* had different results. Of the 450 articles that were reviewed by two or more reviewers, the results are summarized in table 2.3.1. With the different assessments, we followed the approach stated below:

- Any article that has been selected by *A* will be part of the survey
- Any article that has been rejected by *A*, but selected by one or more of the other assessors will once more be assessed by *A* and then either selected or once more rejected with a rationale for the rejection
- The rejections and their rationale will then be evaluated by the other assessors, which will yield the final selection
- The number of articles that were originally rejected, but were selected after the review round, will give a measure for the quality of the overall selection; see section 4.1 for a discussion of this set

The result from the collective selection over these 450 articles reviewed by multiple assessors was that 10 articles missed by assessor *A* had to be added to the reading stage (step 3) as they were pertinent to the research based on the title and abstract, while six had to be assessed further to determine if they were pertinent (categorized as ‘uncertain’). See section 4.1.

2.3.4. Step 3: Article selection based on full text and references

The list of 247 articles (231 from the first selection and 16 from the multi-assessor review) was the reading list for collecting the analysis methods. After downloading and reading all papers, the final list of available and relevant articles ended up containing 224 articles – 23 articles were duplicates of other selected articles or were dropped due to language (some articles both have an English abstract and title and an abstract and title in the original language. Only after inspection of the article proper were we able to determine that it was written in another language than English). Of this list, 65 were unavailable due to restricted access or due to missing article text (only reference information) so that a total of 88 articles were excluded in this phase. Furthermore, after reading these articles, we found 57 additional relevant articles (manuals to analysis methods and definitions of methods discussed in the list of 159 (247 - 88) articles). Hence, the total corpus under consideration was 216. This list is printed in the bibliography to this part.

The sixteen articles that were selected as a result of the collective selection do not feature in this list: they were unavailable to us, written in another language than English or upon closer inspection did not meet the other inclusion criteria.

2.3.5. Step 4: Data extraction

In the articles we found 63 methods. Table A.3.1 in section A.3 of the appendix describes a number of important properties of these methods: the method described, the domain it is applied to and the year it was published. Furthermore, per method we extracted the class of the model and the modelling narrative - which is a very short story describing the entities in the model and their relations. Of these methods, the 22 that have been mentioned at least three times have been subjected to further, quantitative analysis in chapter 3.3 (Qualitative Analysis).

3. Results

3.1. Introduction

In order to provide some structure, we have divided the analysis methods into four categories. Three of these have been identified by Hollnagel ([94], [100]) and they form three classes of methods, based on the accident model that they employ. The fourth is a rest category ('Other'), containing methods and models that are either defined very superficially, rendering them impossible to categorize, or are not analysis methods *per se*.

Sequential Sequential accident models describe the accident as the end point of a string of causes. This category is called "sequential" by Hollnagel because originally, many methods restricted themselves to a sequential string of causes. However, in general, there may be several causes contributing to an incident or accident.

Epidemiological models describe the accident as the product of the interaction among a set of entities and actors, some of which may be visible, and others invisible. This model is similar to models of how diseases develop. 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 Systemic accident models describe the accident as the result of the interaction within a system and between a system and its context. Feedback loops may play an important role in these models.

Other There are a host of methods and models that do not belong to one of the categories mentioned in this list. These are discussed as part of the "other" group.

Table A.3.1 contains an overview of accident analysis methods with some characteristics.

3.2. Descriptive statistics

The full result set of the literature review can be found in appendix A.3. In this chapter, we describe some characteristics of the corpus of literature we researched. In the next chapter we give a qualitative analysis of the methods in the appendix. Due to the sheer number of methods found, we chose to only discuss the top 22 as measured by the number of articles (see Figure 3.2.1). Appendix A.6 contains the total list of papers reviewed. Please note that in total, 23 methods were mentioned three times or more. However, PRISMA is not an analysis method *per se* (category "other"), which is why we won't include it in the analysis.

From Figure 3.2.1, we conclude that there is a clear distinction between the number 1 (STAMP) and the rest of the field. This is partially due to four PhD Theses that have been supervised by Leveson. It is a popular subject for theses anyway: both Master's (4) and PhD (6) theses apply it or compare it against other methods. No other method has been the subject of so many theses.

3.2.1. Domains in the corpus

We have cast our net wide when selecting articles for this review and the corpus of literature we researched contained a broad spectrum of domains covered by the methods considered. 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.

The graph in Figure 3.2.2 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. But the number of applied methods is low, so we cannot have a more rigorous statistical discussion based on these numbers. One counter example for this hypothesis is the low number of Top 22 methods for aviation accidents — a field for which we would expect some maturity, given the practice of sharing accident and near miss information between countries and technical aids such as black boxes.

Please note that for nuclear accidents, the number of methods is 0. This is due to our selection criteria: for nuclear installations, rigorous tests and analyses take place before the installation is commissioned. But these methods and simulations are all ‘before the fact’ and are more of a hazard and risk analysis nature, while we limited our research to retrospective methods. For reasons of completeness, we also added the methods for telecommunications (which is 0, as stated above).

3.2.2. Articles per class and per year

Figure 3.2.3a describes the distribution of articles in the corpus over time. The trend in these numbers 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.

As can be seen from these graphs, the general trend is that interest in accident methods is growing over time (*see* Figure 3.2.3a), with the sequential methods starting early (3.2.3b), followed by epidemiological (3.2.3c) and systemic (3.2.3d), 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.

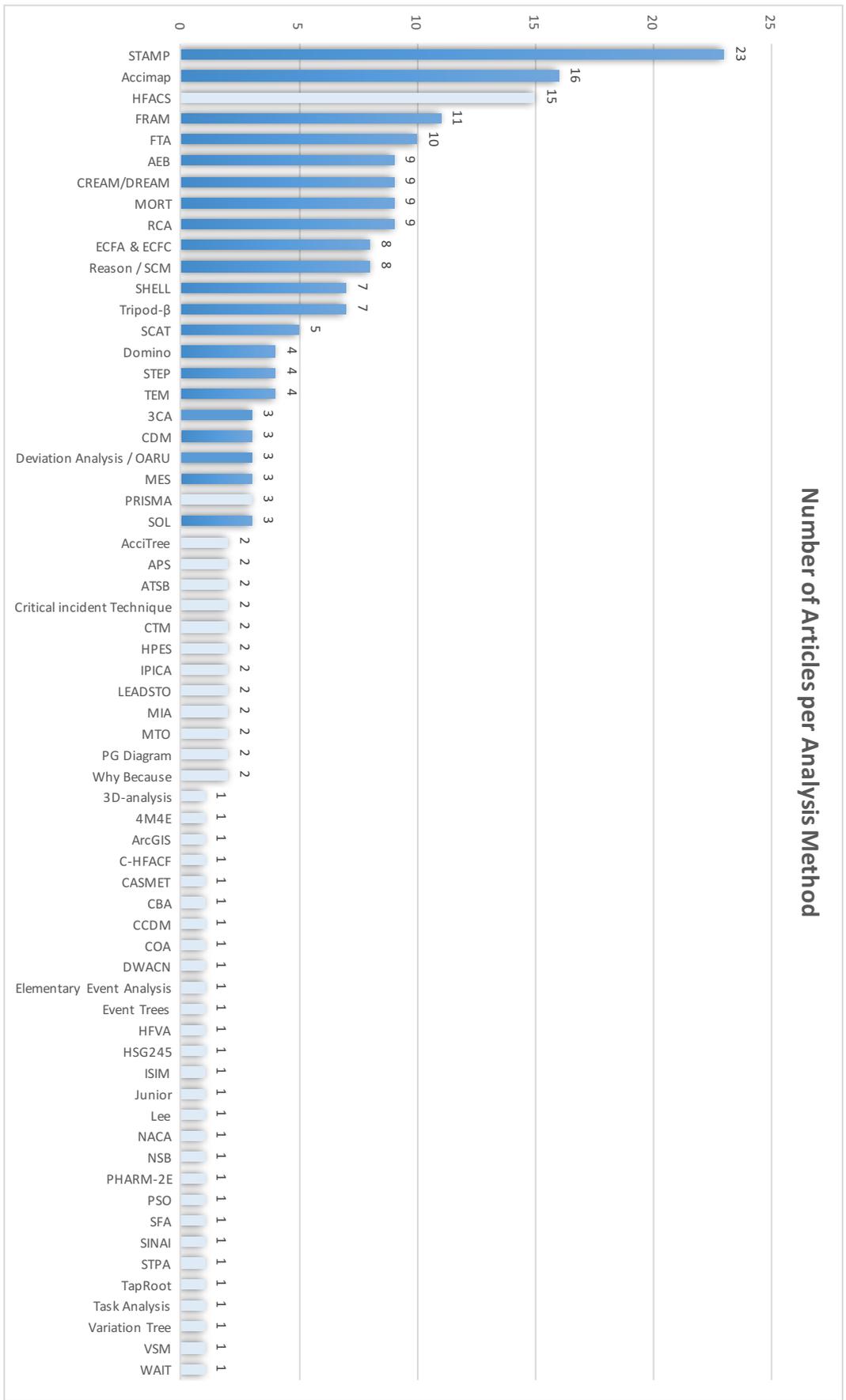


Figure 3.2.1.: The number of times a method was mentioned in the articles researched. *Note:* only when actually defined, applied or used in a comparison — not mere mentions. The methods we discuss in this article are in medium blue, the others in light blue

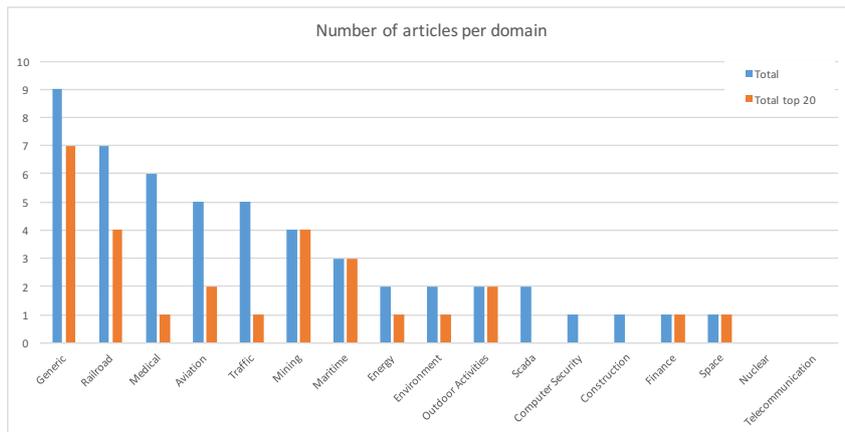
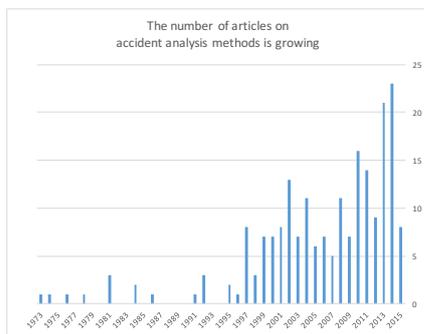
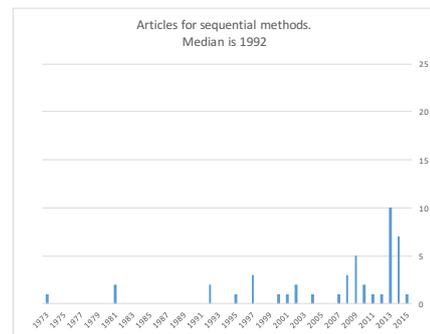


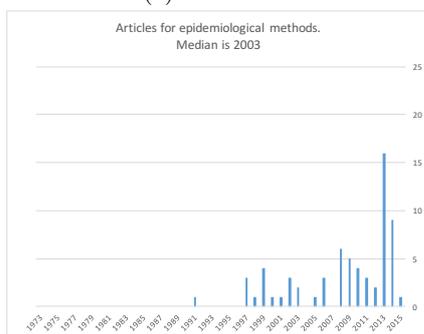
Figure 3.2.2.: The number of analysis methods per domain. As can be seen from the graph, the number of more accepted methods (those that are in the top 22) differ strongly per domain.



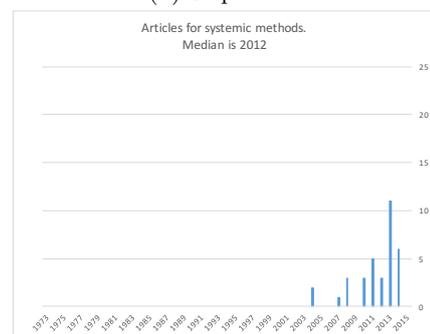
(a) All classes



(b) Sequential



(c) Epidemiological



(d) Systemic

Figure 3.2.3.: Articles per year for the different method classes

3.3. Qualitative Analysis

This section will discuss the three classes of methods introduced in section 1.2, along with some other characteristics of accident analysis. The top 22 has representatives of all three classes along with a few other methods, as can be seen from table 3.3.1. Note, some authors categorise the Accimap method as Systemic, while others categorise it as Epidemiological. In our opinion, AcciMap is an epidemiological method, as it does not have the strong, directly influencing links and couplings that are a part of the Systemic models. The output-input links are in many cases mediated through actions by humans that have a behavioral variability and skill for improvisation that is in contradiction with the tight, direct couplings that characterize Systemic models.

Table 3.3.1.: 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, HFACS, SHELL

3.3.1. Sequential Methods

Sequential methods describe sequences of *events*. Events constitute the main entities of the models describing accidents in a sequential method. Some methods add *barriers* that prevent or inhibit events from happening or from developing into accidents. The accident itself is an event as well. Other methods use *conditions* that enable the event.

A typical example of a sequential method is the Fault Tree Analysis - or FTA. The FTA constructs a tree of events following one another in time. Events can be combined through logic gates and give rise to or may inhibit other events. FTA recognises 5 types of event: Basic events, Conditioning events, Undeveloped events, External events and Intermediate events. Figure 3.3.1 shows the FTA model for the sinking of the Titanic [80].

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 sequential picture of the events leading up to the accident. As a result of this understanding, 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) of events and states leading up to an accident, which causes an injury; branches may be AND or OR branches (and merges too). 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 includes events in the social environment. If an earlier risk assessment has been done, then some of the events in the risk assessment may have occurred, others may not have occurred.

It should be noted that one sequential method (MORT) specifically uses energy transfers as the main entity. This method was developed for the nuclear industry and that explains this choice.

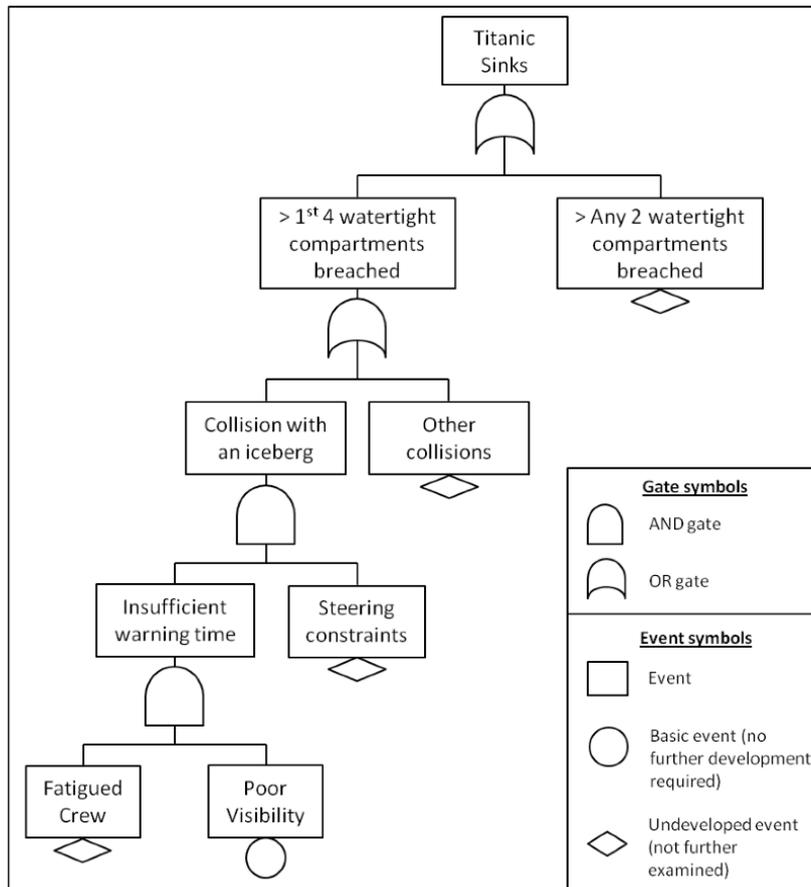


Figure 3.3.1.: An example of an FTA-model, taken from [80]

3.3.2. Epidemiological Methods

Epidemiological methods are also modelled 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 [96], 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* (organisational goals, safety culture, limited 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.

The main benefit of this class of methods is that they take a serious look at the socio-technical context. 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.

One of the more prominent methods is the AcciMap method (*see* Figure 3.3.2). Its model clearly shows the socio-technical environment in which an accident develops.

In appendix A.3, we have also created narratives for the epidemiological models we found. The overarching result is:

Actions have (Direct or Indirect) Consequences due to the behavioral variability

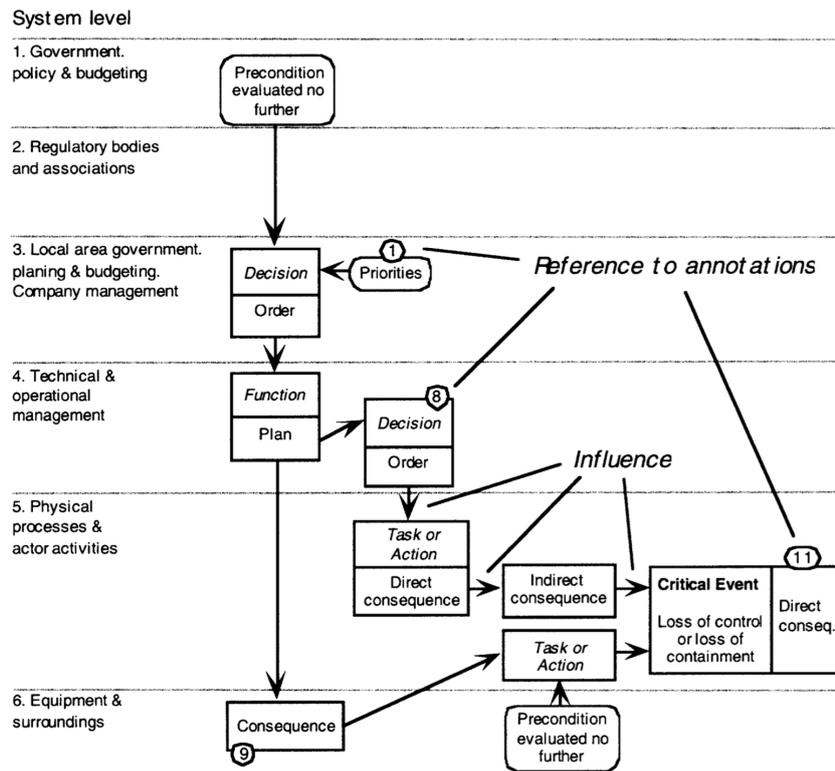


Figure 3.3.2.: The AcciMap model — an example of an Epidemiological method.
Taken from [246]

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.

To be more specific: 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.

Actions and conditions can be visualized using a graph.

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

3.3.3. Systemic Methods

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. Events are the outputs of the functions and FRAM is created in analogy with stochastic resonance, where variabilities sometimes enhance each other, leading to (in FRAM's case) undesired effects. Figure 3.3.3 shows the way FRAM describes a system in order to analyze accidents. Figure 3.3.4 shows the way STAMP takes the socio-technical context into account while showing control-feedback loops throughout the whole socio-technical system. Please note that due to STAMP's model, we find the control-feedback loops not only in the technical part of the diagram, but also in the higher levels. These levels do not exhibit the

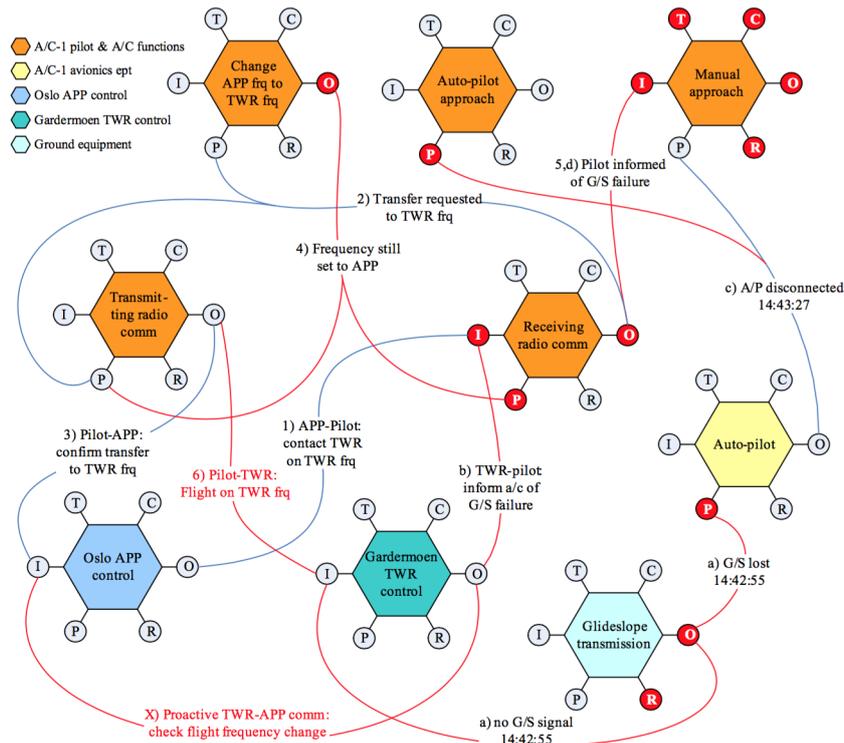


Figure 3.3.3.: An analysis using FRAM. Taken from [92]

tight coupling that is present at the technical level, but the model can be used for those levels nonetheless.

In short, the only obvious similarity between STAMP and FRAM is the way in which they link different parts of the system by acknowledging the tight coupling of individual functions and constituents of the system. 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. Therefore, we have formulated two narratives for these methods:

FRAM A system interacts with its context through a collection of functions, that can be characterized by input, output, resources it needs, its control and real-time behavior. Functions interact through these aspects. Please note that this is a functional view of systems that abstracts away from its internal components and concentrates on logical behavior. It is similar to the view of systems taken by structured analysis for real-time systems [86], [162].

STAMP A system interacts with its context by means of feedback and feed-forward loops. The context contains operators that interact with the system, as well as constraints, legislation and managerial activities.

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 organisation 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 [28] and incidents [92] and naval accidents (Herald of Free Enterprise [204]) for FRAM and Master's and PhD research projects for STAMP ([89], [123], [52], [238], [146]). Leveson herself applied STAMP to a friendly fire incident, the loss of a satellite and a bacterial contamination of a water supply [145], all three examples of accidents with a high impact, for government organizations that do not need to make a profit and that make other considerations when choosing an accident analysis method.

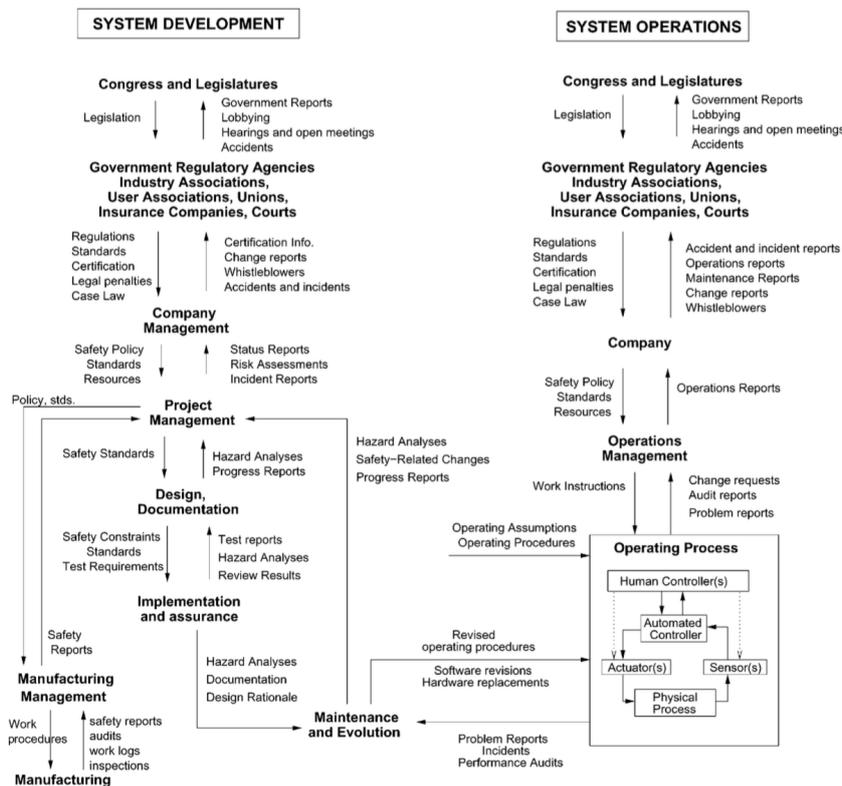


Figure 3.3.4.: The general socio-technical control model of STAMP. Taken from [144]

3.3.4. Conclusions

When comparing the three methods and their underlying models, it is convenient to do so along two axes: type of coupling and contextual awareness (*see* figure 3.3.5). The historical development of these methods (from the lower left quarter through the lower right quarter up to the upper right quarter) shows that the addition of the socio-technical context is so valuable that in developing models for tightly coupled systems, this context is explicitly taken into account. We did not find any methods or models that analyze tightly coupled system that did not take the socio-technical context into account.

Please note the empty quadrant in the top left corner. It reflects the progressive insights in accident analysis: 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 saw the additional value of the socio-technical context and made it an integral part of their methods.

3.3.5. Generic Accident Analysis Method

The three methods do share a common approach that adds steps as we go from Sequential through Epidemiological to Systemic methods:

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)

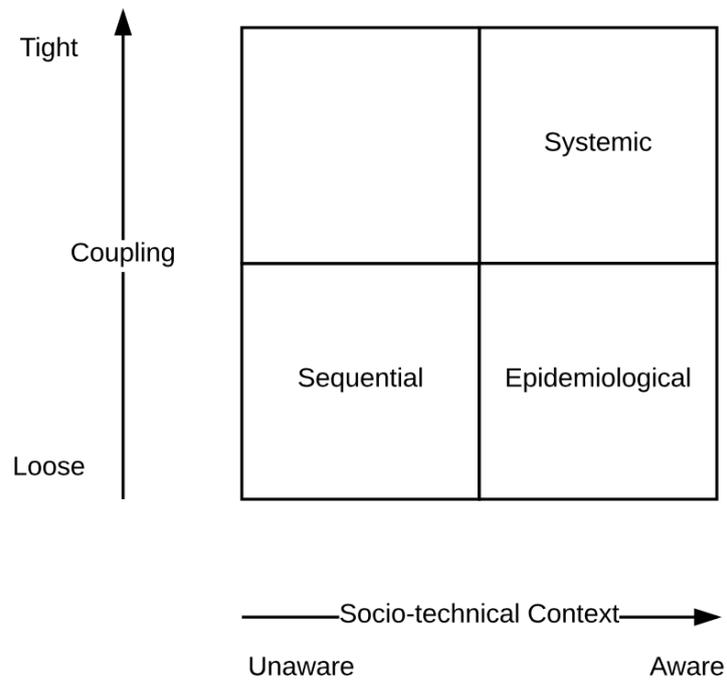


Figure 3.3.5.: Comparing the three classes of models along two distinguishing axes

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

4. Discussions and Conclusions

4.1. Threats to validity

The inclusion criteria were defined clearly and during the discussions in the different assessment stages, the four assessors agreed on the interpretation of the criteria, which was evidenced by the discussions during our final assessment. We may have missed some relevant articles by only reading articles that we assessed to be interesting based on their title and abstract only, as described in section 2, but the point of the research is to find structured methods. These methods are usually defined once and applied several times. Missing the article in which the method is defined will not necessarily mean that the method as such will be missed: application articles will refer to it and a search of the references will yield the original definition so that the method will still be included in the research. We therefore think that this threat to validity is limited.

4.1.1. Estimation of the size of the validity threat

Over all 450 articles that we considered in the multi-reviewer selection, there was a difference of opinion on 79 articles which were rejected by *A* (all articles that were included by *A* were not considered, as these would be included anyway). After careful re-examination of those discrepancies, 10 were accepted and of 6 the verdict was postponed due to unclarities in abstracts (4) or due to access restrictions to the original article (2). If the same ratios apply to those articles that were assessed by *A* only (which seems a reasonable assumption because articles were selected randomly for assessment by *B*, *C*, and *D*), then this means that over the total of 1775 articles, $1775/450 \times 10 \approx 39$ articles may have been missed, with a further 24 ($1775/450 \times 6$) falling into the category ‘uncertain’. We are confident that any significant method for accident analysis will be discussed or referred to in one of the 247 other selected articles. If we miss a method due to it not being included in any reference in the selected articles, we feel we may safely conclude that it is a method that is not widely applied.

4.2. Answers to research questions

The questions we posed ourselves were:

1. What is the state of the art in incident and accident analysis methods?
 - a) Which incident analysis methods are in use today?
 - b) Which incident 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 incident methods and models?
 - a) What are domain-specific entities, attributes, and relationships in incident models?
 - b) Can we formulate a generic analysis method and model?

We have found the following answers to these questions

4.2.1. Answers to research question 1

The literature recognizes three different classes of analysis methods and models: the Sequential, the Epidemiological, and the Systemic. The state of the art of accident analysis methods is described in table A.3.1. This table describes the methods (Question 1a) in use today and in

sections 3.3.1 through 3.3.3 we describe models (Question 1b) and the relative strengths and weaknesses of these methods (1c).

4.2.2. Answers to research question 2

We found that the individual models do not contain domain specific entities, attributes or relations (Research Question 2a). 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.

We have been able to formulate generic models for two of the three classes of models (Sequential and Epidemiological). The Systemic models (notably FRAM and STAMP) differ in so many respects that formulating a generic model was not feasible. The generic models we found for the other two classes are:

Sequential A sequential model can be represented by a causal network (with branches and merges) of events and states leading up to an accident, which causes an injury; branches may be AND or OR branches (and merges too). 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, which implies that the network includes events in the social environment.

Epidemiological 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.

Furthermore, we have been able to formulate a generic method for accident analysis. The number of steps depends on the class of analysis method:

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

4.3. Conclusions

The research in accident analysis methods is growing, as evidenced by the number of articles per year (*cf.* Figure 3.2.3a). 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, although the literature in general makes a clear distinction between accident and incident (the distinction being that accidents are harmful and incidents are not), the domains of medicine and telecommunications do not adhere to this convention, instead opting to call incidents what in other domains are called accidents.

We find that many of the methods (41 out of 63) are only mentioned once or twice in the corpus of literature we studied. Furthermore, we see a clear distinction in the classifications between the groups: if we disregard the methods that we did not classify (the categories ‘Not applicable’, ‘Passing’ and ‘Unknown’), we find for the Top 23 methods that 17% falls outside the three main classes, while for the remaining 27 methods, 48% falls outside the three main classes. This is an indication that many of the less mentioned methods are due to the authors being 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. It should be noted, that as each method uses its own model, choosing a method implies choosing a model. This in turn influences the outcome of the incident or accident analysis. According to Lundberg *et al.* (*What you look for is what you find*, [155]), the model (or more specifically, the class of models) defines which causes an analysis will find. As we are looking at them from the point of view of a telecommunications company that needs to 1) quickly resolve the incident and restart the service and 2) 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, 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.

We observe that the different methods are not always clear in their intended audience. Whether the results of the analysis are meant for architects or management (or other bodies, even) will influence the level of detail in and the presentation of the conclusions.

We conclude that 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 few and light casualties. Furthermore, safety is an emergent property in systemic methods. That makes it harder to formulate corrective measures that can be implemented by management.

In conclusion, 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.

4.4. Future work

In order to apply some of the methods found specifically to telecommunications, we may have to adapt them. This will be the subject of future research. In our future research we will be applying the current status of accident analysis techniques to telecommunications networks and we will have to find out if there are specific domain dependent entities and relations that will be part of a model for telecommunications networks that cannot be found in the more generic models. From the Top 22 methods, we chose 5 methods that we want to use for this future research. We feel that these 5 methods are a good representation of the field: they are relatively easy to apply, take the socio-technical context into account and have clear manuals. The five methods selected are MORT, Tripod- β , FRAM, Fault TreeAnalysis and AcciMap.

A. Query Results and overview of accident analysis methods

A.1. Query Results

The following table contains the results of the execution of the research query on the different databases at our disposal.

Table A.1.1.: Query Results

database	Type of entries	Selected?	exclusion criteria	number of hits
ABC	Numerical and factual data	no	No articles	NA
ACM Digital Library	Articles	yes		0
ACM The Guide to Computing literature	Articles	yes		6
ACS full text	Articles	yes		0
Analytical Abstracts Online	Articles	yes		0
ArXiv.org	Articles	yes		0
Astrophysics Data System (ADS)	Articles	no	Not pertinent	NA
Biografisch woordenboek van Nederland	Articles	no	Not pertinent	NA
Business Source Elite (EBSCO)	Articles	yes		6
Chemiekaarten	Numerical and factual data	no	No articles	NA
CiteSeerX	Articles	yes		87
Civil Engineering Database	Articles	yes		253
Design and Applied Arts (CSA)	Articles	yes		0
Directory of Open Access Journals (DOAJ)	Articles	yes		279
Directory of Published Proceedings (DoPP)	Articles	yes		0
Documentatiecentrum Nederlandse Politieke Partijen (DNPP)	Index	no	Not pertinent	NA
EconLit	Articles	no	No phrase search	NA
Emerald Journals	Articles	yes		0
Encyclopedia of Geography	Dictionaries and Encyclopedia	no	No articles	NA
Encyclopedia of Materials: Science and Technology	Dictionaries and Encyclopedia	no	No articles	NA
Encyclopedia of Philosophy (2nd edition)	Dictionaries and Encyclopedia	no	No articles	NA
Encyclopedia of Science, Technology and Ethics	Dictionaries and Encyclopedia	no	No articles	NA
Encyclopedia of Smart Materials	Dictionaries and Encyclopedia	no	No articles	NA
Encyclopedia of Statistical Sciences	Dictionaries and Encyclopedia	no	No articles	NA

database	Type of entries	Selected?	exclusion criteria	number of hits
EpistemeLinks	Internet resources	no	No articles	NA
ERIC	Articles	no	Not pertinent	NA
Espacenet	Patents	no	No articles	NA
Essential Science Indicators	Numerical and factual data	no	No articles	NA
Ethics updates	Internet resources	no	No articles	NA
EUR-Lex	Articles	no	Not pertinent	NA
Europa : official website of the European Union	Internet resources	no	No articles	NA
Eurostat	Numerical and factual data	no	No articles	NA
Geo Abstracts	Articles	yes		0
Geobase	Articles	yes		2
Google Scholar	Articles	yes		536
GreenFILE (EBSCO)	Articles	yes		1
Grijze Literatuur in Nederland (GLIN)	Articles	yes		0
Hydrotheek	Articles	yes		0
IDEAS	Articles	yes		0
IEEE Xplore Digital Library	Articles	yes		211
Instructional Design	Internet resources	no	No articles	NA
International Abstracts in Operations Research	Articles	yes		0
International Encyclopedia of Communication	Dictionaries and Encyclopedia	no	No articles	NA
International Encyclopedia of the Social Sciences	Dictionaries and Encyclopedia	no	No articles	NA
Intute	Internet resources	no	No articles	NA
IOPscience	Articles	no	Not pertinent	NA
IOS Press	Articles	yes		0
IPL2 (Internet Public Library)	Internet resources	no	No articles	NA
Journal Citation Reports	Numerical and factual data	no	No articles	NA
JSTOR	Articles	yes		0
Kluwer Navigator	Articles	yes		0
LexisNexis	News(papers)	no	No articles	NA
Library Faculty of Geo-Information Science and Earth Observation Catalogue Adlib	Catalogue	no	Not pertinent	NA
Library, Information Science & Technology Abstracts (EBSCO)	Articles	no	Not pertinent	NA
MathSciNet	Articles	no	Not pertinent	NA
MatWeb	Numerical and factual data	no	No articles	NA
Medline	Articles	no	Not pertinent	NA
MERLOT (Multimedia Educational Resource for Learning and Online Teaching)	Internet resources	no	No articles	NA
NARCIS	Numerical and factual data , Articles	no	No articles	NA
National Technical Information Service (NTIS)	Articles	no	No phrase search	NA
Newspaperindex	News(papers)	no	No articles	NA
NOD Nederlandse Onderzoek Databank	Numerical and factual data	no	No articles	NA
OpenAIRE	Articles	yes	No phrase search	NA

database	Type of entries	Selected?	exclusion criteria	number of hits
OPmaat	Articles	no	Not pertinent	NA
ORBIS	Numerical and factual data	no	No articles	NA
Overheid.nl : officiële publicaties nederlandse overheid	Articles	no	No articles	NA
Oxford Advanced Learner's Compass	Dictionaries and Encyclopedia	no	No articles	NA
Oxford Journals	Articles	yes		1
Patents database US (USPTO)	Patents	no	No articles	NA
Philosopher's Index	Articles	no	Not pertinent	NA
PhilSci archive	Internet resources	no	No articles	NA
Physical Review Online Archive (PROLA)	Articles	no	Not pertinent	NA
PiCarta	Articles	no	Too general	NA
Plastics Technology Online	Numerical and factual data	no	No articles	NA
PsycArticles	Articles	no	Not pertinent	NA
Psychology & Behavioral Sciences Collection	Articles	no	Not pertinent	NA
PsycINFO	Articles	no	Not pertinent	NA
PubMed	Articles	no	Not pertinent	NA
Reach	Numerical and factual data	no	No articles	NA
Rechtsorde.nl	Articles	no	Not pertinent	NA
Regional Business News	News(papers)	no	No articles	NA
ResearchProfessional	Funding opportunities	no	No articles	NA
Routledge Encyclopedia of Philosophy	Dictionaries and Encyclopedia	no	No articles	NA
SAGE Journals Online	Articles	yes		6
ScienceDirect	Articles	yes		96
SciFinder	Articles	no	Not pertinent	NA
SciTech	Articles	no	No phrase search	NA
Scopus	Articles	yes		20
Siam Journals Online	Articles	no	Not pertinent	NA
SpringerLink	Articles	yes		19
Stanford Encyclopedia of Philosophy	Dictionaries and Encyclopedia	no	No articles	NA
Staten-generaal Digitaal	Articles	no	Not pertinent	NA
StatLine	Numerical and factual data	no	No articles	NA
Stevens' Handbook of Experimental Psychology	Dictionaries and Encyclopedia	no	No articles	NA
Taylor & Francis	Articles	yes		0
The Collection of Computer Science Bibliographies	Articles	no	Not pertinent	NA
The encyclopedia of earth	Articles	no	Not pertinent	NA
The World Factbook	Numerical and factual data	no	No articles	NA
TRID Online	Articles	yes		6
Ullmann's Encyclopedia of Industrial Chemistry	Dictionaries and Encyclopedia	no	No articles	NA
Ulrichsweb	Numerical and factual data	no	No articles	NA
University of Twente Library Catalogue	Catalogue	no	No articles	NA
UTpublications	Articles	yes		0
Web of Science	Articles	yes		14
Wijsbegeerte in Nederland	Articles	no	Not pertinent	NA

database	Type of entries	Selected?	exclusion criteria	number of hits
Wiley Online Library	Articles	yes		6
World Data on Education (WDE)	Numerical and factual data	no	No articles	NA
World Energy Base (ET-DEWEB)	Articles	yes		226
Total				1775

A.2. Number of articles per journal

The following table contains the number of articles per journal. Note that this is only for papers that were published in academic journals: theses, conference proceedings and books are not part of this list.

Table A.2.1.: Number of articles per journal

Journal title	Articles
Accident Analysis & Prevention	7
Applied Ergonomics	1
BMC Medical Education	1
BMC Medical Informatics and Decision Making	1
BMC Surgery	1
Chinese Journal of Electronics	1
Chinese Journal of Aeronautics	1
Cognition, Technology & Work	3
Discrete Dynamics in Nature and Society	1
Ergonomics Australia Journal	1
Ergonomics	2
Evidence Based Library and Information Practice	1
Human Factors and Aerospace Safety	2
Human Factors: The Journal of the Human Factors and Ergonomics Society	1
ITOR International Transactions in Operational Research	1
International Journal of Academic Research	1
International Journal of Industrial Ergonomics	1
International journal of occupational hygiene	1
Journal of Construction Engineering and Management	1
Journal of Clinical Engineering	1
Journal of Hazardous Materials	4
Journal of Loss Prevention in the Process Industries	4
Journal of Occupational Accidents Journal of Occupational Accidents	1
Journal of Safety Science and Technology	1
Journal of Scientific & Industrial Research	2
Journal of occupational accidents	2
Japanese Journal of Pharmaceutical Health Care and Sciences	1
Jundishapur Journal of Health Sciences	1
Lecture notes in computer science	1
Physica A: Statistical Mechanics and its Applications	1

Journal title	Articles
Procedia Engineering	2
Process Safety and Environmental Protection	1
Psychological bulletin	1
Reliability Engineering & System Safety	4
Reviews of Human Factors and Ergonomics	1
Safety Science Monitor	1
Safety Science	15
Scandinavian Journal of Work, Environment & Health	1
The Ergonomics Open Journal	1
The International Journal of Aviation Psychology	1

A.3. Characteristics for 63 methods

The following table contains the characteristics for the different methods we found. The different characteristics are as follows:

Method The name of the method. In some cases, the method does not have an established name. In that case, the name of the first author of the article is used (*e. g.* for *Junior*). The meaning of the abbreviations can be found in section A.4

Type Whether the method is sequential, epidemiological, systemic, or other. Some of the methods are not analysis methods, but *e. g.* taxonomies, or are not discussed at all in the article in which they were mentioned. In these cases, we have put N/A in the type.

Domains The domains in which the method is applied. Note that in some cases, this may only mean that a comparative article has tested the method in a certain domain (such as in Strömngren *et al.* [244]), while in other cases the method has been applied extensively in the industry.

Steps The number of steps in the method

Number of types of entities The number of different types of entities in the model

Modelling narrative This places the most important entities into context. Entity names start with capitals.

Number of publications found The number of articles, manuals, books, PhD theses we found in the different databases that discuss, define or apply the method.

Manual present? Does the method have a manual in English that clearly describes how to apply it in practice?

Table A.3.1.: Overview of all accident analysis methods discussed in this report

Method	Type	Domains ²	Weight	# steps	# of types of entities	Modelling narrative	# of publications found ³	Manual present? ⁴	References
3CA	Epi	CI, ES	M	3	6	An <i>Agent</i> causes a <i>Change</i> and in the absence of preventive <i>Measures</i> , this causes an <i>Event</i> with an <i>Effect</i>	3	yes [127]	[70] [122] [127]
3D-analysis	Oth	MD	L	N/A	N/A	N/A	1	no	[167]
4M4E	Oth	N/A	N/A	N/A	N/A	N/A	1	no	[66]
Accimap	Epi	AV, CI, EI, ES, MD, ML, MT, OA, OC, RW, RT, SF	H	N/A	11	An accident is a <i>Direct Consequence</i> of a <i>Critical Event</i> . Such an event is itself the direct or <i>Indirect consequence</i> of an <i>Action</i> . Often, these actions are taken as part of fulfilling a <i>Task</i> which in turn is based on an <i>Order</i> from a higher <i>System Level</i> . Often, orders arise from <i>Decisions</i> based on certain <i>Preconditions</i> or on a <i>Plan</i> . The creation of these plans by certain <i>Functions</i> in a socio-technical environment may in turn be triggered by orders from different system levels.	16	no	[220] [257] [225] [223] [244] [178] [76] [222] [254] [258] [259] [205] [219] [246] [243] [271]
AcciTree	Epi	AV	H	14	9	N/A	2	no	[76] [77]
AEB	Epi	AV, CI, MT, OC, RW	M	2	6	If an <i>Error Event</i> is not blocked by a functioning <i>Barrier</i> , it may cause an <i>Accident</i> . Error events are caused by <i>Actions</i> or by previous error events	9*	yes [248]	[250] [244] [171] [247] [102] [96] [248]
APS	Seq	RT	M	5	N/A	The sequence of <i>Situations</i> leading up to the <i>Accident</i> can be divided into <i>Phases</i> . In each phase, a situation causes an <i>Event</i> which in turn creates a new situation	2	no	[62] [153]

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Table A.3.1.: Overview of all accident analysis methods discussed in this report (cont'd)

Method	Type	Domains ²	Weight	# steps	# of types of entities	Modelling narrative	# of publications found ³	Manual present? ⁴	References
ArcGIS	Oth	RT	N/A	N/A	N/A	N/A	1	no	[114]
ATSB	Epi	RW	H	5	9	In an organisation, employees work to attain <i>Production Goals</i> . Sometimes, certain <i>Technical Events</i> and <i>Individual Actions</i> may cause <i>Incidents</i> . Proper <i>Recovery Risk Controls</i> may stop these incidents from developing into <i>Accidents</i> . Organisations create <i>Preventative Risk Controls</i> to prevent these incidents from happening in the first place, but <i>Organisational Influences</i> may impact these controls and create <i>Local Conditions</i> in which the occurrence of incidents is more probable	2	yes [19]	[259] [19]
C-HFACF	Oth	AV	L	N/A	N/A	N/A	1	no	[276]
CASMET	Epi	MT	H	5	4	<i>Management</i> and the allocation of <i>Resources</i> govern <i>Daily Operations</i> . If this is done inadequately, <i>Accident Events</i> (including a <i>Casualty Event</i>) may develop	1	yes [27]	[27]
CBA	Oth	UNK	H	unk	unk	unk	1	no	[171]
CCDM	Seq	NI	M	N/A	2	A combination of <i>Failures</i> causes an <i>Event</i>	1	no	[180]

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Table A.3.1.: Overview of all accident analysis methods discussed in this report (cont'd)

Method	Type ¹	Domains ²	Weight	# steps	# of types of entities	Modelling narrative	# of publications found ³	Manual present? ⁴	References
CDM	Oth	MD, MI, NI	M	4	3	Human actions are divided into <i>Activity Chunks</i> , which may be physical or cognitive. They transition into each other. These transitions may be controlled by <i>Potential Risk Controls</i>	3	no	[149] [93] [143]
COA	N/A	N/A	N/A	N/A	N/A	N/A	1	unk	[73]
CREAM/DREAM	Epi	ES, MD, NI, RW, RT	M	4	5	The probable cause(s) of an analysed <i>Event</i> are <i>Consequent-Antecedent Links</i> that trigger <i>Probable Error Modes</i> in the <i>Task</i> executed under <i>Common Performance Conditions</i>	9	yes [98]	[217] [226] [244] [98] [7] [102] [96] [227] [283]
Critical incident Technique	Oth	MD	M	5	N/A	N/A	2	yes	[159] [60]
CTM	Seq	N/A	L	N/A		An <i>Accident</i> is the result of a chain of <i>Events</i> . These events may be <i>Incidental Factors</i> that together or on their own cause <i>Branching</i> or a <i>Confluence</i> in the <i>Event Chain</i> .	2	no	[122] [141]
Deviation Anal- ysis (OARU)	Seq	CI, EI, ES, MD, ML, MT, OA, RW,RT	L	3	3	An accident sequence consists of <i>Deviations</i> from the norm. These deviations are ordered chronologically throughout the three <i>Phases</i> of the sequence (<i>Initiatory, Concluding and Injury</i>). Underlying <i>Determining Factors</i> are highlighted.	3	no	[244] [122] [129]

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Method	Type	Domains ²	Weight	# steps	# of types of entities	Modelling narrative	# of publications found ³	Manual present? ⁴	References
Domino Accident Model	Seq	IN	M	unk	5	Accidents happen in a <i>Social Environment</i> . In this — and possibly due to this — environment, a person makes an error, a <i>Fault of Person</i> . When this results in an <i>Unsafe Act</i> , this can lead to an <i>Accident</i> , causing an <i>Injury</i>	4*	no	[257] [252] [166]
DWACN	Oth	RW	H	N/A	2	This is a network modelling technique, connecting components (nodes) to each other through relations (vertices)	1	no	[289]
ECFA & C	Seq	EN	H	14	N/A	<i>Events</i> happen and cause other events. They may be enabled by <i>Conditions</i> and <i>Causal Factors</i>	8	yes [23]	[170] [225] [171] [70] [102] [260] [243] [23]
Elementary Event Analysis Method	Oth	UNK	unk	unk	unk	unk	1*	no	
Event Trees	Seq	AV	L	unk	3	An event tree describes an accident as a sequence of bifurcations in which each branch describes a possible outcome of the branching <i>Event or Action</i> and each leaf a final <i>Consequence</i> . Events can be occurring or nonoccurring and actions can be successes or failures.	1	no	[13]

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Table A.3.1.: Overview of all accident analysis methods discussed in this report (cont'd)

Method	Type ¹	Domains ²	Weight	# steps	# of types of entities	Modelling narrative	# of publications found ³	Manual present? ⁴	References
FRAM	Sys	AV, MD	H	6	7	A system is a collection of interacting Functions . Each function has six Aspects , which may or may not be relevant to the evolution of the system towards an accident. These are the Input to the function, the Output of the function, the Pre-conditions to start the function, the Resources needed by the function, the Control that regulates the function and how Time affects the execution of the function. Each function is linked to another function through one of these aspects.	11	yes [101]	[257] [204] [92] [13] [100] [252] [258] [99] [102] [28] [101]
FTA	Seq	EI, ES, MT	M	N/A	5	The FTA constructs a tree of events following one another in time. Combinations of events (through logic gates) give rise to or may inhibit other events. FTA recognises 5 types of event.	10	yes [267]	[132] [244] [171] [267] [258] [257] [269] [80] [122] [54]
HFACS	N/A	N/A	N/A	N/A	N/A	N/A	15*	yes [231]	[257] [76] [276] [272] [232] [93] [8] [1] [31] [102] [219] [243] [231] [230]
HFVA	N/A	N/A	N/A	N/A	N/A	N/A	1	unk	[26]
HPES	Pas	N/A	N/A	N/A	N/A	N/A	2	unk	[102] [248]

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Method	Type ¹	Domains ²	Weight	# steps	# of types of entities	Modelling narrative	# of publications found ³	Manual present? ⁴	References
HSG245	Pas	N/A	N/A	N/A	N/A	N/A	1	unk	[122]
Ipica	Epi	EC	H	5	unk	Extension of RCA with elements from STAMP and Safety Management Methodologies	2	no	[59] [58]
ISIM	Epi	AV, EN, MT, RW	L	2	8	Information about Tasks , Personel , Equipment and Environmental Conditions in the sequence of Events is analysed to find underlying Factors and unsafe Conditions . The status of relevant Barriers is then examined	1	no	[122]
Junior	Epi	CI	M	7	3	An Accident is caused by behavioural variability, not human error. Events and Conditions in which they occur cause accidents due to the Behavioural Variability always present in a Socio-technical system .	1	no	[119]
LEADSTO	Seq	N/A	N/A	N/A	N/A	N/A	2	yes [14]	[13] [14]
Lee	N/A	N/A	N/A	N/A	N/A	N/A	1	no	[139]
MES	Seq	AV	M	unk	3	Events are Actors taking an Action . They propell a stable situation into an accident	3	no	[225] [122] [290]
MIA	Oth	MD	M	7	N/A	No real model, more of a meta analysis of incident reports	2	no	[41] [45]

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Method	Type	Domains ²	Weight	# steps	# of types of entities	Modelling narrative	# of publications found ³	Manual present? ⁴	References
MORT	Seq	NI	M	2	3	Unwanted <i>Energy Transfer</i> takes place due to inadequate <i>Energy Barriers</i> or <i>Controls</i> . MORT knows <i>Omissions, Risks</i> and <i>Management Characteristics</i>	9	yes [130]	[171] [70] [269] [122] [130] [65] [118] [173] [172]
MTO	Pas	AV, CI, EI, ES, MD, MT, OA, OC, RW, RT, SF	N/A	N/A	N/A	N/A	2	no	[244] [102]
NACA	Pas	AV	N/A	N/A	N/A	N/A	1	no	[103]
NSB	Pas	RW	N/A	N/A	N/A	N/A	1	no	[122]
PG Diagram	Epi	RW	M	N/A	2	Looks at accidents from <i>Human, Technical, Organizational, Social</i> and <i>Environmental/Cultural</i> aspects. Creates a graph with <i>Conditions</i> as nodes and <i>Interactions</i> as vertices	2	no	[186] [95]
PHARM-2E	Epi	MD	unk	unk	unk	unk	1	no	[133]
PRISMA	Oth	CI, MD	N/A	N/A	N/A	Combination of analysis method, classification and actions for improvement	3	yes [261]	[263] [261] [168]
PSO	Oth	N/A	N/A	N/A	N/A	Optimization algorithm in Machine Learning	1	no	[73]
RCA	Seq	CI	H	4	N/A	The RCA has four steps, of which one is an ECFC. It does not have an accident model	9	yes [214]	[170] [223] [171] [59] [214] [45] [63] [102] [111]

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Reason / SCM	Epi	AV	M	N/A	5	<i>Wrong Decisions</i> by decision makers, incompetent <i>Actions</i> from line management, unmet <i>Preconditions</i> for production, unsafe <i>Acts</i> in production and inadequate <i>Defences</i> ultimately cause accidents	8*	no	[257] [208] [252] [258] [259] [102] [166]
SCAT	Epi	AV, CI, EI, MD, MT, OC, RT	M	5	3	<i>Common Categories of Contact</i> (e.g. with a hazardous situation) can lead to an <i>Accident</i> . The <i>Causes</i> for this <i>Contact</i> are split into <i>Immediate Causes</i> and <i>Underlying Causes</i> .	5	yes, cf. [244]	[244] [269] [122] [85] [102]
SFA	Pas	AV, CI, MD, OC, RW, RT	N/A	N/A	N/A	N/A	1	yes, cf. [244]	[244]
SHEL(L)	Pas	AV	N/A	N/A	4	Acronym for <i>Software, Hardware, Environment, Liveware</i> (twice)	7*	no	[76] [186] [27] [31] [66] [115]
SINAI	Oth	EI	N/A	N/A	N/A	SINAI is a computer system that facilitates incident analysis in SCADA systems	1	no	[164]
SOL	Epi	AV	M	5	2	SOL places <i>Events</i> in a timeline by organizing events into <i>Event Building Blocks</i> and ordering them in a <i>Time-Actor</i> diagram. The event building blocks are characterized by time, location, action and actor. This helps to identify <i>Contributing Factors</i> for each building block	3	no	[225] [117] [274]

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STAMP	Sys	AV, CI, EN, FI, FS, MD, MT, OA, RT, RW, SF	H	9	6	An <i>Operator</i> controls a <i>System</i> through <i>Actuators</i> , responding to readings from <i>Sensors</i> and according to a conceptual <i>Model</i> of the system in his head. <i>Safety Constraints</i> control the different actions taken by the operator. This cycle goes for physical systems and controls, but also for higher level systems and feedback / feed-forward loops such as legislation and managerial supervision	23	yes [145]	[257] [225] [13] [252] [258] [259] [124] [193] [131] [144] [52] [102] [89] [219] [238] [123] [145] [146] [256] [166] [183] [243] [76]
STEP	Seq	CI, EI, ES, ML, MT, RW, RT	N/A	N/A	3	STEP contains <i>Event Building Blocks</i> , linking one <i>Actor</i> to one <i>Action</i> .	4	no	[92] [244] [269] [102]
STPA	N/A	N/A	N/A	N/A	N/A	Not an accident analysis method	1	yes [145]	[123]
TapRoot	unk	UNK	unk	7	unk	unk	1	yes [198]	[18]
Task Analysis	N/A	N/A	N/A	N/A	N/A	Task Analysis is a way to assess how people perform tasks and not an analysis tool	1	unk	[54]
TEM	Epi	AV, MD	M	3	5	TEM models accidents as <i>Latent</i> and <i>Overt Threats</i> that result in <i>Errors</i> . <i>Error Management</i> determines at least in part the <i>Outcome</i> of the error	4*	unk	[91] [43] [90]

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Tripod- β	Epi	CI	H	6	7	An <i>Agent of Change</i> threatens an <i>Object</i> . In the absence of a functioning <i>Barrier</i> , this may result in an undesirable <i>Event</i> . Barrier Failure may have one <i>Immediate Cause</i> that is triggered by <i>Underlying Causes</i> , depending on certain <i>Preconditions</i>	7	yes [253]	[170] [171] [176] [269] [122] [56] [253]
Variation Tree	Pas	UNK	unk	unk	unk	unk	1	no	[66]
VSM	Oth	N/A	N/A	N/A	N/A	N/A	1	no	[124]
WAIT	Pas	ALL	M	2		N/A	1	no	[122]
Why Because	Seq	AV	M	iterative	5	Incidents are caused by <i>Events</i> , <i>Non-events</i> , <i>Processes</i> , <i>States</i> and <i>Other</i> factors, which in turn have causes of their own.	2	no	[225] [71]

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A.4. Abbreviations

3CA	Control Change Cause Analysis
AEB	Accident Evolution and Barrier Function
APS	Accident Prototypical Scenario
C-HFACF	Complex Human Factor Analysis and Classification Framework
CASMET	Casualty Analysis Methodology for Maritime Operations
CAST	Causal Analysis using STAMP
CCDM	Cause-Consequence Diagram Method
CIAF	Canadian Incident Analysis Framework
COA	Change Optimisation Algorithm
COCOM	Contextual Control Model
CPC	common performance conditions
CREAM	Cognitive Reliability and Error Analysis Method
CTM	Causal Tree Method
DAM	Domino Accident Model
DREAM	Driver's Reliability and Error Analysis Method
ECFA	Events and causal factors analysis
ECFC	Events and causal factors charting
FRAM	Functional Resonance Analysis Method
FTA	Fault Tree Analysis
HEP	Human Error Probability
HFACS	Human Factors Analysis and Classification System
HOE	Human and Organizational Errors
HIP	Human Information Processing
HPES	Human Performance Enhancement System
HRA	Human Reliability Analysis
HSG245	Health and Safety Guidance
IAAM	Incident or Accident Analysis Method
INPO	Institute for Nuclear Power Operations
INRS	Institut National de la Recherche et de Sécurité
ISIM	Integrated Safety Investigation Methodology
MES	Multilinear Events Sequencing
MIA	Multi-Incident Analysis
MORT	Management Oversight and Risk Tree
MTO	Man, Technology, Organisation
NACA	National Advisory Committee for Aeronautics
NSB	Norske Statesbaner
OARU	Integrated safety investigation methodology

PRISMA	Prevention and Recovery Information System for Monitoring and Analysis
PSF	Performance Shaping Factor
PSO	Particle Swarm Optimisation
RCA	Root Cause Analysis
SCAT	Systemic Cause Analysis Technique
SCM	Swiss Cheese Model
SFA	Safety Function Analysis
SHEL	Software, Hardware, Environment, Liveware
SOL	Safety through Organizational Learning
STAMP	System Theoretical Accident Model and Processes
STEP	Sequentially Timed Events Plotting
STPA	System-Theoretic Process Analysis
TEM	Threat and Error Management
VSM	Viable Systems Model
WAIT	Work accidents investigation technique
WBA	Why-Because Analysis

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