Methods for accident investigation

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TITLE

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SUMMARY

This report gives an overview of some important, recognized, and commonly used methods for investigation of major accidents. Investigation of major accidents usually caused by multiple, interrelated causal factors should be performed by a multi-disciplinary investigation team, and supported by suitable, formal methods for accident investigation. Each of the methods has different areas of application and a set of methods ought to be used in a comprehensive accident investigation. The methods dealt with are limited to methods used for in-depth analysis of major accidents.

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Summary

This report gives an overview of some important, recognized, and commonly used methods for investigation of major accidents. The methods dealt with are limited to methods used for in-depth analysis of major accidents.

The objective of accident investigation, as seen from a safety engineer's point of view are to identify and describe the true course of events (what, where, when), identify the direct and root causes or contributing factors to the accident (why), and to identify risk reducing measures in order to prevent future accidents (learning).

Investigation of major accidents usually caused by multiple, interrelated causal factors should be performed by a multi-disciplinary investigation team, and supported by suitable, formal methods for accident investigation. A number of methods are described in this report. Each of the methods has different areas of application and a set of methods ought to be used in a comprehensive accident investigation.

A comprehensive accident investigation should analyse the influence of all relevant actors on the accident sequence. Relevant actors might span from technical systems and front-line personnel via managers to regulators and the Government.

Contents

1 Introduction

1.1 Introduction to accident investigation and delimitations of the report

The accident investigation process consists of a wide range of activities, and is described somewhat different by different authors. DOE (1999) divide the investigation process into three phases; collection of evidence and facts, analysis of these facts, and development of conclusions and development of judgments of need and writing the report, see Figure 1. These are all overlapping phases and the whole process is iterative. Some authors also include the implementation and follow-up of recommendations in the investigation phase (e.g., Kjellén, 2000).

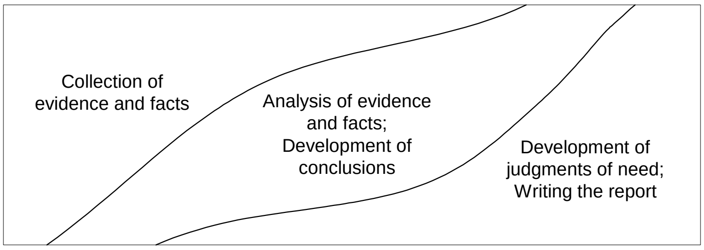

Figure 1. Three phases in an accident investigation.

In this report it is focused on the analysis of data and especially on methods applicable to this work. The focus on the data analysis, do not means that the other phases are not as important, but is a way of limiting the scope of the report.

According to Kjellén (2000), certain priorities have to be made in order to focus on the accidents and near accidents that offer the most significant opportunities for learning. He recommends the following approach (see Figure 2)[1]:

[1] This approach is not limited to major accidents, but also include occupational accidents.

1. All reported incidents (accidents and near accidents) are investigated immediately at the first level by the supervisor and safety representative.
2. A selection of serious incidents, i.e. frequently recurring types of incidents and incidents with high loss potential (actual or possible) are subsequently investigated by a problem-solving group.
3. On rare occasions, when the actual or potential loss is high, an accident investigation commission carries out the investigation. This commission has an independent status in relation to the organisations that are responsible for the occurrence.

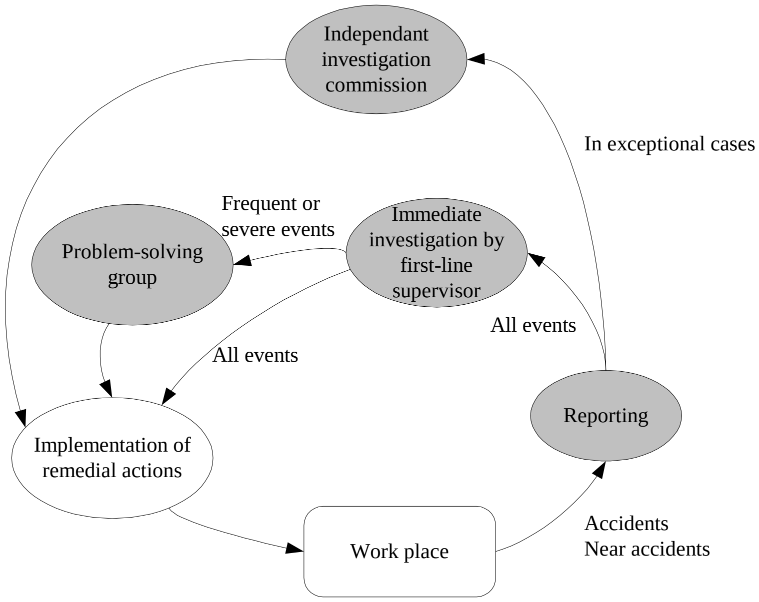

Figure 2. Accident investigation at three levels (Kjellén, 2000).

This last category will also include events that Reason calls organisational accidents (Reason, 1997). Organisational accidents are the comparatively rare, but often catastrophic, events that occur within complex, modern technologies such as nuclear power plants, commercial aviation, petrochemical industry, etc. Organisational accidents have multiple causes involving many people operating at different levels of their respective companies. By contrast, individual accidents are accidents in which a specific person or a group is often both the agent and the victim of the accident. Organisational accidents are according to Reason (1997) a product of technological innovations that have radically altered the relationship between systems and their human elements.

Rasmussen (1997) proposes different risk management strategies for different kinds of accidents, see Figure 3. The accident investigation methods dealt with in this report are limited to methods used for evolutionary safety control, i.e. in-depth analysis of major accidents (ref. Kjelléns third point and Reasons organisational accidents). Methods used for empirical safety control (e.g., statistical data analysis) and analytical safety control (probabilistic risk analysis) are not treated separately in this report, even though some of the methods may also be used in probabilistic risk analysis.

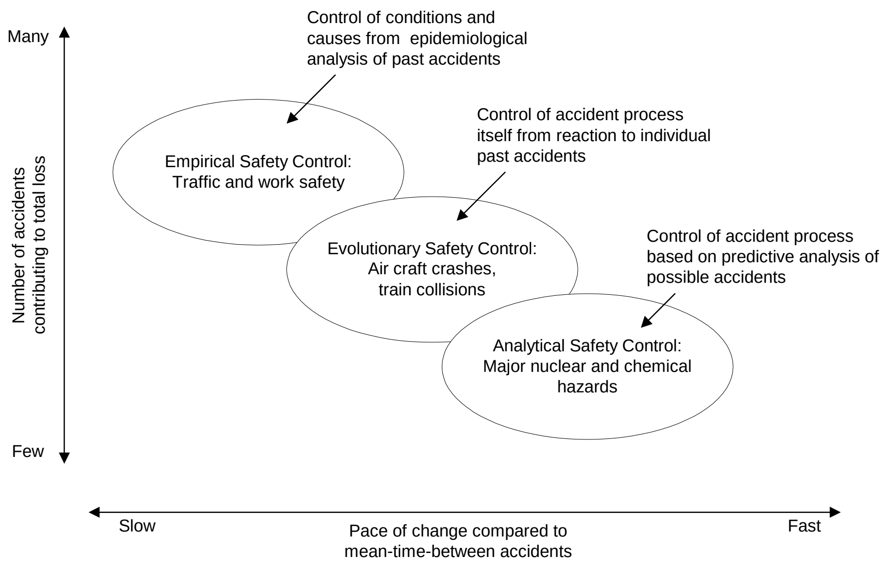

Figure 3. Rasmussen's risk management strategies.

The various accident investigations methods are usually based on different models for accident causation[2], in which help to establish a

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[2] A study by Andersson & Menckel (1995) identified eleven conceptually different models. The general trend they found is that most "primitive" models focus on one accident, one factor or one individual, while the more recent models refer to more complex disorders, multifactorial relationships, many or all persons in a society, and the environment as whole. Interest and focus have an ever increasing time-span, and concentrate increasingly on the "before the

shared understanding of how and why accidents happen. A detailed description of the different accident models will not be given in this report, only a listing of the main "classes" of accident models. For those interested in more details about accident models, Kjellén's description of these models in his book (Kjellén, 2000) is recommended as a starting point.

The main classes of accident models are (based on Kjellén, 2000):

1. Causal-sequence models
2. Process models
3. Energy model
4. Logical tree models
5. Human information-processing models
6. SHE management models

To summarise the purpose and delimitations, this report will focus on methods for analysis of major accidents usually caused by multi-factorial system failures.

1.2 Glossary / definitions and abbreviations

1.2.1 Definitions and terms used in accident investigation

Within the field of accident investigation, there is no common agreement of definitions of concepts. Especially the notion of cause has been discussed. While some investigators focus on causal factors (e.g., DOE, 1997), others focus on determining factors (e.g., Kjellén and Larsson, 1981), contributing factors (e.g., Hopkins, 2000), active failures and latent conditions (e.g., Reason, 1997) or safety problems (Hendrick & Benner, 1987).

Hopkins (2000) defines cause in the following way: "one thing is said to be a cause of another if we can say ***but for*** the first the second would not have occurred". Leplat (1997) expresses this in a more formal way by saying that in general, the following type of definition of cause is accepted: "to say that event X is the cause of event Y is to say that the

accident" period instead of on the mitigation of the consequence of the accident.

occurrence of X is a necessary condition to the production of Y, in the circumstances considered". Such a definition implies that if any one of the causal pathways identified are removed, the outcome would probably not have occurred. Using the term contributing factor may be less formal, if an event has not occurred, this would necessarily not prevented the occurrence of the accident. Kletz (2001) recommends avoiding the word cause in accident investigations and rather talk about what might have prevented the accident.

Accident investigators may use different frames for their analysis of accidents, but nevertheless the conclusions about what happened, why did it happen and what may be done in order to prevent future accidents may be the same.

Some definitions are included in this chapter. These definitions are meant as an introduction to the terms. Several of the terms are defined in different ways by different authors. The definitions are quoted without any comments or discussions in this report in order to show some of the specter. Therefore, these definitions represent the authors' opinions.

Accident	A sequence of logically and chronologically related deviating events involving an incident that results in injury to personnel or damage to the environment or material assets. (Kjellén, 2000) An unwanted transfer of energy or an environmental condition that, due to the absence or failure of barriers and controls, produces injury to persons, damage to property, or reduction in process output. (DOE, 1997)
Barrier	Anything used to control, prevent, or impede energy flows. Common types of barriers include equipment, administrative procedures and processes, supervision/management, warning devices, knowledge and skills, and physical. Barriers may be either control or safety. (DOE, 1997)
Barrier analysis	An analytical technique used to identify the energy sources and the failed or deficient barriers and controls that contributed to an accident. (DOE, 1997)

Causal factor An event or condition in the accident sequence necessary and sufficient to produce or contribute to the unwanted result. Causal factors fall into three categories; direct cause, contributing cause and root cause. (DOE, 1997)

Cause of accident Contributing factor or root cause. (Kjellén, 2000)

Contributing cause An event or condition that collectively with other causes increases the likelihood of an accident but which individually did not cause the accident. (DOE, 1997)

Contributing factor More lasting risk-increasing condition at the workplace related to design, organisation or social system. (Kjellén, 2000)

Controls Those barriers used to control wanted energy flows, such as the insulation on an electrical cord, a stop sign, a procedure, or a safe work permit. (DOE, 1997)

Direct cause The immediate events or conditions that caused the accident. (DOE, 1997)

Event An occurrence; something significant and real-time that happens. An accident involves a sequence of events occurring in the course of work activity and culminating in unintentional injury or damage. (DOE, 1997)

Events and causal factor chart Graphical depiction of a logical series of events and related conditions that precede the accident. (DOE, 1997)

Root cause An underlying system-related prime (the most basic) reason why an incident occurred (CCPS, 1992)

The causal factor(s) that, if corrected, would prevent recurrence of the accident. (DOE, 1997)

Most basic cause of an accident/incident, i.e. a lack of adequate management control resulting in deviations and contributing factors. (Kjellén, 2000)

Root cause analysis Any methodology that identifies the causal factors that, if corrected, would prevent recurrence of the accident. (DOE, 1997)

1.2.2 Abbreviations

AEB-analysis	Accident evolution and barrier analysis
BRF	Basic Risk Factors
CCPS	Center for Chemical Process Safety
DOE	U.S. Department of Energy
MORT	Management and Organisational Review Technique
MTO	Menneske, teknologi og organisasjon
PSF	Performing Shaping Factor
SCAT	Systematic Cause Analysis Technique
STEP	Sequential Timed Events Plotting

2 What is accident investigation about?

2.1 Preconditions for accident investigation

This chapter starts with some preconditions for accident investigation that every accident investigator should bear in mind at work:

- Major accidents are unplanned and unintentional events that result in harm or loss to personnel, property, production, the environment or anything that has some value.
- Barriers (physical and management) should exist to prevent accidents or mitigate their consequences. Major accidents occur when one or more barriers in a work system fail, to fulfill its functions, or do not exist.
- Major accidents almost never result from a single cause; most accidents involve multiple, interrelated causal factors.
- Major accidents are usually the result of management system failures, often influenced by environmental factors or the public safety framework (e.g., set by contracts, the market, the regulators or the Government)
- Accident investigators should remain neutral and independent and present the results from the investigations in an unbiased way[3].

2.2 An useful framework for accident investigation

According to Rasmussen (1997), accidents are caused by loss of control of physical processes that are able to injure people, and/or damage the environment or property. The propagation of an accidental course of events is shaped by the activity of people, which can either trigger an accidental flow of events or divert a normal flow.

[3] Hopkins (2000) identified three distinct principles of causal selection being in operation at the Commission after the Longford-accident:
1. Self-interest, select causes consistent with self-interest
2. Accident prevention, select causes which are most controllable
3. The legal perspective, select causes which generate legal liability

Many levels of politicians, managers, safety officers, and work planners are involved in the control of safety by means of laws, rules, and instructions that are established to control some hazardous, physical process. The socio-technical system actually involved in the control of safety is shown in Figure 4.

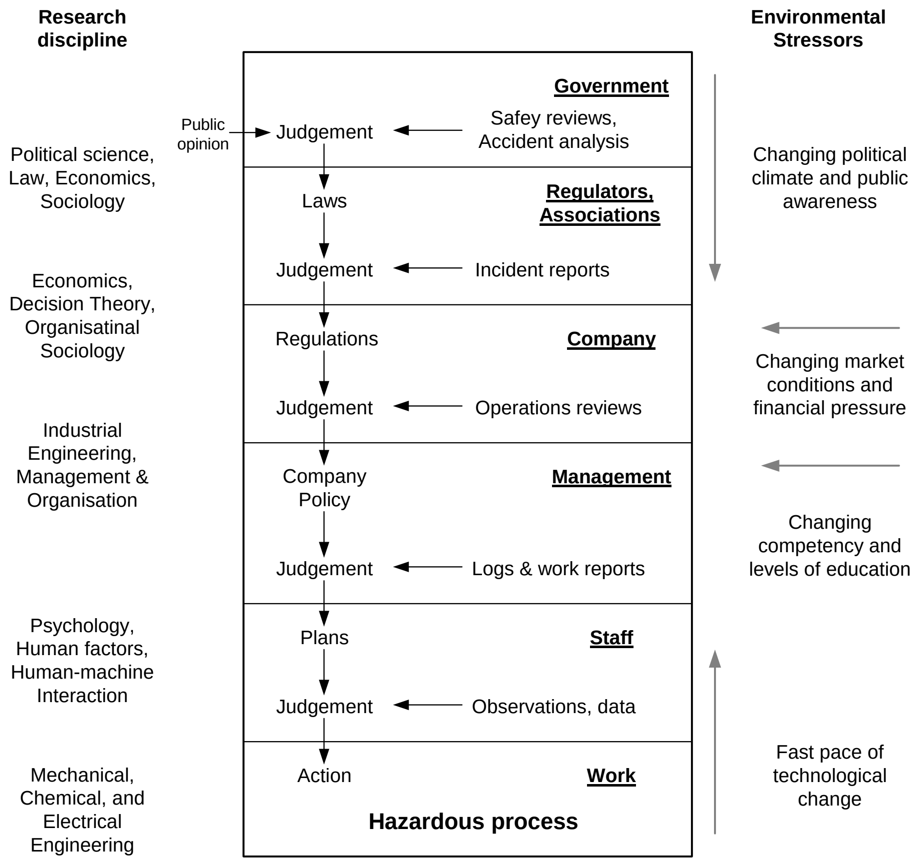


Figure 4. The socio-technical system involved in risk management (Rasmussen, 1997).

This framework is chosen as a view on investigation of major accidents and will be discussed further in the discussion in chapter 5.

2.3 The purpose of accident investigation

An accident investigation may have different purposes:

- Identify and describe the true course of events (***what, where, when***)
- Identify the direct and root causes / contributing factors of the accident (***why***)
- Identify risk reducing measures to prevent future, comparable accidents (***learning***)
- Investigate and evaluate the basis for potential criminal prosecution (***blame***)
- Evaluate the question of guilt in order to assess the liability for compensation (***pay***)

As we see, there may be different purposes in which initiate accident investigations. The different purposes will not be discussed anymore in this report.

2.4 Responsibility for accident investigation

Who should be responsible for performing accident investigations and how thoroughly should the accident be investigated?

The history of accident investigation in the past decades shows a trend to go further and further back in the analysis, i.e., from being satisfied with identifying human errors by front-personnel or technical failures to identify weaknesses in the governmental policies as root causes. In order to know when we should stop our investigation, we need what Rasmussen (1990) called stop-rules. Reason (1997) suggests that we should stop when the causes identified are no longer controllable.

The stopping rule suggested by Reason (1997), leads to different stopping points for different parties. Companies should trace causes back to failures in their own management systems and develop risk-reducing measures that they have authority to implement.

Supervisory authorities (e.g., The Norwegian Petroleum Directorate), appointed governmental commissions of inquiries (e.g., the Sleipner-commission, and the Åsta-commission) or permanent investigation boards (e.g., The Norwegian Aircraft Accident Investigation Board) should in addition focus on regulatory systems and ask whether weaknesses in these systems contributed to the accident.

The police and the prosecuting authority are responsible for evaluating the basis for potential criminal prosecution, while the court of justice is responsible for passing sentence on a person or a company.

The liability for compensation is within the insurance companies' and the lawyer's range of responsibility.

2.5 Criteria for accident investigations

What is a "good" accident investigation? This question is difficult to answer in a simple way, because the answer depends on the purpose of the investigation. Nevertheless, I have included ten fundamental criteria for accident investigations stated by Hendrick & Benner (1987). Three criteria are related to objectives and purposes of the accident investigation, four to investigative procedures, and three to the outputs from the investigation and its usefulness.

Criteria related to objectives and purposes

- *Realistic*
  The investigation should result in a realistic description of the events that have actually occurred.
- *Non-causal*
  An investigation should be conducted in a non-causal framework and result in an objective description of the accident process events. Attribution of cause or fault can only be considered separate from, and after the understanding of the accident process is completed to satisfy this criterion.
- *Consistent*
  The investigation performance from accident to accident and among investigations of a single accident to different investigators should be consistent. Only consistency between results of different investigations enables comparison between them.

Criteria related to investigation procedures

- *Disciplining*
  An investigation process should provide an orderly, systematic framework and set of procedures to discipline the investigators' tasks in order to focus their efforts on important and necessary tasks and avoid duplicative or irrelevant tasks.
- *Functional*
  An investigation process should be functional in order to make the job efficient, e.g. by helping the investigator to determine which events were part of the accident process as well as those events that were unrelated.
- *Definitive*
  An investigation process should provide criteria to identify and define the data that is needed to describe what happened.
- *Comprehensive*
  An investigation process should be comprehensive so there is no confusion about what happened, no unsuspected gaps or holes in the explanation, and no conflict of understanding among those who read the report.

Criteria related to output and usefulness

- *Direct*
  The investigation process should provide results that do not require collection of more data before the needed controls can be identified and changes made.
- *Understandable*
  The output should be readily understandable.
- *Satisfying*
  The results should be satisfying for those who initialised the investigation and other individuals that demand results from the investigations.

Some of these criteria are debatable. For instance will the second criterion related to causality be disputable. Investigators using the causal-sequence accident model will in principle focus on causes during their investigation process. Also the last criterion related to satisfaction might be discussed. Imagine an investigation initialised by the top management in a company. If the top management is criticised in the accident report, they are not necessarily satisfied with the results, but nevertheless it may be a “good” investigation.

3 The accident investigation process

Figure 5 shows the detailed accident investigation process as described by DOE (1999). As shown in the figure, the process starts immediately when an accident occurs, and the work is not finished before the final report is accepted by the appointing official. This report focuses on the process of analysing evidence to determine and evaluate causal factors (see chapter 4), but first a few comments to the other main phases.

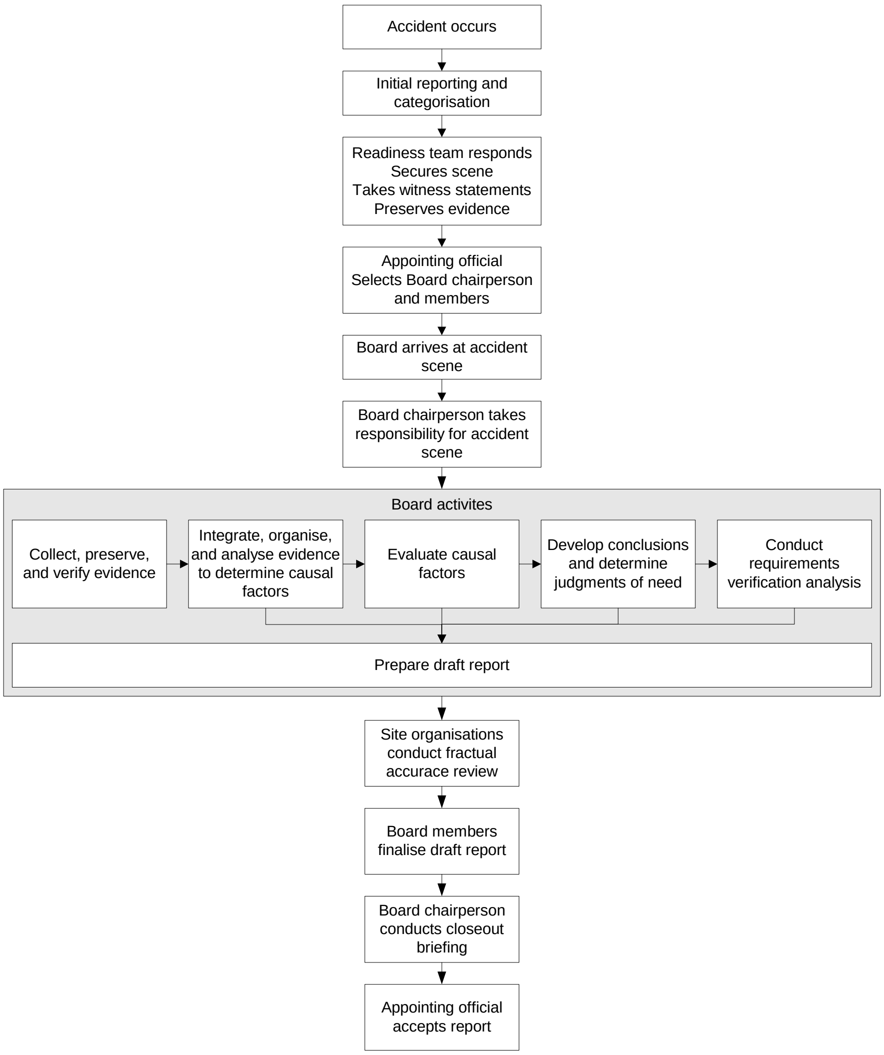


Figure 5. DOE's process for accident investigation (DOE, 1999).

3.1 Collecting evidence and facts

Collecting data is a critical part of the investigation. Three key types of evidence are collected during the investigation process:

- *Human or testamentary evidence*
  Human or testamentary evidence includes witness statements and observations.

- *Physical evidence*
  Physical evidence is matter related to the accident (e.g. equipment, parts, debris, hardware, and other physical items).

- *Documentary evidence*
  Documentary evidence includes paper and electronic information, such as records, reports, procedures, and documentation.

The major steps in gathering evidence are collecting human, physical and documentary evidence, examining organisational concerns, management systems, and line management oversight and at last preserving and controlling the collected evidence.

Collecting evidence can be a lengthy, time-consuming, and piecemeal process. Witnesses may provide sketchy or conflicting accounts of the accident. Physical evidence may be badly damaged or completely destroyed, Documentary evidence may be minimal or difficult to access. Thorough investigation requires that board members are diligent in pursuing evidence and adequately explore leads, lines of inquiry, and potential causal factors until they gain a sufficiently complete understanding of the accident.

This topic will not be discussed anymore in this report, but for those interested in the topic are the following references useful; DOE (1999), CCPS (1992) and Ingstad (1988).

3.2 Analysis of evidence and facts

Analysis of evidence and facts is the process of determining causal factors, identify latent conditions or contributing factors (or whatever you want to call it) and seeks to answer the following two questions:

- What happened where and when?
- Why did it happen?

DOE (1999) describes three types of causal factors:

1. Direct cause
2. Contributing causes
3. Root causes

A *direct cause* is an immediate event or condition that caused the accident (DOE, 1997). A *contributing cause* is an event or condition that together with other causes increase the likelihood of an accident but which individually did not cause the accident (DOE, 1997). A *root cause* is the causal factor(s) that, if corrected, would prevent recurrence of the accident (DOE, 1997).

There are different opinions of the concept of causality of accidents, see comments in section 1.2.1, but this topic will not be discussed any further here.

CCPS (1992) lists three analytical approaches by which conclusions can be reached about an accident:

- Deductive approach
- Inductive approach.
- Morphological approach

In addition, there exists different concepts for accident investigation not as comprehensive as these system-oriented techniques. These are categorized as non-system-oriented techniques.

The ***deductive approach*** involves reasoning from the general to the specific. In the deductive analysis, it is postulated that a system or process has failed in a certain way. Next an attempt is made to determine what modes of system, component, operator and organisation behaviour contribute to the failure. The whole accident investigation process is a typical example of a deductive reasoning. Fault tree analysis is also an example of a deductive technique.

The ***inductive approach*** involves reasoning from individual cases to a general conclusion. An inductive analysis is performed by postulating that a particular fault or initiating event has occurred. It is then determined what the effects of the fault or initiating event are on the system operation. Compared with the deductive approach, the inductive approach is an “overview” method. As such it bring an overall structure to the investigative process. To probe the details of the causal factors, control and barrier function, it is often necessary to apply deductive analysis. Examples of inductive techniques are failure mode and effects analysis (FMECA), HAZOP’s and event tree analysis.

The ***morphological approach*** to analytical incident investigation is based on the structure of the system being studied. The morphological approach focuses directly on potentially hazardous elements (for example operation, situations). The aim is to concentrate on the factors having the most significant influence on safety. When performing a morphological analysis, the analyst is primarily applying his or her past experience of incident investigation. Rather than looking at all possible deviations with and without a potential safety impact, the investigation focuses on known hazard sources. Typically, the morphological approach is an adaptation of deductive or inductive approaches, but with its own guidelines.

SINTEF has developed a useful five-step model for investigation of causes of accidents. The model is illustrated in Figure 6.

Step 1 is identification of the event sequences just before the accident. Step 2 is identification of deviations and failures influencing the event sequence that led to the accident. This includes deviations from existing procedures, deviations from common practice, technical failures and human failures. Step 3 is identification of weaknesses and defects with the management systems. The objective is to detect possible causes of the deviations or failures identified in Step 2. Step 4 is identification of weaknesses and defects related to the top management of the company, because it is their responsibility to establish the necessary management systems and ensure that the systems are complied with. Step 5 is identification of potential deficiencies related to the public safety framework, i.e. marked conditions, laws and regulations.

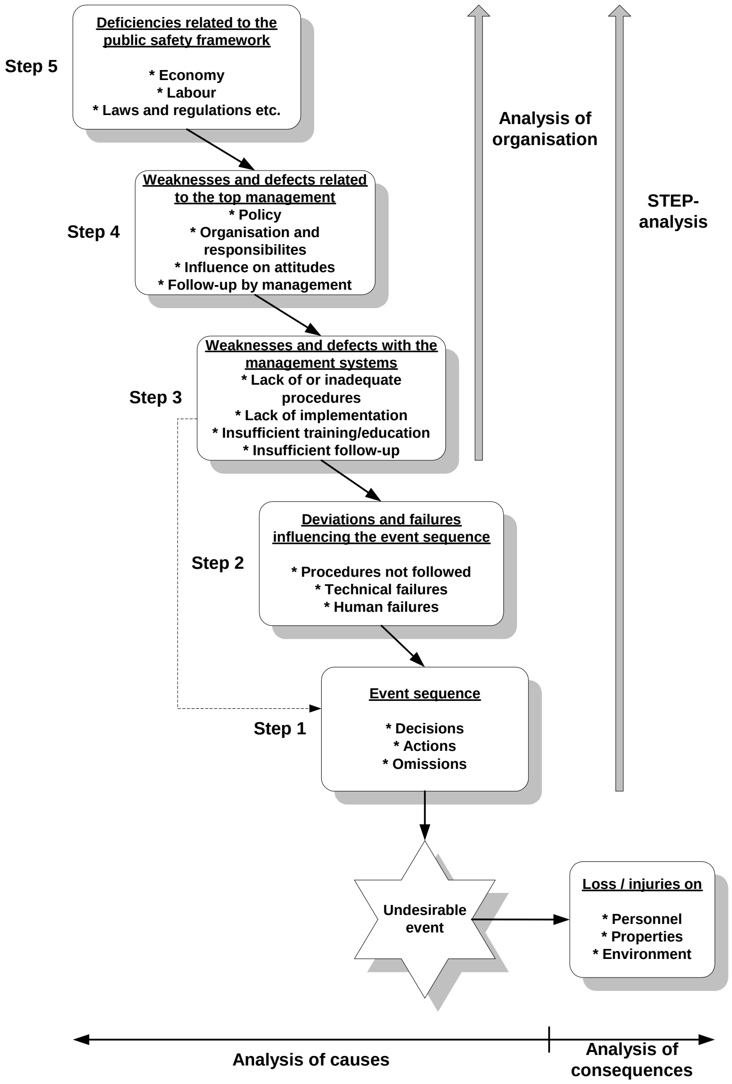


Figure 6. SINTEF's model for analysis of accident causes (Arbeidsmiljøsenteret, 2001).

Different methods for analysis of evidence and facts are further discussed in chapter 4.

3.3 Recommendations and reporting

One of the main objectives of performing accidents investigations is to identify recommendations that may prevent the occurrence of future accidents. This topic will not be discussed any further, but the recommendations should be based on the analysis of evidence and facts in order to prevent that the revealed direct and root causes might lead to future accidents. At the company level the recommended risk reducing measures might be focused on technical, human, operational and/or organisational factors. Often, it is even more important to focus attention towards changes in the higher levels in Figure 4, e.g., by changing the regulations or the authoritative supervisory practice. A useful tip is to be open-minded in the search for risk reducing measures and not to be narrow in this part of the work.

Hendrick and Benner (1987) says that two thoughts should be kept in mind regarding accident reports:

- Investigations are remembered trough their reports
- The best investigation will be wasted by a poor report.

4 Methods for accident investigations

A number of methods for accident investigation have been developed, with their own strengths and weaknesses. Some methods of great importance are selected for further examination in this chapter. The selection of methods for further description is not based on any scientific selection criteria. But the methods are widely used in practice, well acknowledged, well described in the literature[4] and some methods that are relatively recently developed.

In order to show the span in different accident investigation methods, Table 1 shows an oversight over methods described by DOE (1999) and Table 2 shows an oversight described by CCPS (1992). Some of the methods in the tables are overlapping, while some are different.

Table 1. Accident investigation analytical techniques presented in DOE (1999).

Core Analytical Techniques
Events and Causal Factors Charting and Analysis Barrier Analysis Change Analysis Root Cause Analysis
Complex Analytical Techniques *For complex accidents with multiple system failures, there may in addition be need of analytical techniques like analytic tree analysis, e.g.*
Fault Tree Analysis MORT (Management Oversight and Risk Tree) PET (Project Evaluation Tree Analysis)
Specific Analytical Techniques
Human Factors Analysis Integrated Accident Event Matrix Failure Modes and Effects Analysis Software Hazards Analysis Common Cause Failure Analysis Sneak Circuit Analysis 72-Hour Profile Materials and Structural Analysis Scientific Modelling (e.g., for incidents involving criticality and atmospheric despersion)

4 Some methods are commercialised and therefore limited described in the public available literature.

Table 2. Accident investigations methods described by CCPS (1992).

Investigation method
Accident Anatomy method (AAM)
Action Error Analysis (AEA)
Accident Evolution and Barrier Analysis (AEB)
Change Evaluation/Analysis
Cause-Effect Logic Diagram (CELD)
Causal Tree Method (CTM)
Fault Tree Analysis (FTA)
Hazard and Operability Study (HAZOP)
Human Performance Enhancement System (HPES)[1]
Human Reliability Analysis Event Tree (HRA-ET)
Multiple-Cause, Systems-oriented Incident Investigation (MCSOII)
Multilinear Events Sequencing (MES)
Management Oversight Risk Tree (MORT)
Systematic Cause Analysis Technique (SCAT)[1]
Sequentially Timed Events Plotting (STEP)
TapRoot™ Incident Investigation System[1]
Technique of Operations Review (TOR)
Work Safety Analysis

[1] Proprietary techniques that requires a license agreement.

These two tables list more than 20 different methods, but do not include a complete list of methods. Other methods are described elsewhere in the literature.

Since DOE's Workbook Conducting Accident Investigation (DOE, 1999) is a comprehensive and well-written handbook, the description of accident investigation methods starts with DOE's core analytical techniques in section 4.1. Their core analytical techniques are:

- Events and Causal Factors Charting and Analysis
- Barrier Analysis
- Change Analysis
- Root Cause Analysis

Further, some other methods are described in section 4.2:

- Fault tree analysis
- Event tree analysis
- MORT (Management Oversight and Risk Tree)

- SCAT (Systematic Cause Analysis Technique)
- STEP (Sequential Timed Events Plotting)
- MTO-analysis
- AEB Method
- TRIPOD-Delta
- Acci-Map

The four last methods are neither listed in Table 1 nor Table 2, but are commonly used methods in different industries in several European countries.

The readers should be aware of that this chapter is purely descriptive. Any comments or assessments of the methods are made in chapter 5.

4.1 DOE's core analytical techniques[5]

4.1.1 Events and causal factors charting (ECFC)

Events and causal factors charting is a graphical display of the accident's chronology and is used primarily for compiling and organising evidence to portray the sequence of the accident's events. The events and causal factor chart is easy to develop and provides a clear depiction of the data. Keeping the chart up-to-date helps insure that the investigation proceeds smoothly, that gaps in information are identified, and that the investigators have a clear representation of accident chronology for use in evidence collection and witness interviewing.

Events and causal factors charting is useful in identifying multiple causes and graphically depicting the triggering conditions and events necessary and sufficient for an accident to occur.

Events and causal factors analysis is the application of analysis to determine causal factors by identifying significant events and conditions that led to the accident. As the results from other analytical techniques are completed, they are incorporated into the events and causal factors chart. "Assumed" events and conditions may also be incorporated in the chart.

[5] The description of DOE's core analytic techniques is based on DOE, 1999.

DOE (1999) pinpoints some benefits of the event and causal factors charting:

- Illustrating and validating the sequence of events leading to the accident and the conditions affecting these events
- Showing the relationship of immediately relevant events and conditions to those that are associated but less apparent – portraying the relationships of organisations and individuals involved in the accident
- Directing the progression of additional data collection and analysis by identifying information gaps
- Linking facts and causal factors to organisational issues and management systems
- Validating the results of other analytic techniques
- Providing a structured method for collecting, organising, and integrating collected evidence
- Conveying the possibility of multiple causes
- Providing an ongoing method for organising and presenting data to facilitate communication among the investigators
- Clearly presenting information regarding the accident that can be used to guide report writing
- Providing an effective visual aid that summarises key information regarding the accident and its causes in the investigation report.

Figure 7 gives an overview over symbols used in an event and causal factor chart and some guidelines for preparing such a chart.

Symbols	Events Accidents Conditions Presumptive events Presumptive conditions or assumptions Connector Transfer between lines LTA Less than adequate (judgment)
Events	- Are active (e.g. "crane strikes building") - Should be stated using one noun and one active verb - Should be quantified as much as possible and where applicable - Should indicate the date and time, when they are known - Should be derived from the event or events and conditons immediately preceding it
Conditions	- Are passive (e.g. "fog in the area") - Describe states or circumstances rather than occurrences or events - As practical, should be quantified - Should indicate date and time if practical/applicable - Are associated with the corresponding event
Primary event sequence	Encompasses the main events of the accident and those that form the main events line of the chart
Secondary event sequence	Encompasses the events that are secondary or contributing events and those that form the secondary line of the chart

Figure 7. Guidelines and symbols for preparing an events and causal factors chart. (DOE, 1999)

Figure 8 shows an event and causal factors chart in general.

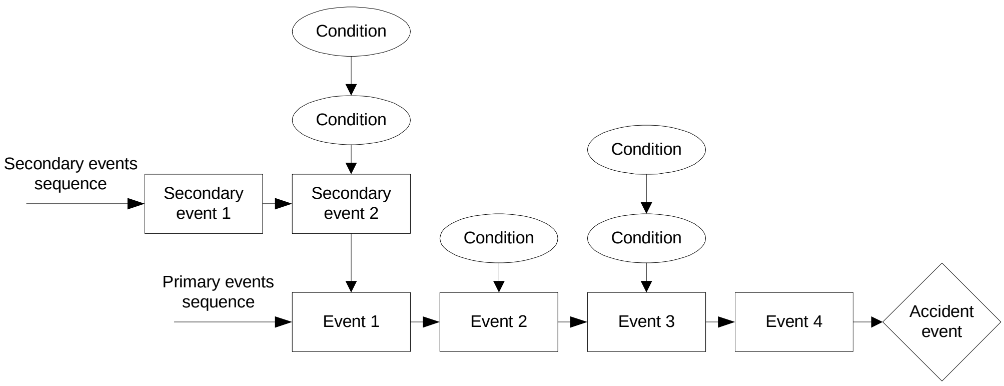


Figure 8. Simplified events and causal factors chart. (DOE, 1999)[6].

6 Similar to MES in Table 2.

4.1.2 Barrier analysis

Barrier analysis is used to identify hazards associated with an accident and the barriers that should have been in place to prevent it. A barrier is any means used to control, prevent, or impede the hazard from reaching the target.

Barrier analysis addresses:

- Barriers that were in place and how they performed
- Barriers that were in place but not used
- Barriers that were not in place but were required
- The barrier(s) that, if present or strengthened, would prevent the same or similar accidents from occurring in the future.

Figure 9 shows types of barriers that may be in place to protect workers from hazards.

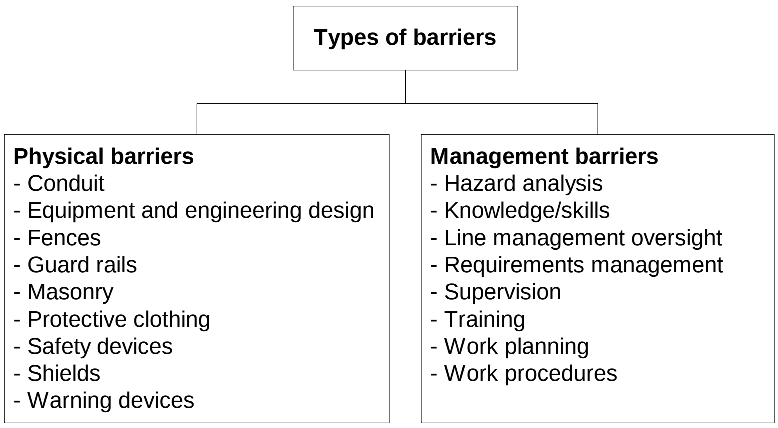


Figure 9. Examples on barriers to protect workers from hazards (DOE, 1999)[7]

Physical barriers are usually easy to identify, but management system barriers may be less obvious (e.g. exposure limits). The investigator must understand each barrier's intended function and location, and how it failed to prevent the accident. There exists different ways in

[7] There exists different barrier models for prevention of accidents based on the defence-in-depth principle in different industries, see. e.g. Kjellén (2000) for prevention of fires and explosions in hydrocarbon processing plants and INSAG-12 for basic safety principles for nuclear power plants.

which defences or barriers may be categorized, i.e. active or passive barriers (see e.g. Kjellén, 2000), hard or soft defences (see e.g. Reason, 1997), but this topic will not be discussed any further in this report.

To analyse management barriers, investigators may need to obtain information about barriers at three organisational levels responsible for the work; the activity, facility and institutional levels. For example, at the activity level, the investigator will need information about the work planning and control processes that governed the work activity, as well as the relevant safety management systems. The investigator may also need information about safety management systems at the facility level. The third type of information would be information about the institutional-level safety management direction and oversight provided by senior line management organisations.

The basic steps of a barrier analysis are shown in Figure 10. The investigator should use barrier analysis to ensure that all failed, unused, or uninstalled barriers are identified and that their impact on the accident is understood. The analysis should be documented in a barrier analysis worksheet. Table 3 illustrates a barrier analysis worksheet.

Basic Barrier Analysis steps

Step 1	Identify the hazard and the target. Record them at the top of the worksheet
Step 2	Identify each barrier. Record in column one.
Step 3	Identify how the barrier performed (What was the barrier's purpose? Was the barrier in place or not in place? Did the barrier fail? Was the barrier used if it was in place?) Record in column two.
Step 4	Identify and consider probable causes of the barrier failure. Record in column three.
Step 5	Evaluate the consequences of the failure in this accident. Record in column four.

Figure 10. Basic steps in a barrier analysis (DOE, 1999).

Table 3. Barrier analysis worksheet.

Hazard: 13.2 kV electrical cable		**Target: Acting pipefitter**	
What were the barriers?	***How did each barrier perform?***	***Why did the barrier fail?***	***How did the barrier affect the accident?***
Engineering drawings	Drawings were incomplete and did not identify electrical cable at sump location	Engineering drawings and construction specifications were not procured Drawings used were preliminary No as-built drawings were used to identify location of utility lines	Existence of electrical cable unknown
Indoor excavation permit	Indoor excavation permit was not obtained	Pipefitters and utility specialist were unaware of indoor excavation permit requirements	Opportunity to identify existence of cable missed

4.1.3 Change analysis

Change is anything that disturbs the “balance” of a system operating as planned. Change is often the source of deviations in system operations.

Change analysis examines planned or unplanned changes that caused undesired outcomes. In an accident investigation, this technique is used to examine an accident by analysing the difference between what has occurred before or was expected and the actual sequence of events. The investigator performing the change analysis identifies specific differences between the accident–free situation and the accident scenario. These differences are evaluated to determine whether the differences caused or contributed to the accident.

The change analysis process is described in Figure 11. When conducting a change analysis, investigators identify changes as well as the results of those changes. The distinction is important, because identifying only the results of change may not prompt investigators to identify all causal factors of an accident. When conducting a change analysis, it is important to have a baseline situation that the accident sequence may be compared to.

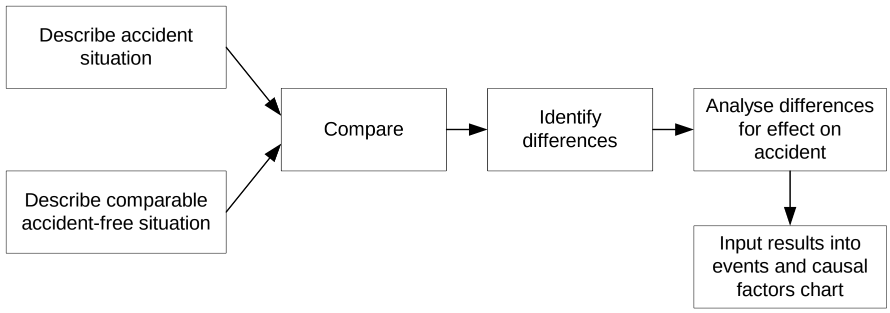


Figure 11. The change analysis process. (DOE, 1999)

Table 4 shows a simple change analysis worksheet. The investigators should first categorise the changes according to the questions shown in the left column of the worksheet, i.e., determine if the change pertained to, for example, a difference in:

- **What** events, conditions, activities, or equipment were present in the accident situation that were not present in the baseline (accident-free, prior, or ideal) situation (or vice versa)
- **When** an event or condition occurred or was detected in the accident situation versus the baseline situation
- **Where** an event or condition occurred in the accident situation versus where an event or condition occurred in the baseline situation
- **Who** was involved in planning, reviewing, authorising, performing, and supervising the work activity in the accident versus the accident-free situation.
- **How** the work was managed and controlled in the accident versus the accident-free situation.

To complete the remainder of the worksheet, first describe each event or condition of interest in the second column. Then describe the related event or condition that occurred (or should have occurred) in the baseline situation in the third column. The difference between the event and conditions in the accident and the baseline situations should be briefly described in the fourth column. In the last column, discuss the effect that each change had on the accident.

The differences or changes identified can generally be described as causal factors and should be noted on the events and causal factors chart and used in the root cause analysis.

A potential weakness of change analysis is that it does not consider the compounding effects of incremental change (for example, a change that was instituted several years earlier coupled with a more recent change). To overcome this weakness, investigators may choose more than one baseline situation against which to compare the accident scenario.

Table 4. A simple change analysis worksheet. (DOE, 1999)

Factors	***Accident situation***	***Prior, ideal, or accident-free situation***	***Difference***	***Evaluation of effect***
What Conditions Occurrences Activities Equipment				
When Occurred Identified Facility status Schedule				
Where Physical location Environmental conditions				
Who Staff involved Training Qualification Supervision				
How Control chain Hazard analysis Monitoring				
Other				

4.1.4 Events and causal factors analysis

The events and causal factors chart may also be used to determine the causal factors of an accident, as illustrated in Figure 12. This process is an important first step in later determining the root causes of an accident. Events and causal factors analysis requires deductive reasoning to determine which events and/or conditions that contributed to the accident.

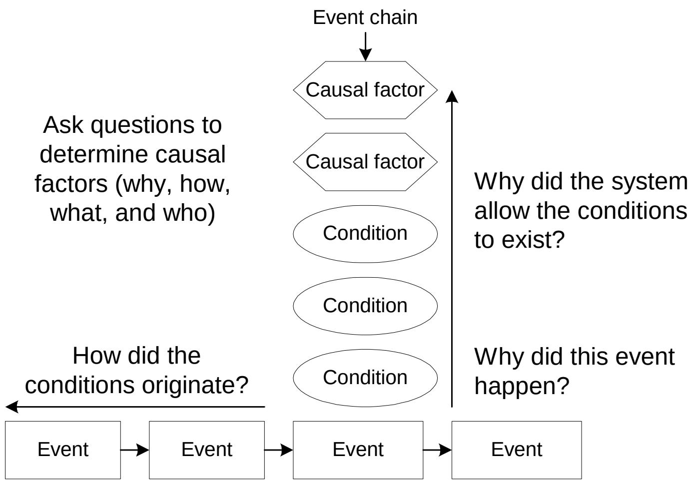


Figure 12. Events and causal factors analysis. (DOE, 1999)

Before starting to analyse the events and conditions noted on the chart, an investigator must first ensure that the chart contains adequate detail. Examine the first event that immediately precedes the accident. Evaluate its significance in the accident sequence by asking:

> *"If this event had not occurred, would the accident have occurred?"*

If the answer is yes, then the event is not significant. Proceed to the next event in the chart, working backwards from the accident. If the answer is no, then determine whether the event represented normal activities with the expected consequences. If the event was intended and had the expected outcomes, then it is not significant. However, if the event deviated from what was intended or had unwanted consequences, then it is a *significant event*.

Carefully examine the events and conditions associated with each significant event by asking a series of questions about this event chain, such as:

- Why did this event happen?
- What events and conditions led to the occurrence of the event?
- What went wrong that allowed the event to occur?
- Why did these conditions exist?
- How did these conditions originate?
- Who had the responsibility for the conditions?
- Are there any relationships between what went wrong in this event chain and other events or conditions in the accident sequence?
- Is the significant event linked to other events or conditions that may indicate a more general or larger deficiency?

The significant events, and the events and conditions that allowed the significant events to occur, are the accident's causal factors.

4.1.5 Root cause analysis

Root cause analysis is any analysis that identifies underlying deficiencies in a safety management system that, if corrected, would prevent the same and similar accidents from occurring. Root cause analysis is a systematic process that uses the facts and results from the core analytic techniques to determine the most important reasons for the accident. While the core analytic techniques should provide answers to questions regarding what, when, where, who, and how, root cause analysis should resolve the question why. Root cause analysis requires a certain amount of judgment.

A rather exhaustive list of causal factors must be developed prior to the application of root cause analysis to ensure that final root causes are accurate and comprehensive.

One method for root cause analysis described by DOE is TIER diagramming. TIER-diagramming is used to identify both the root causes of an accident and the level of line management that has the responsibility and authority to correct the accident's causal factors. The investigators use TIER-diagrams to hierarchically categorise the causal factors derived from the events and causal factors analysis.

Linkages among causal factors are then identified and possible root causes are developed. A different diagram is developed for each organisation responsible for the work activities associated with the accident.

The causal factors identified in the events and causal factors chart are input to the TIER-diagrams. Assess where each causal factor belong in the TIER-diagram. After arranging all the causal factors, examine the causal factors to determine whether there is linkage between two or more of them. Evaluate each of the causal factors statements if they are root causes of the accident. There may be more than one root cause of a particular accident.

Figure 13 shows an example on a TIER-diagram.

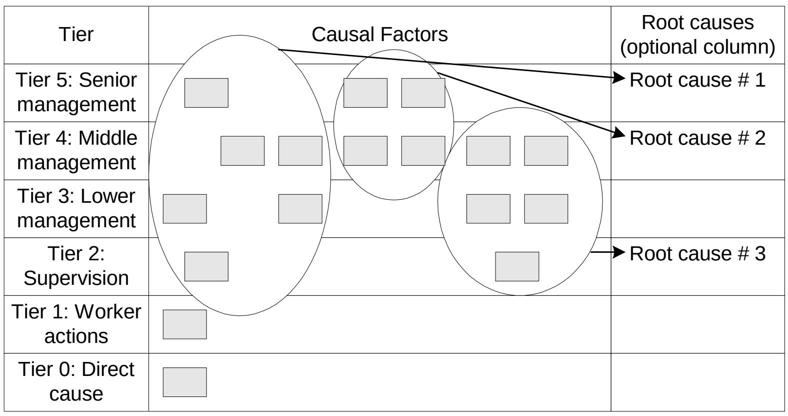


Figure 13. Identifying the linkages to the root causes from a TIER-diagram.

4.2 Other accident investigation methods

4.2.1 Fault tree analysis[8]

Fault tree analysis is a method for determining the causes of an accident (or top event). The fault tree is a graphic model that displays the various combinations of normal events, equipment failures, human errors, and environmental factors that can result in an accident. An example of a fault tree is shown in Figure 14.

[8] The description is based on Høyland & Rausand, 1994.

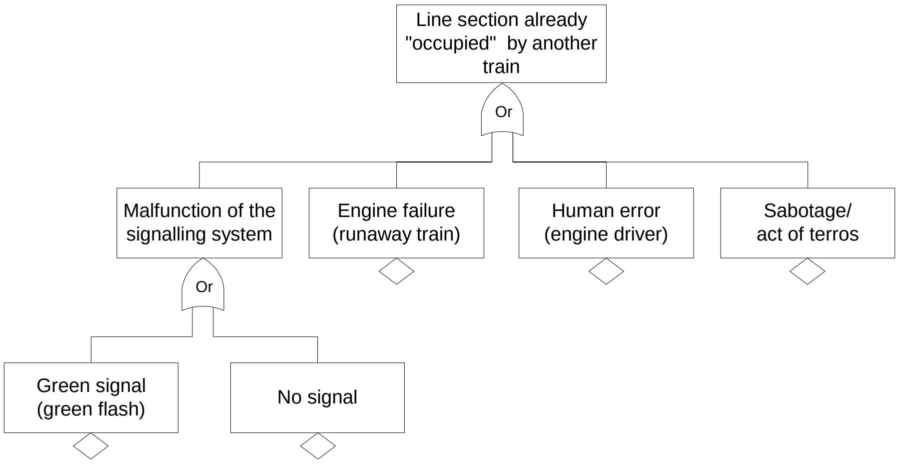


Figure 14. Illustration of a fault tree (example from the Åsta-accident).

A fault tree analysis may be qualitative, quantitative, or both. Possible results from the analysis may be a listing of the possible combinations of environmental factors, human errors, normal events and component failures that may result in a critical event in the system and the probability that the critical event will occur during a specified time interval.

The strengths of the fault tree, as a qualitative tool is its ability to break down an accident into root causes.

The undesired event appears as the top event. This event is linked to the basic failure events by logic gats and event statements. A gate symbol can have one or more inputs, but only one output. A summary of common fault tree symbols is given in Figure 15. Høyland and Rausand (1994) give a more detailed description of fault tree analysis.

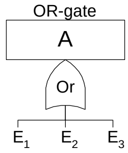
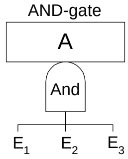
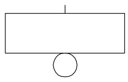
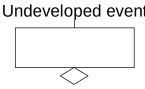
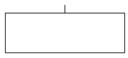
	Symbol	Description
Logic gates	OR-gate 	The OR-gate indicates that the output event A occurs if any of the input events E_i occur.
	AND-gate 	The AND-gate indicates that the output event A occurs when all the input events E_i occur simultaneously.
Input events	Basic event 	The basic event represents a basic equipment failure that requires no further development of failure causes
	Undeveloped event 	The undeveloped event represents an event that is not examined further because information is unavailable or because its consequences is insignificant
Description of state	Comment rectangle 	The comment rectangle is for supplementary information
Transfer symbols	Transfer-out 	The transfer-out symbol indicates that the fault tree is developed further at the occurrence of the corresponding
	Transfer-in 	Transfer-in symbol

Figure 15. Fault tree symbols.

4.2.2 Event tree analysis[9]

An event tree is used to analyse event sequences following after an initiating event. The event sequence is influenced by either success or failure of numerous barriers or safety functions/systems. The event sequence leads to a set of possible consequences. The consequences may be considered as acceptable or unacceptable. The event sequence

9 The description is based on Villemeur, 1991.

is illustrated graphically where each safety system is modelled for two states, operation and failure.

Figure 16 illustrates an event tree of the situation on Rørosbanen just before the Åsta-accident. This event tree reveals the lack of reliable safety barriers in order to prevent train collision at Rørosbanen at that time.

An event tree analysis is primarily a proactive risk analysis method used to identify possible event sequences. The event tree may be used to identify and illustrate event sequences and also to obtain a qualitative and quantitative representation and assessment. In an accident investigation we may illustrate the accident path as one of the possible event sequences. This is illustrated with the thick line in Figure 16.

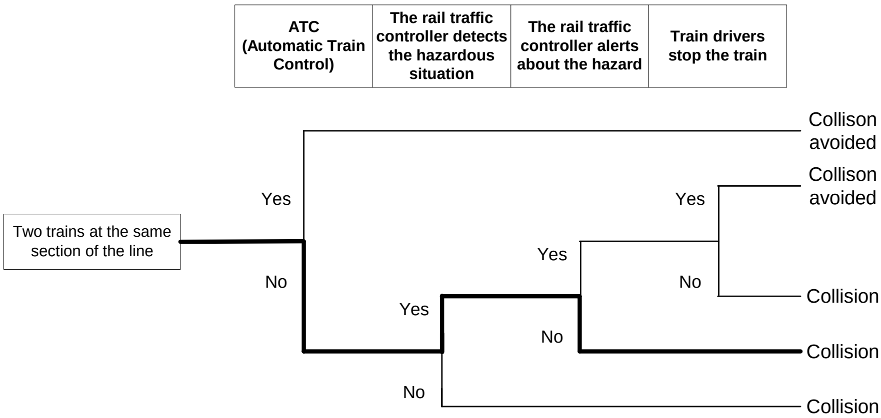


Figure 16. Simplified event tree analysis of the risk at Rørosbanen just before the Åsta-accident.

4.2.3 MORT[10]

MORT provides a systematic method (analytic tree) for planning, organising, and conduction a comprehensive accident investigation. Through MORT analysis, investigators identify deficiencies in specific

10 The description is based on Johnson W.G., 1980.

control factors and in management system factors. These factors are evaluated and analysed to identify the causal factors of the accident.

Basically, MORT is a graphical checklist in which contains generic questions that investigators attempt to answer using available factual data. This enables investigators to focus on potential key causal factors. The upper levels of the MORT diagram are shown in Figure 17.

MORT requires extensive training to effectively perform an in-depth analysis of complex accidents involving multiple systems. The first step of the process is to select the MORT chart for the safety program area of interest. The investigators work their way down through the tree, level by level. Events should be coded in a specific colour relative to the significance of the accident. An event that is deficient, or Less Than Adequate (LTA) in MORT terminology is marked red. The symbol is circled if suspect or coded in red if confirmed. An event that is satisfactory is marked green in the same manner. Unknowns are marked in blue, being circled initially and coloured if sufficient data do not become available, and an assumption must be made to continue or conclude the analysis.

When the appropriate segments of the tree have been completed, the path of cause and effect (from lack of control by management, to basic causes, contributory causes, and root causes) can easily be traced back through the tree. The tree highlights quite clearly where controls and corrective actions are needed and can be effective in preventing recurrence of the accident.

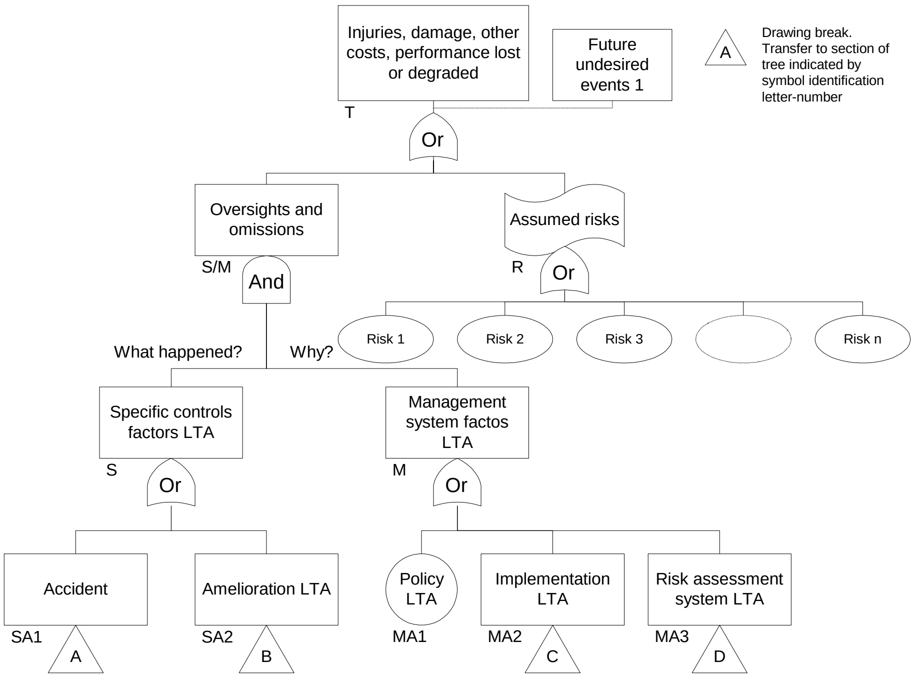


Figure 17. The upper levels of the MORT-tree.

PET (Project Evaluation Tree) and SMORT (Safety Management and Organisations Review Technique) are both methods based on MORT but simplified and easier to use. PET and SMORT will not be described further. PET is described by DOE (1999) and SMORT by Kjellén et al (1987).

4.2.4 Systematic Cause Analysis Technique (SCAT)[11]

The International Loss Control Institute (ILCI) developed SCAT for the support of occupational incident investigation. The ILCI Loss Causation Model is the framework for the SCAT system (see Figure 18).

[11] The description of SCAT is based on CCPS (1992) and the description of the ILCI-model is based on Bird & Germain (1985).

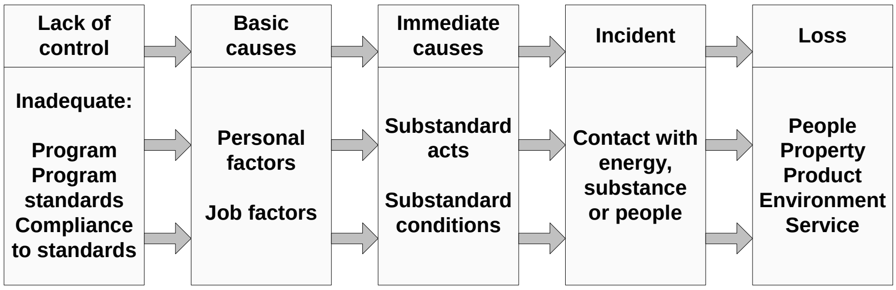


Figure 18. The ILCI Loss Causation Model (Bird and Germain, 1985).

The result of an accident is loss, e.g. harm to people, properties, products or the environment. The incident (the contact between the source of energy and the "victim") is the event that precedes the loss. The immediate causes of an accident are the circumstances that immediately precede the contact. They usually can be seen or sensed. Frequently they are called unsafe acts or unsafe conditions, but in the ILCI-model the terms substandard acts (or practices) and substandard conditions are used. Substandard acts and conditions are listed in Figure 19.

Substandard practices/acts	Substandard conditions
1. Operating equipment without authority 2. Failure to warn 3. Failure to secure 4. Operating at improper speed 5. Making safety devices inoperable 6. Removing safety devices 7. Using defective equipment 8. Using equipment improperly 9. Failing to use personal protective equipment 10. Improper loading 11. Improper placement 12. Improper lifting 13. Improper position for task 14. Servicing equipmnet in operation 15. Horseplay 16. Under influence of alcohol/drugs	1. Inadequate guards or barriers 2. Inadequate or improper protective equipment 3. Defective tools, equipment or materials 4. Congestion or restricted action 5. Inadequate warning system 6. Fire and explosion hazards 7. Poor housekeeping, disorderly workplace 8. Hazardous environmental conditions 9. Noise exposures 10. Radiation exposures 11. High or low temperature exposures 12. Inadequate or excessive illumination 13. Inadequate ventilation

Figure 19. Substandard acts and conditions in the ILCI-model.

Basic causes are the diseases or real causes behind the symptoms, the reasons why the substandard acts and conditions occurred. Basic causes help explain why people perform substandard practices and why substandard conditions exists. An overview of personal and job factors are given in Figure 20.

Personal factors	Job factors
1. Inadequate capability - Physical/physiological - Mental/psychological 2. Lack of knowledge 3. Lack of skill 4. Stress - Physical/physiological - Mental/psychologica 5. Improper motivation	1. Inadequate leadership and/or supervision 2. Inadequate engineering 3. Inadequate purchasing 4. Inadequate maintenance 5. Inadequate tools, equipment, materials 6. Inadequate work standards 7. Wear and tear 8. Abuse or misuse

Figure 20. Personal and job factors in the ILCI-model.

There are three reasons for lack of control:

1. Inadequate program
2. Inadequate program standards and
3. Inadequate compliance with standards

Figure 21 shows the elements that should be in place in a safety program. The elements are based on research and experience from successful safety programs in different companies.

Elements in a safety program	
1. Leadership and administration	11. Personal protective equipment
2. Management training	12. Health control
3. Planned inspection	13. Program evaluation system
4. Task analysis and procedures	14. Engineering controls
5. Accident/incident investigation	15. Personal communications
6. Task observations	16. Group meetings
7. Emergency preparedness	17. General promotion
8. Organisational rules	18. Hiring and placement
9. Accident/incident analysis	19. Purchasing controls
10. Employee training	20. Off-the-job safety

Figure 21. Elements in a safety program in the ILCI-model.

The Systematic Cause Analysis Technique is a tool to aid an investigation and evaluation of incidents through the application of a SCAT chart. The chart acts as a checklist or reference to ensure that an investigation has looked at all facets of an incident. There are five blocks on a SCAT chart. Each block corresponds to a block of the loss causation model. Hence, the first block contains space to write a description of the incident. The second block lists the most common categories of contact that could have led to the incident under investigation. The third block lists the most common immediate causes, while the fourth block lists common basic causes. Finally, the bottom block lists activities generally accepted as important for a successful loss control program. The technique is easy to apply and is supported by a training manual.

The SCAT seems to correspond to the SYNERGI tool for accident registration used in Norway. At least, the accident causation models used in SCAT and SYNERGI are equivalent.

4.2.5 STEP (Sequential timed events plotting)[12]

The STEP-method was developed by Hendrick and Benner (1987).

They propose a systematic process for accident investigation based on multi-linear events sequences and a process view of the accident phenomena.

STEP builds on four concepts:

1. Neither the accident nor its investigation is a single linear chain or sequence of events. Rather, several activities take place at the same time.
2. The event Building Block format for data is used to develop the accident description in a worksheet. A building block describes one event, i.e. one actor performing one action.
3. Events flow logically during a process. Arrows in the STEP worksheet illustrate the flow.
4. Both productive and accident processes are similar and can be understood using similar investigation procedures. They both involve actors and actions, and both are capable of being repeated once they are understood.

With the process concept, a specific accident begins with the action that started the transformation from the described process to an

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[12] The description is based on Hendrick & Benner, 1987.

accident process, and ends with the last connected harmful event of that accident process.

The STEP-worksheet provides a systematic way to organise the building blocks into a comprehensive, multi-linear description of the accident process. The STEP-worksheet is simply a matrix, with rows and columns. There is one row in the worksheet for each actor. The columns are labelled differently, with marks or numbers along a time line across the top of the worksheet, as shown in Figure 22. The time scale does not need to be drawn on a linear scale, the main point of the time line is to keep events in order, i.e., how they relate to each other in terms of time.

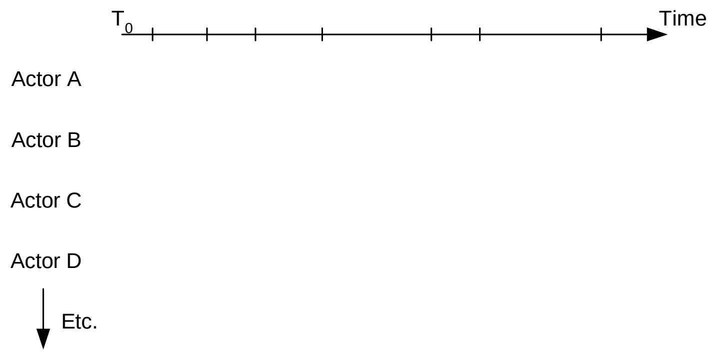

Figure 22. STEP-worksheet.

An event is one actor performing one action. An actor is a person or an item that directly influences the flow or events constituting the accident process. Actors can be involved in two types of changes, adaptive changes or initiating changes. They can either change reactively to sustain dynamic balance or they can introduce changes to which other actors must adapt. An action is something done by the actor. It may be physical and observable, or it may be mental if the actor is a person. An action is something that the actor does and must be stated in the active voice.

The STEP worksheet provides a systematic way to organise the building blocks (or events) into a comprehensive, multi-linear description of the accident process. Figure 23 shows an example on a

STEP-diagram of an accident where a stone block falls off a truck and hits a car[13].

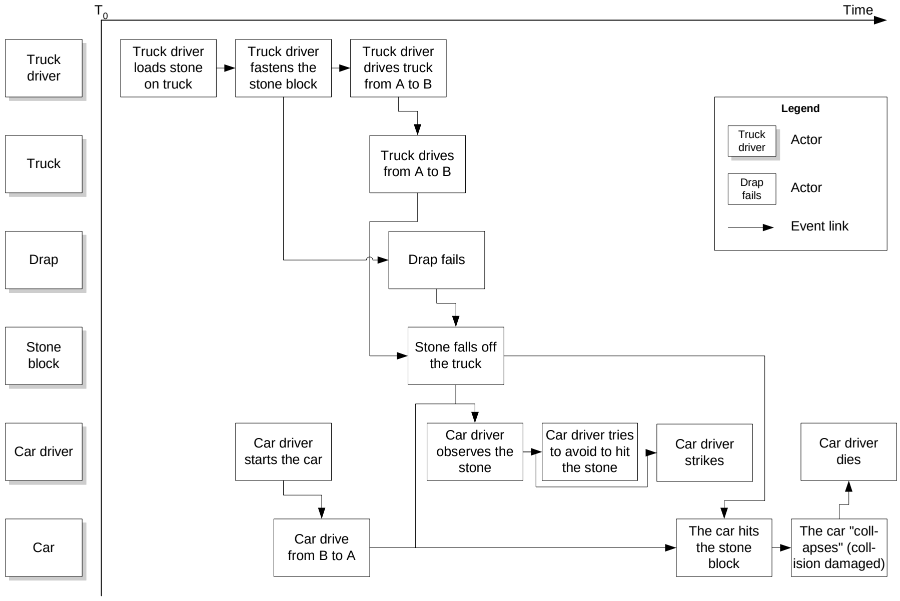

Figure 23. An example on a simple STEP-diagram for a car accident.

The STEP-diagram in Figure 23 also shows the use of arrows to link tested relationships among events in the accident chain. An arrow convention is used to show precede/follow and logical relations between two or more events. When an earlier action is necessary for a latter to occur, an arrow should be drawn from the preceding event to the resultant event. The thought process for identifying the links between events is related to the change of state concepts underlying STEP methods. For each event in the worksheet, the investigator asks, “Are the preceding actions sufficient to initiate this actions (or event) or were other actions necessary?” Try to visualize the actors and actions in a “mental movie” in order to develop the links.

Sometimes it is important to determine what happened during a gap or time interval for which we cannot gather any specific evidence. Each remaining gap in the worksheet represents a gap in the understanding of the accident. ***BackSTEP*** is a technique by which you reason your way backwards from the event on the right side of the worksheet gap

13 The STEP-diagram is based on a description of the accident in a newspaper article.

toward the event on the left side of the gap. The BackSTEP procedure consists of asking a series of “What could have led to that?” questions and working backward through the pyramid with the answers. Make tentative event building blocks for each event that answers the question. When doing a BackSTEP, it is not uncommon to identify more than one possible pathway between the left and right events at the gap. This tells that there may be more than one way the accident process could progress and may led to development of hypothesis in which should be further examined.

The STEP-procedure also includes some rigorous technical truth-testing procedures, the row test, the column test, and the necessary-and-sufficient test.

The ***row (or horizontal) test*** tells you if you need more building blocks for any individual actor listed along the left side of the worksheet. It also tells you if you have broken each actor down sufficiently.

The ***column (or vertical) test*** checks the sequence of events by pairing the new event with the actions of other actors. To pass the column test, the event building block being tested must have occurred

- After all the event in all the columns to the left of that event,
- Before all the events in all columns to the right of that event, and
- At the same time as all the events in the same column.

The row test and the column test are illustrated in Figure 24.

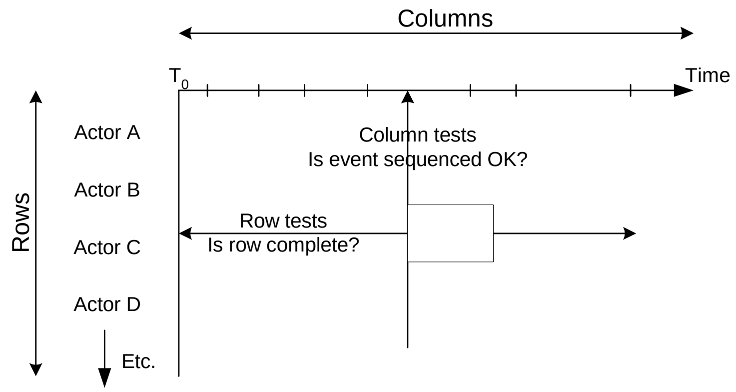

Figure 24. Worksheet row test and column test.

The ***necessary-and-sufficient test*** is used when you suspect that actions by one actor triggered subsequent actions by another actor on the worksheet, and after you have tested their sequencing. The question is whether the earlier action was indeed sufficient by itself to produce the later event or whether other actions were also necessary. If the earlier action was sufficient, you probably have enough data. If the earlier action does not prove sufficient to produce the later event, then you should look for the other actions that were necessary in order for the event to occur.

The STEP methodology also includes a recommended method for identification of safety problems and development of safety recommendations. The ***STEP event set approach*** may be used to identify safety problems inherent in the accident process. With this approach, the analyst simply proceeds through the worksheet one block at a time and an arrow at a time to find event sets that constitute safety problems, as determined by the effect the earlier event had on the later event. In the original STEP framework those, which warrant safety action, are converted to statements on need, in which are evaluated as candidate recommendations for corrective action. These are marked with diamonds in the STEP worksheet. A somewhat different approach has been applied by SINTEF in their accident investigation. The safety problems are marked as triangles in the worksheet (see Figure 25). These safety problems are further analysed in separate analyses. As Figure 25 illustrates, a STEP-diagram is a useful tool in order to identify possible safety problems.

The STEP change analysis procedure in which includes five related activities may be used for evaluation of safety countermeasures:

1. Identification of possible counterchanges
2. A ranking of the safety effects of the counterchanges
3. An assessment of the tradeoffs involved
4. Selection of the best recommendations
5. A final quality check of the selected recommendations

Development of risk reducing measures fell outside the scope of this report and this procedure is not described in this report.

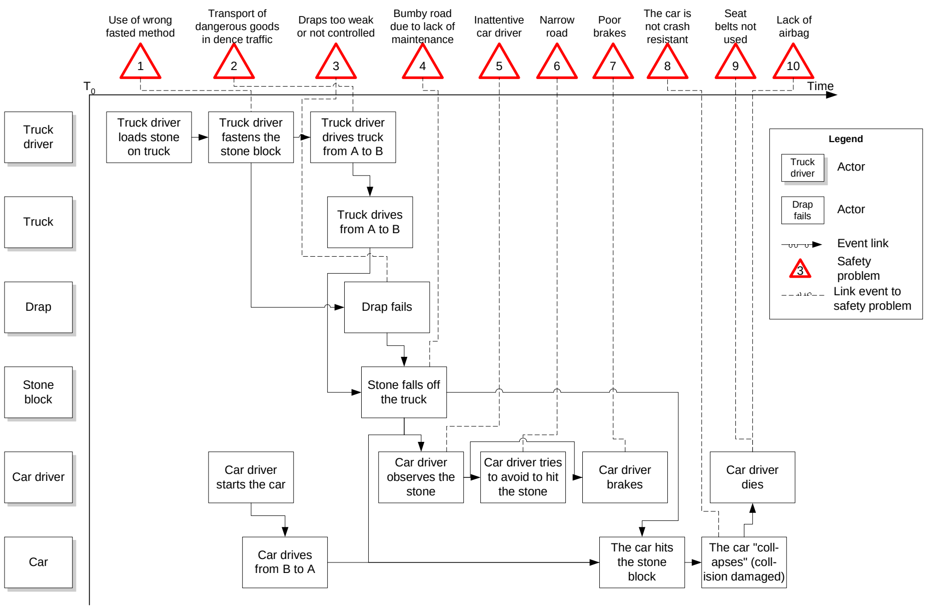

Figure 25. Step worksheet with safety problems.

Regarding the term cause, Hendrick and Benner (1987) say that you will often be asked to identify the cause of the accident. Based on the STEP worksheet, we see that the accident was actually a number of event pairs. How to select one event pair and label it "the cause" of the accident? Selection of one problem as the cause will focus attention on that one problem. If we are able to list multiple causes or cause factors, we may be able to call attention to several problems needing correction. If possible, leave the naming of causes to someone else who finds a need to do that task, like journalists, attorneys, expert witnesses, etc., and focus on the identified safety problems and the recommendations from the accident investigation.

4.2.6 MTO-analysis[14] [15]

The basis for the MTO[16]-analysis is that human, organisational, and technical factors should be focused equally in an accident

14 The descripton is based on Rollenhagen, 1995 and Bento, 1999.

15 The MTO-analysis has been widely used in the Norwegian offshore industry recently, but it has been difficult to obtain a comprehensive description of the method.

16 MTO ~ (Hu)Man, Technology and Organisation (Menneske, Teknologi og Organisasjon)

investigation. The method is based on HPES (Human Performance Enhancement System) which is mentioned in Table 2, but not described further in this report.

The MTO-analysis is based on three methods:

1. Structured analysis by use of an event- and cause-diagram[17].
2. Change analysis by describing how events have deviated from earlier events or common practice[18].
3. Barrier analysis by identifying technological and administrative barriers in which have failed or are missing[19].

Figure 26 illustrates the MTO-analysis worksheet.

The first step in an MTO-analysis is to develop the event sequence longitudinally and illustrate the event sequence in a block diagram. Identify possible technical and human causes of each event and draw these vertically to each event in the diagram.

Further, analyse which technical, human or organisational barriers that have failed or was missing during the accident progress. Illustrate all missing or failed barriers below the events in the diagram.

Assess which deviations or changes in which differ the accident progress from the normal situation. These changes are also illustrated in the diagram (see Figure 26).

The basic questions in the analysis are:

- What may have prevented the continuation of the accident sequence?
- What may the organisation have done in the past in order to prevent the accident?

The last important step in the MTO-analysis is to identify and present recommendations. The recommendations should be as realistic and specific as possible, and might be technical, human or organisational.

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17 See subsection 4.1.1.
18 See subsection 4.1.3.
19 See subsection 4.1.2.

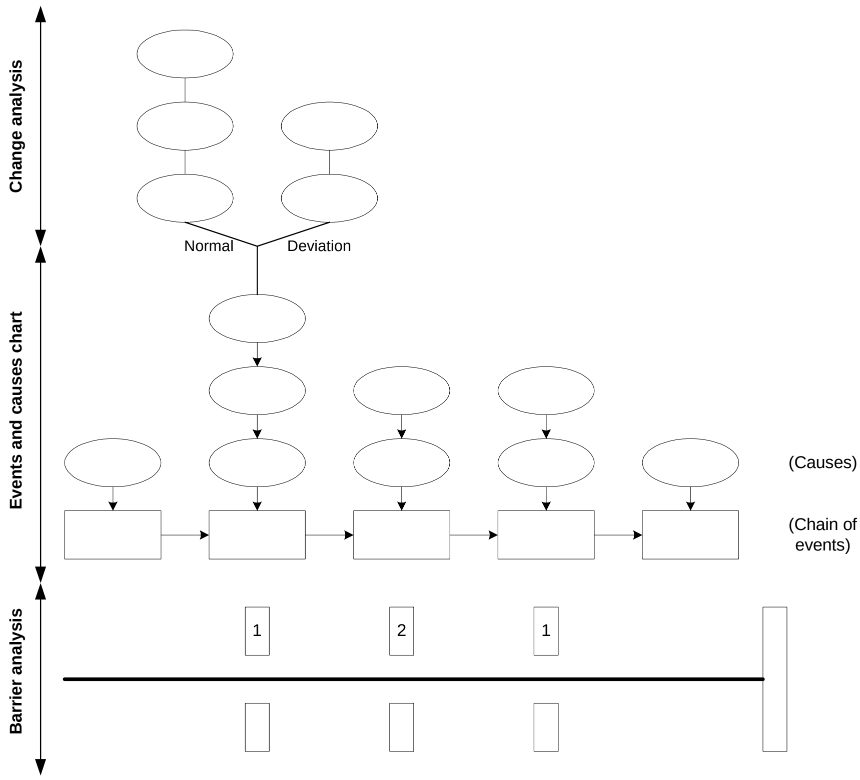

Figure 26. MTO-analysis worksheet.

A checklist for identification of failure causes (“felorsaker”) is also part of the MTO-methodology (Bento, 1999). The checklist contains the following factors:

1. Organisation
2. Work organisation
3. Work practice
4. Management of work
5. Change procedures
6. Ergonomic / deficiencies in the technology
7. Communication
8. Instructions/procedures
9. Education/competence
10. Work environment

For each of these failure causes, there is a detailed checklist for basic or fundamental causes ("grundorsaker"). Examples on basic causes for the failure cause work practice are:

- Deviation from work instruction
- Poor preparation or planning
- Lack of self inspection
- Use of wrong equipment
- Wrong use of equipment

4.2.7 Accident Analysis and Barrier Function (AEB) Method[20]

The Accident Evolution and Barrier Function (AEB) model provides a method for analysis of incidents and accidents that models the evolution towards an incident/accident as a series of interactions between human and technical systems. The interaction consists of failures, malfunctions or errors that could lead to or have resulted in an accident. The method forces analysts to integrate human and technical systems simultaneously when performing an accident analysis starting with the simple flow chart technique of the method.

The flow chart initially consists of empty boxes in two parallel columns, one for the human systems and one for the technical systems. Figure 27 provides an illustration of this diagram. During the analysis these error boxes are identified as the failures, malfunctions or errors that constitute the accident evolution. In general, the sequence of error boxes in the diagram follows the time order of events. Between each pair of successive error boxes there is a possibility to arrest the evolution towards an incident/accident. Barrier function systems (e.g. computer programs) that are activated can arrest the evolution through effective barrier functions (e.g. the computer making an incorrect human intervention modelled in the next error box impossible through blocking a control).

Factors that have an influence on human performance have been called ***performance shaping factors*** (by Swain and Guttman, 1983). Examples of such factors are alcohol, lack of sleep and stress. In application of the AEB model those factors are included in the flow

[20] The description is based on Svensson, 2000.

diagram only as PSFs and they are analysed after the diagram has been completed. PSFs are included in the flow diagram in cases where it is possible that the factor could have contributed to one or more human error events. Factors such as alcohol and age are modelled as PSFs, but never as human error events or failing barrier functions. Organisational factors may be integrated as a barrier function with failing or inadequate barrier functions. Organisational factors should always be treated in a special way in an AEB analysis because they include both human and technical systems.

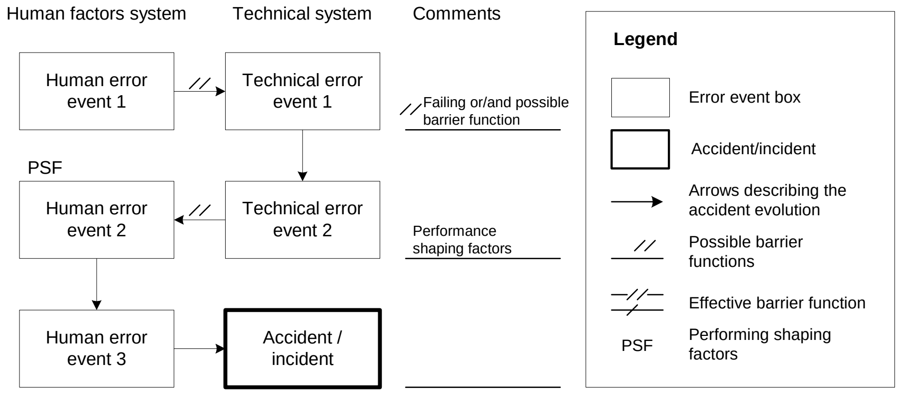

Figure 27. Illustration of an AEB analysis.

An AEB analysis consists of two main phases. The first phase is to model the accident evolution in a flow diagram. It is important to remember that AEB only models errors and that it is not an event sequence method. Arrows link the error event boxes together in order to show the evolution. The course of events is described in an approximate chronological order. It is not allowed to let more than one arrow lead to an error box or to have more than one arrow going from a box.

The second phase consists of the barrier function analysis. In this phase, the barrier functions are identified (ineffective and/or non existent). A barrier function represents a function that can arrest the accident evolution so that the next event in the chain will not be realised. A barrier function is always identified in relation to the systems it protects, protected or could have protected. Barrier function systems are the systems performing the barrier functions. Barrier function systems can be an operator, an instruction, a physical separation, an emergency control system, other safety-related systems, etc. The same barrier function can be performed by different barrier function systems. Correspondingly, a barrier function system may perform different barrier functions.

An important purpose of the AEB-analysis is to identify broken barrier functions, the reasons for why there were no barrier functions or why the existing ones failed, and to suggest improvements.

Barrier functions belong to one of the three main categories:

- ***Ineffective barrier functions*** – barrier functions that were ineffective in the sense that they did not prevent the development toward an accident
- ***Non-existing barrier functions*** – barrier functions that, if present, would have stopped the accident evolution.
- ***Effective barrier functions*** – barrier functions that actually prevented the progress toward an accident.

If a particular accident should happen, it is necessary that all barrier functions in the sequence are broken and ineffective. The objective of an AEB-analysis is to understand why a number of barrier functions failed, and how they could be reinforced or supported by other barrier functions. From this perspective, identification of a root-cause of an accident is meaningless. The starting point of the analysis cannot be regarded as the root cause because the removal of any of all the other errors in the accident evolution would also eliminate the accident.

It is sometimes difficult to know if an error should be modelled as an error or as a failing barrier function. As a rule of thumb, when uncertain the analysts should choose a box and not a barrier function representation in the initial AEB-analysis.

The barrier function analysis phase may be used for modelling of subsystems interactions that cannot be represented sequentially in AEB.

All barriers function failures, incidents and accidents take place in man – technology – organisations contexts. Therefore, an AEB-analysis also includes issues about the context in which the accident took place. Therefore, the following questions have to be answered:

1. To increase safety, how is it possible to *change the organisation*, in which the failure or accident took place?
2. To increase safety, how is it possible to *change the technical systems context,* in which the failure or accident took place?

It is important to bear in mind that when changes are made in the organisational and technical systems at the context level far reaching effects may be attained.

4.2.8 TRIPOD[21]

The whole research into the TRIPOD concept started in 1988 when a study that was contained in the report "TRIPOD, A principled basis for accident prevention" (Reason et al, 1988) was presented to Shell Internationale Petroleum Maatschappij, Exploration and Production. The idea behind TRIPOD is that organisational failures are the main factors in accident causation. These factors are more "latent" and, when contributing to an accident, are always followed by a number of technical and human errors.

The complete TRIPOD-model[22] is illustrated in Figure 28.

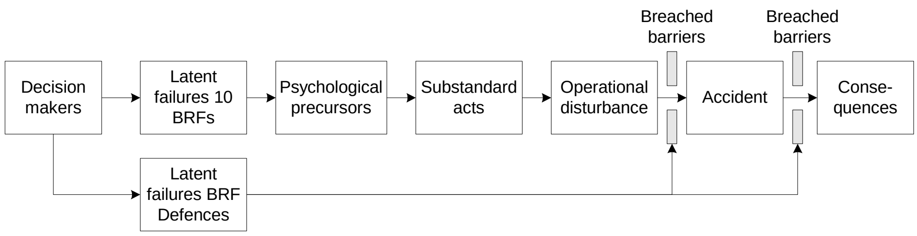

Figure 28. The complete TRIPOD model.

Substandard acts and situations do not just occur. They are generated by mechanisms acting in organisations, regardless whether there has been an accident or not. Often these mechanisms result from decisions

21 This description is based on Groeneweg, 1998.

22 The TRIPOD-model described here might be different from previously published models based on the TRIPOD theory, but this model is fully compatible with the most resent version of the accident investigation tool TRIPOD Beta described later in this chapter.

taken at high level in the organisation. These underlying mechanisms are called Basic Risk Factors[23] (BSFs). These BSFs may generate various psychological precursors in which may lead to substandard acts and situations. Examples on psychological precursors of slips, lapses and violations are time pressure, being poorly motivated or depressed. According to this model, eliminating the latent failures categorized in BRFs or reducing their impact will prevent psychological precursors, substandard acts and the operational disturbances. Furthermore, this will result in prevention of accidents.

The identified BRFs cover human, organisational and technical problems. The different Basic Risk Factors are defined in Table 5. Ten of these BRFs leading to the “operational disturbance” (the “preventive” BRFs), and one BRF is aimed at controlling the consequences once the operational disturbance has occurred (the “mitigation” BRF). There are five generic prevention BRFs (6 – 10 in Table 5) and five specific BRFs (1 – 5 in Table 5). The specific BRFs relate to latent failures that are specific for the operations to be investigated (e.g. the requirements for Tools and Equipment are quite different in a oil drilling environment compared to an intensive care ward in a hospital).

These 11 BRFs have been identified as a result of brainstorming, a study of audit reports, accident scenarios, a theoretical study, and a study on offshore platforms. The division is definitive and has shown to be valid for all industrial applications.

23 These mechanisms were initially called General Failure Types (GFTs).

Table 5. The definitions of the basic risk factors (BRFs) in TRIPOD.

No	Basic Risk Factor	Abbr.	Definition
1	Design	DE	Ergonomically poor design of tools or equipment (user-unfriendly)
2	Tools and equipment	TE	Poor quality, condition, suitability or availability of materials, tools, equipment and components
3	Maintenance management	MM	No or inadequate performance of maintenance tasks and repairs
4	Housekeeping	HK	No or insufficient attention given to keeping the work floor clean or tidied up
5	Error enforcing conditions	EC	Unsuitable physical performance of maintenance tasks and repairs
6	Procedures	PR	Insufficient quality or availability of procedures, guidelines, instructions and manuals (specifications, "paperwork", use in practice)
7	Training	TR	No or insufficient competence or experience among employees (not sufficiently suited/inadequately trained)
8	Communication	CO	No or ineffective communication between the various sites, departments or employees of a company or with the official bodies
9	Incompatible goals	IG	The situation in which employees must choose between optimal working methods according to the established rules on one hand, and the pursuit of production, financial, political, social or individual goals on the other
10	Organisation	OR	Shortcomings in the organisation's structure, organisation's philosophy, organisational processes or management strategies, resulting in inadequate or ineffective management of the company
11	Defences	DF	No or insufficient protection of people, material and environment against the consequences of the operational disturbances

TRIPOD Beta

The TRIPOD Beta-tool is a computer-based instrument that provides the user with a tree-like overview of the accident that was investigated. It is a menu driven tool that will guide the investigator through the process of making an electronic representation of the accident.

The BETA-tool merges two different models, the HEMP (The Hazard and Effects Management Process) model and the TRIPOD model. The merge has resulted in an incident causation model that differs conceptually from the original TRIPOD model. The HEMP model is presented in Figure 29.

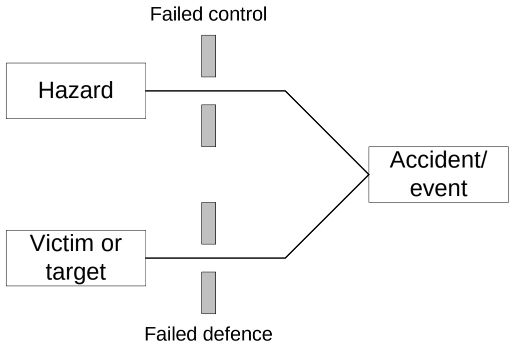

Figure 29. “Accident mechanism” according to HEMP.

The TRIPOD Beta accident causation model is presented in Figure 30. This string is used to identify the causes that lead to the breaching of the controls and defences presented in the HEMP model.

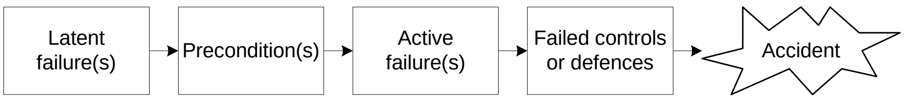

Figure 30. TRIPOD Beta Accident Causation Model.

Although the model presented in Figure 30 looks like the original TRIPOD model, its components and assumptions are different. In the Beta-model the defences and controls are directly linked to unsafe acts, preconditions and latent failures. Unsafe acts describe how the barriers were breached and the latent failures why the barriers were breached.

An example of a TRIPOD Beta accident analysis is shown in Figure 31.

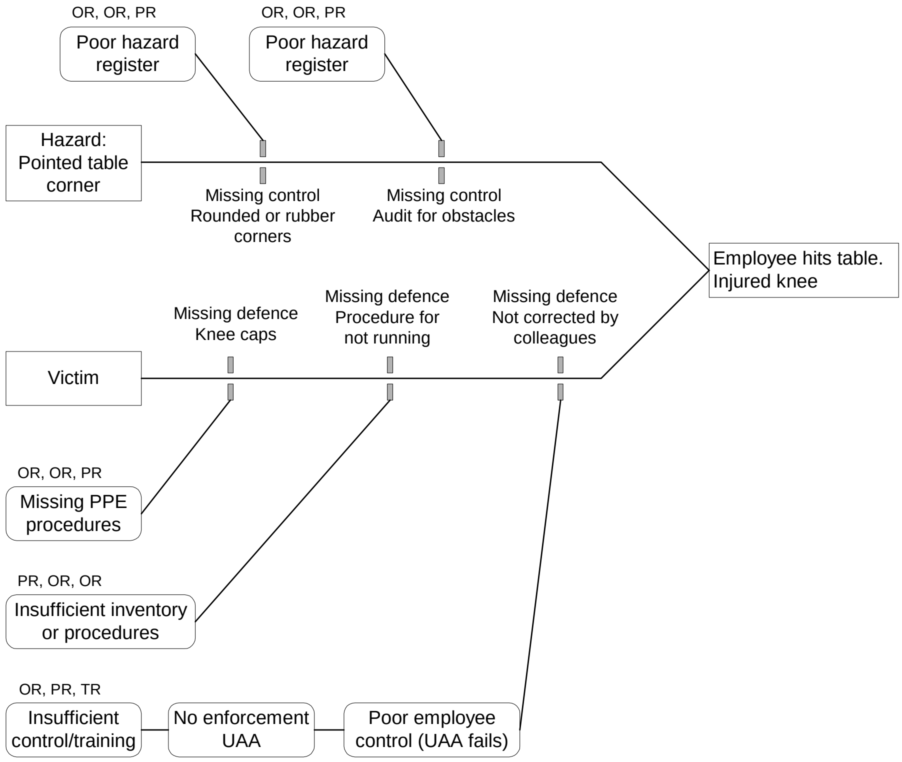

Figure 31. Example on a TRIPOD Beta analysis.

The new way of investigating accidents (see Figure 32) is quite different from the conventional ones. No research is done to identify all the contributing substandard acts or clusters of substandard acts, the target for investigation is to find out whether any of the Basic Risk Factors are acting. When the BRFs have been identified, their impact can be decreased or even be eliminated. The real source of problems is tackled instead of the symptoms.

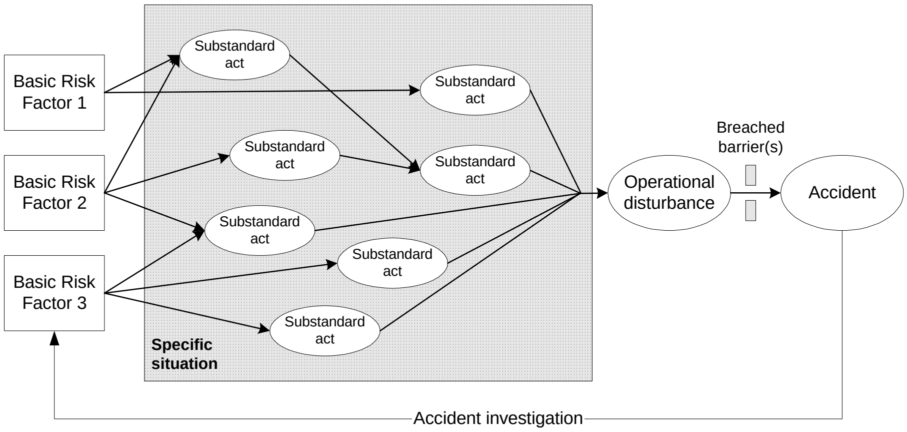

Figure 32. A new way of accident investigation.

4.2.9 Acci-map[24]

Rasmussen & Svedung (2000) describe a recently developed methodology for proactive risk management in a dynamic society. The methodology is not a pure accident investigation tool, but a description of some aspects of their methodology is included because it gives some interesting and useful perspectives on risk management and accident investigation not apparent in the other methods.

They call attention to the fact that many nested levels of decision-making are involved in risk management and regulatory rule making to control hazardous processes (see Figure 4). Low risk operation depends on proper co-ordination of decision making at all levels. However, each of the levels is often studied separately within different academic disciplines. To plan for a proactive risk management strategy, we have to understand the mechanisms generating the actual behaviour of decision-makers at all levels. The proposed approach to proactive risk management involves the following analysis:

- A study of the normal activities of the actors who are preparing the landscape of accidents during their normal work, together with an analysis of the work features that shape their decision-making behaviour.

[24] The description is based on Rasmussen & Svedung, 2000.

- A study of the present information environment of these actors and the information flow structure analysed from a control theoretic point of view.
- A review of the potential for improvement by changes of this information environment (top-down communication of values and objectives and bottom-up information flow about the actual state-of-affairs)
- Guidelines for improving these aspects in practical work environment for different classes of risk sources and management strategies.

Modelling the performance of a closed-loop, proactive risk management strategy must be focused on the following questions:

1. The decision-makers and actors who are involved in the control of the productive processes at the relevant levels of the socio-technical system must be identified.
2. The part of the work-space under their control must be defined, that is, the criteria guiding the allocation of roles to the individual controllers must be found.
3. The structure of the distributed control systems must be defined, that is, the structure of the communication network connecting collaborating decision-makers must be analysed.

This approach involves the study of the communication structure and the information flow in a particular organisation to evaluate how it meets the control requirements of particular hazardous processes.

Analyses of past accident scenarios serve to describe the socio-technical context which accidental flow of events are conditioned and ultimately take place. These analyses have several phases:

1. Accident analysis
2. Identification of actors
3. Generalisation
4. Work analysis

The first phase of the analysis is to identify the potential accident patterns. Based on a representative set of accident cases, a cause-consequence-chart (CCC) is developed from a study of the causal structure of the system. The CCC formalism gives a detailed overview of the potential accident scenarios to consider for design of safety measures related to a particular activity of a work system. CCCs have been used as a basis for predictive risk analysis. These charts are developed around a “critical event” that represents the release of a particular hazard source. Several different causes may release a particular hazard source and are represented by a causal tree connected to the critical event see Figure 33.

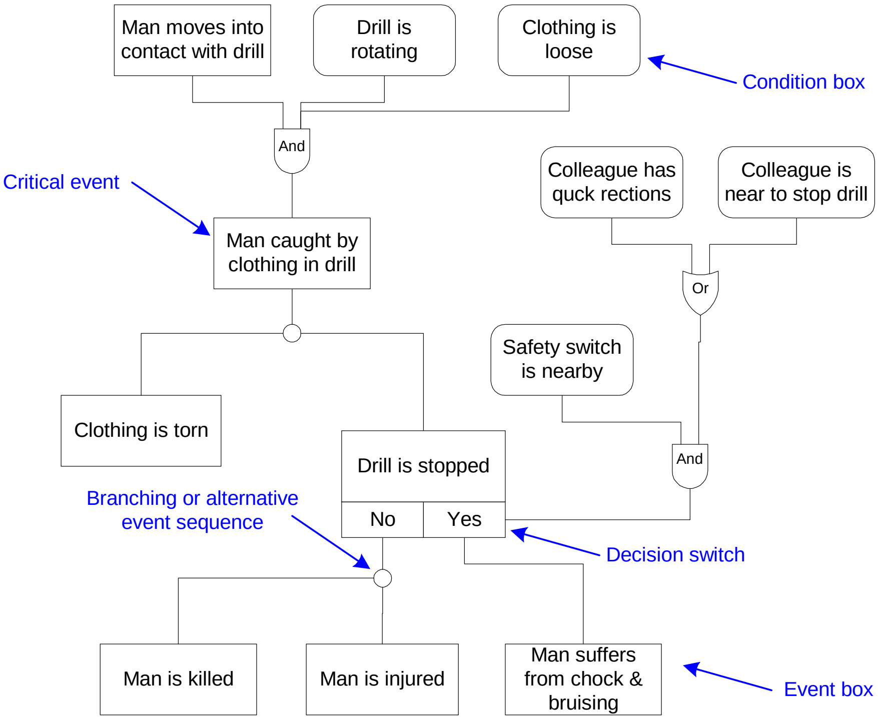

Figure 33. Cause-consequence diagram.

Depending on actions taken by people in the system or by automatic safety systems, several alternative routes may be taken by the accidental flow once the hazard source is released. Event trees following the critical event represent these routes and include “decision switches” that represent such effects of protective actions. A particular CCC represents a generalisation that aggregates a set of accidental courses of events related to the release of a particular hazard source represented by the critical event.

The aim of an analysis is to analyse the normal work conditions in the different organisations that may contribute to the creation of an accidental flow path to reveal the potential for a connected set of side effects. From here, the aim of risk management is to create a work support system that in some way makes decision-makers aware of the potentially dangerous network of side effects.

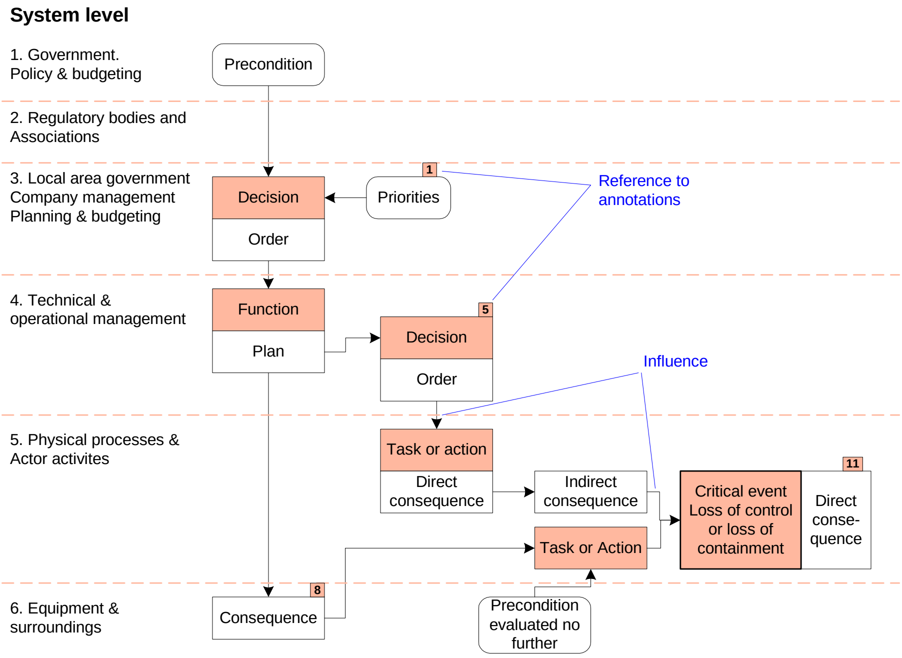

Figure 34. An approach to structure an AcciMap and a proposed legend of symbols.

The basic AcciMap represents the conditioning system and the flow of events from on particular accident. A generalisation is necessary based on a set of accident scenarios.

The generic AcciMap gives an overview of the interaction among the different decision-makers potentially leading up to release of accidents. An ActorMap, as in Figure 35, is an extract of the generic AcciMap showing the involved decision-makers. Such an ActorMap gives an overview of the decision-making bodies involved in the preparation of the "landscape" in which an accidental flow of events may ultimately evolve. Based on an ActorMap, an InfoMap might be developed, indicating the structure of the information flow. The InfoMap shows the downward flow of objectives and values (the targets of control), and the upward flow of state information (the measurements of control).

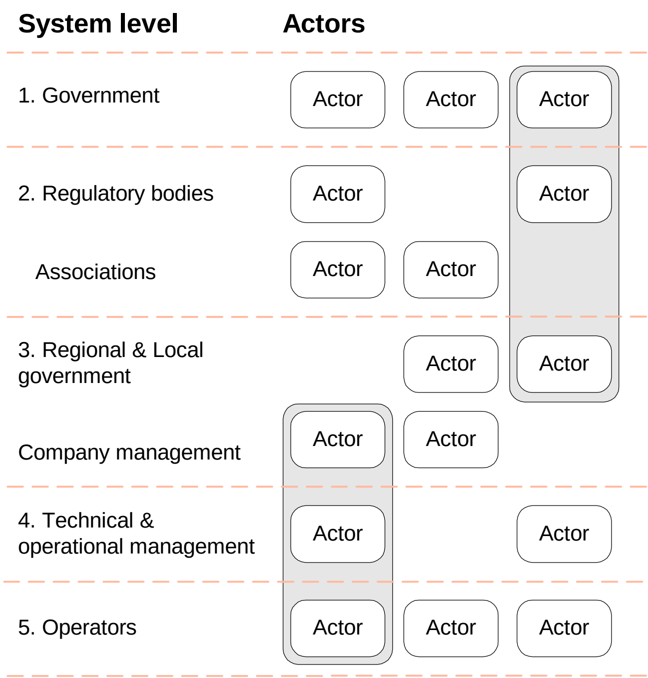

Figure 35. Principal illustration of an ActorMap.

5 Discussion and conclusion

5.1 Discussion

Within the field of accident investigation, there are no common agreement of definitions of concepts, it tend to be a little confusion of ideas. Especially the notion of cause has been discussed. While some investigators focus on causal factors (e.g. DOE, 1997), others focus on determining factors (e.g. Kjellén and Larsson, 1981), contributing factors (e.g. Hopkins, 2000), active failures and latent conditions (e.g. Reason, 1997) or safety problems (Hendrick & Benner, 1987). Kletz (Kletz, 2001) recommends avoiding the word cause in accident investigations and rather talk about what might have prevented the accident. Despite the accident investigators may use different frameworks and methods during the investigation process, their conclusions about what happened, why did it happen and what may be done in order to prevent future accidents ought to be the same.

There exists different frameworks or methods for accident investigation, each of them with different characteristics. Table 6 shows a summary of some characteristics of the different methods described in this report. Column one in the table shows the name of the methods.

In the second column there is made a statement whether the methods give a graphical description of the event sequence or not. Such a graphical illustration of the event sequence is useful during the investigation process. The graphical illustration of the event sequence gives an easy understandable overview of the events and the relations between the different events. It facilitates communication among the investigators and the informants and makes it easy to identify eventually "missing links" or lack of information in order to fully understand the accident scenario.

ECFC, STEP and MTO-analysis are all methods that give graphical illustrations of the accident scenario. By use of ECFC and MTO-analysis the events are drawn along one horizontal line, while the STEP diagram in addition includes the different actors along the vertical axis. My opinion is that the STEP-method gives the best overview of the event sequence. This method makes it easy to illustrate simultaneously events and the different relationships between events (one-to-one, one-to-many, many-to-one and many-to-many). The "single line" approach used by ECFC and MTO-analysis do not illustrate these complex relations in which often cause accidents as well as STEP.

The graphical illustrations used by ECFC and MTO-analysis also include conditions that influenced the event sequence and causal factors that lead to the accident. In STEP, safety problems are only illustrated by triangles or diamonds and analysed in separate ways.

Two strengths of the MTO-analysis are that both the results from the change analysis and the barrier analysis are illustrated in the graphical diagram.

Some of the other methods also include graphical symbols as part of the method, but none of them illustrate the total accident scenario. The fault tree analysis use predefined symbols in order to visualize the causes of an initiating event. The event tree uses graphical annotation to illustrate possible event sequences following after an initiation event influenced by the success or failure of different safety systems or barriers. The AEB method illustrates the different human or technical failures or malfunctions leading to an accident (but not the total event sequence). The TRIPOD Beta illustrates graphically a target (e.g. worker), a hazard (e.g. hot pipework) and the event (e.g. worker gets burned) in addition to the failed or missing defences caused by active failures, preconditions and latent failures (BRF) ("event trios").

The third column covers the level of scope of the different analysis methods. The levels correspond to the different levels of the socio-technical system involved in risk management illustrated in Figure 4. The different levels are:

1. The work and technological system
2. The staff level
3. The management level
4. The company level
5. The regulators and associations level
6. The Government level

As shown in Table 6, the scope of most of the methods is limited to level 1 – 4. Although STEP was originally developed to cover level 1 – 4, experience from SINTEF's accident investigations shows that the method also may be used to analyse events influenced by the regulators and the Government. In addition to STEP, only Acci-Map put focus on level 5 and 6. This means that investigators focusing on the Government and the regulators in their accident investigation to a great extend need to base their analysis on experience and practical judgement more than on results from formal analysis methods.

The fourth column states whether the methods are a primary method or a secondary method. Primary methods are stand-alone techniques while secondary methods provide special input as supplement to other methods. Events and causal factors charting, STEP, MTO-analysis, TRIPOD and Acci-map are all primary methods. The fault tree analysis and event tree analysis might be both primary and secondary methods. The other methods are secondary methods.

In the fifth column the different methods are categorized as deductive, inductive, morphological or non-system oriented. Fault tree analysis and MORT are deductive methods while event three analysis is an inductive method. Acci-map might be both inductive and deductive. The AEB-method is characterized as morphological, while the other methods are non-system oriented.

In the sixth column the methods are linked to different types of accident models in which have influenced the methods. The following accident models are used:

A Causal-sequence model
B Process model
C Energy model
D Logical tree model
E SHE-management models

Root cause analysis, SCAT and TRIPOD are based on causal-sequence models. Events and causal charting, change analysis, events and causal factors analysis, STEP, MTO-analysis and AEB-method are based on process models. The barrier analysis is based on the energy model. Fault tree analysis, event tree analysis and MORT are based on logical tree models. MORT and SCAT are also based on SHE-management models. The Acci-map is based on a combination of a causal-sequence model, a process model and a logical tree model.

In the last column, there is made an assessment of the need of education and training in order to use the methods. The terms “Expert”, “Specialist” and “Novice” are used in the table. Expert indicates that there is need of formal education and training before people are able to use the methods in a proper way. Some experience is also beneficial. Fault tree analysis, MORT and Acci-map enter into this category. Novice indicates that people are able to use the methods after and orientation of the methods without hands-on training or experience. Events and causal factors charting, barrier analysis, change analysis and STEP enter into this category. Specialist is somewhere between expert and novice and events and causal factors analysis, root cause analysis, event tree analysis, SCAT, MTO-analysis, AEB-method and TRIPOD enter into this category.

Table 6. Characteristics of different accident investigation methods.

Method	**Accident sequence**	**Levels of analysis**	**Primary / secondary**	**Analytical approach**	**Accident model**	**Training need**
Events and causal factors charting	Yes	1-4	Primary	Non-system oriented	B	Novice
Barrier analysis	No	1-2	Secondary	Non-system oriented	C	Novice
Change analysis	No	1-4	Secondary	Non-system oriented	B	Novice
Events and causal factors analysis		1-4	Secondary	Non-system oriented	B	Specialist
Root cause analysis	No	1-4	Secondary	Non-system oriented	A	Specialist
Fault tree analysis	No	1-2	Primary/ Secondary	Deductive	D	Expert
Event Tree analysis	No	1-3	Primary/ Secondary	Inductive	D	Specialist
MORT	No	2-4	Secondary	Deductive	D / E	Expert
SCAT	No	1-4	Secondary	Non-system oriented	A / E	Specialist
STEP	Yes	1-6	Primary	Non-system oriented	B	Novice
MTO-analysis	Yes	1-4	Primary	Non-system oriented	B	Specialist/ expert
AEB-method	No	1-3	Secondary	Morpho-logical	B	Specialist
TRIPOD	Yes	1-4	Primary	Non-system oriented	A	Specialist
Acci-Map	No	1-6	Primary	Deductive & inductive	A / B / D	Expert

5.2 Conclusion

Major accidents almost never result from one single cause, most accidents involve multiple, interrelated causal factors. All actors or decision-makers influencing the normal work process might also influence accident scenarios, either directly or indirectly. This complexity should also reflect the accident investigation process.

The aim of accident investigations should be to identify the event sequences and all (causal) factors influencing the accident scenario in order to be able to suggest risk reducing measures in which may prevent future accidents. This means that all kind of actors, from technical systems and front-line operators to regulators and the Government need to be analysed.

Often, accident investigations involve using of a set of accident investigation methods. Each method might have different purposes and may be a little part of the total investigation process. Remember, every piece of a puzzle is as important as the others.

Graphical illustrations of the event sequence are useful during the investigation process because it provides an effective visual aid that summaries key information and provide a structured method for collecting, organising and integrating collected evidence to facilitate communication among the investigators. Graphical illustrations also help identifying information gaps.

During the investigation process different methods should be used in order to analyse arising problem areas. Among the multi-disciplinary investigation team, there should be at least one member having good knowledge about the different accident investigation methods, being able to choose the proper methods for analysing the different problems. Just like the mechanicians have to choose the right tool on order to repair a technical system, an accident investigator has to choose proper methods analysing different problem areas.

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