National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Fifteen years of incident analysis

Causes, consequences, and other characteristics of incidents with hazardous substances at major hazard companies in the period 2004-2018

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RIVM report 2020-0115

Colophon

DOI 10.21945/RIVM-2020-0115

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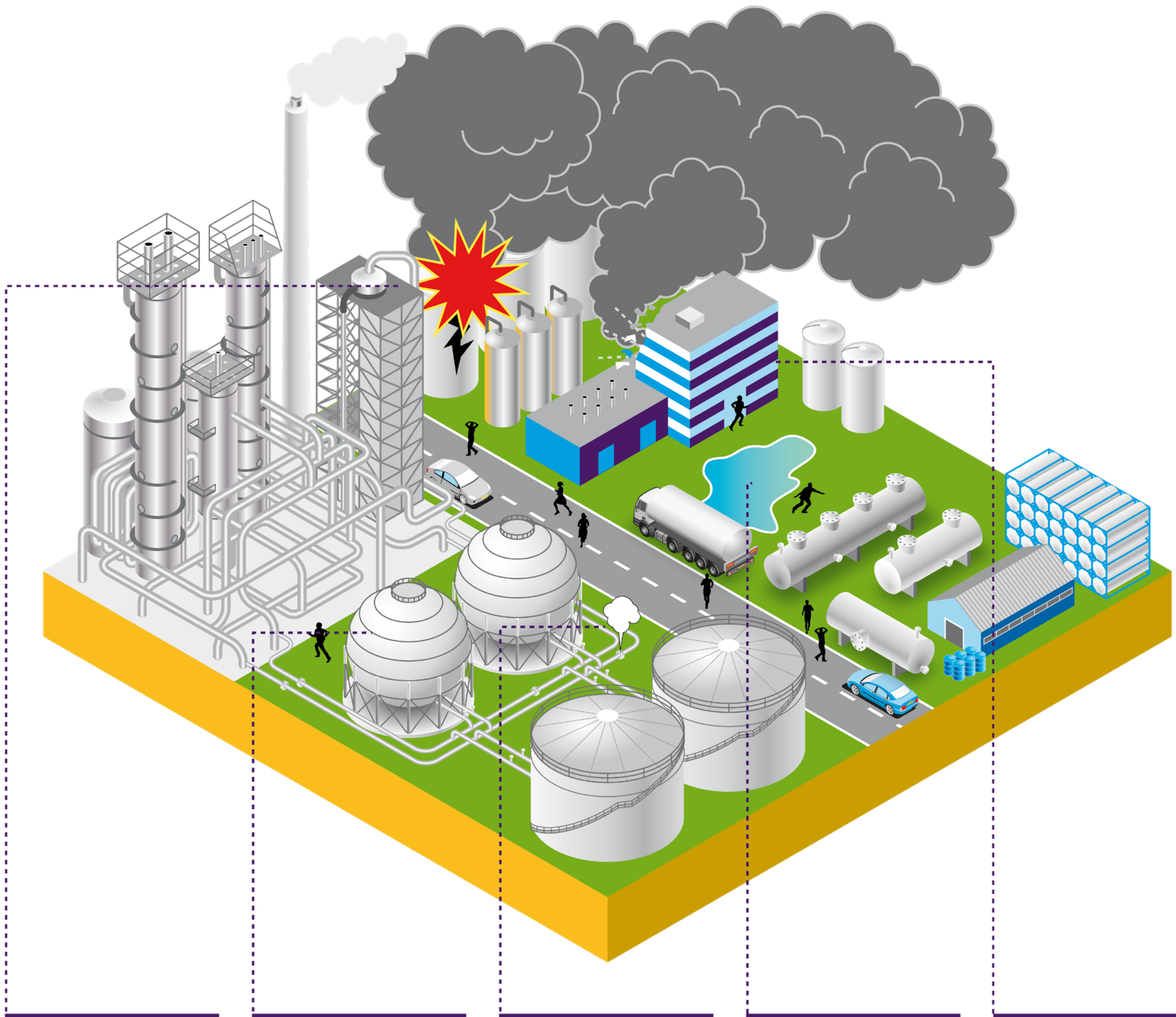
In memory of our friend and colleague Martijn Mud (1962 - 2020) who dedicated much of his life to improving safety through the understanding of the causes of accidents. Martijn's contribution was made with an enthusiasm and good humour that persisted to the end of his life. It was a pleasure to work with him and he will be greatly missed.

This study was commissioned by the Ministry of Social Affairs and Employment, in the context of Z/110021/20/MH - Analysis of MHC accidents using Storybuilder.

Published by:
National Institute for Public Health and the Environment, RIVM
P.O. Box1 | 3720 BA Bilthoven
The Netherlands
www.rivm.nl/en



Incidents

28% of incidents involved a fire or an explosion. In 71% of the incidents hazardous substances were released without fire or explosion. In three incidents (1%), workers entered a confined space that contained hazardous substances.

Circumstances

Most of the incidents occurred during normal operation (60%) and maintenance (20%) activities. The maintenance-related incidents involved a relatively large number of victims. Most of these victims suffered burns or inhaled toxic substances.

Items of equipment

Most of these incidents occurred with items of equipment in process installations, such as process piping, reactor vessels and product separators. Items of equipment in storage, transport and loading systems were less frequently involved.

Immediate causes

The most common immediate causes were errors in human actions and material degradation. Together these two immediate causes were responsible for 56% of all incidents.

Prevention

Incidents mainly result from deviations that occur in normal operational processes but go unnoticed. Safety could be improved by introducing additional measures for promptly identifying any deviations and for their recovery.

Synopsis

Fifteen years of incident analysis
Causes, consequences, and other characteristics of incidents with hazardous substances during the 2004-2018 period

RIVM has analysed 326 incidents involving hazardous substances that took place at chemical companies between 2004 and 2018. These incidents posed a threat to the safety of workers. A total of 215 persons were injured, including five fatalities. The nature, scale and causes of the incidents remained the same during the period analysed. The number of incidents per year with relatively serious consequences also did not change significantly during the same period.

Hazardous substances were released in 90% of the incidents. A fire or explosion occurred in 28%. In three incidents (1%), workers entered a confined space that contained hazardous substances. Most of the incidents took place during normal work activities (60%) or during maintenance (20%). Victims inhaled toxic or hazardous substances or suffered burn wounds caused by chemical reactions or heat. The incidents that took place during maintenance resulted in a relatively larger number of victims.

Chemical companies are responsible for ensuring that their installations are in order and that their production processes and activities are carried out safely. The incidents took place because things went wrong during the regular operational processes. The resulting deviations were not noticed in time. One of the ways to improve safety is to implement suitable measures to identify and correct these deviations in time before incidents occur. This would, for example, reduce the risk of incidents occurring as a result of unwanted human actions or material degradation.

Incident investigations carried out by the SZW (Ministry of Social Affairs and Employment) Inspectorate were used for the analysis at hand. RIVM is commissioned by the Ministry of Social Affairs and Employment to analyse the similarities and differences between the investigated incidents. Inspection services can use this analysis for their inspection and enforcement strategies. Companies can use the insights gained to improve safety.

Keywords: safety, hazardous substances, incidents, Brzo (Major Accidents (Risks) Decree), incident analysis, learning from accidents, Storybuilder

Publiekssamenvatting

Vijftien jaar incidentanalyse
Oorzaken, gevolgen en andere kenmerken van incidenten met gevaarlijke stoffen in de periode 2004-2018

Het RIVM heeft 326 incidenten met gevaarlijke stoffen geanalyseerd die tussen 2004 en 2018 plaatsvonden bij grote chemische bedrijven. Bij deze incidenten was de veiligheid van werknemers in het geding. In totaal vielen er 215 slachtoffers, onder wie vijf doden. De aard, omvang en oorzaken van de incidenten zijn in de onderzochte periode gelijk gebleven. Het jaarlijkse aantal incidenten met relatief ernstige gevolgen is in de periode ook niet wezenlijk veranderd.

Bij 90 procent van de incidenten kwamen gevaarlijke stoffen vrij. Bij 28 procent ontstond een brand of explosie. Drie keer (1 procent) gingen werknemers een besloten ruimte met gevaarlijke stoffen binnen. Incidenten ontstonden vooral tijdens de normale werkzaamheden (60 procent) of tijdens het onderhoud (20 procent). Slachtoffers ademden giftige of schadelijke stoffen in of kregen brandwonden door chemische reacties of hitte. Bij de incidenten tijdens het onderhoud vielen verhoudingsgewijs meer slachtoffers.

Chemische bedrijven zijn ervoor verantwoordelijk dat installaties op orde zijn en de productieprocessen en -werkzaamheden veilig worden uitgevoerd. De incidenten ontstonden doordat in de reguliere procesvoering dingen mis gingen. De afwijkingen die daar het gevolg van waren, zijn niet op tijd opgemerkt. De veiligheid kan onder meer worden verbeterd door geschikte maatregelen in te voeren om deze afwijkingen op tijd in beeld te krijgen en te herstellen. Dit verkleint onder andere de kans dat incidenten ontstaan door ongewenste menselijke handelingen of door materiaalverzwakking.

Voor deze analyse zijn incidentonderzoeken van de Inspectie SZW gebruikt. In opdracht van het ministerie van SZW gaat het RIVM na wat de overeenkomsten en verschillen tussen de onderzochte incidenten zijn. Inspectiediensten kunnen de analyse gebruiken voor hun inspectie- en handhavingsstrategieën. Bedrijven kunnen de inzichten gebruiken om de veiligheid te verbeteren.

Kernwoorden: veiligheid, gevaarlijke stoffen, incidenten, Staat van de Veiligheid, Brzo, incidentanalyse, leren van ongevallen, Storybuilder

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Summary

RIVM has analysed 326 incidents involving hazardous substances that occurred at major hazard chemical companies between 2004 and 2018. These incidents involved 215 victims, including five fatalities. The incidents in question were all investigated by the Inspectorate SZW's Major Hazard Control Department. There are sufficient data to draw robust conclusions. These data can be used to identify any similarities between incidents and any developments over time. They can also be used to highlight any correlations between a range of incident characteristics. Inspection services can use these findings to refine their inspection and enforcement strategies. Companies can use these insights to improve their safety measures.

As might be expected given the Major Hazard Control Department's field of operation, the vast majority (97%) of these incidents occurred at establishments that fall under the EU Seveso III directive. These Seveso establishments were mainly upper-tier establishments (88%). Relatively few lower-tier establishments were involved (12%). Half of these incidents occurred in items of equipment in process installations, such as process piping, reactor vessels and product separators. Items of equipment in storage, transport and loading systems were less frequently involved. Sixty per cent of these incidents occurred during normal operation and 20% during maintenance activities.

Incident characteristics – the victims and the severity of their injuries
90% of the incidents involved the release of hazardous substances. 28% of incidents involved a fire or an explosion. In three incidents (1%), workers entered a tank containing hazardous substances. The most common immediate causes were human error and material degradation. Together these two immediate causes were responsible for 56% of all incidents.

As might be expected, the victims were mainly maintenance workers and process operators. Five of the 215 victims died and at least ten suffered permanent physical injuries. In some cases (62 victims or 29%), it was unknown whether the physical injuries involved were temporary or permanent in nature. The other 138 victims (64%) suffered temporary injuries. The victims had either inhaled toxic or harmful substances or had suffered chemical or thermal burns. Three of the five fatalities died as a result of an explosion within a containment. Two others died when they entered a hazardous substance containment. In a relatively large number of cases, the permanent injuries involved burns caused by chemical reactions or heat.

Incidents during maintenance activities and those associated with manual operations resulted in serious injuries in a relatively large number of cases. Neither the hazard categories of the hazardous substances involved nor the immediate causes of these incidents were demonstrably relevant to the severity of the injuries sustained – nor were the professions, employment duration and ages of the victims in question.

Underlying causes
The circumstances of these incidents and their underlying causes were investigated in detail using Storybuilder MHC (a scientifically underpinned model). This model includes 41 safety measures aimed at preventing incidents or limiting their consequences. These 41 safety measures are subdivided into six protective layers or lines of defence (LoD).

- **1st LoD: process control.** Incidents start with deficiencies (errors) in terms of standard process control. This LoD involves a range of deficiencies. 42% of the incidents concerned failures of the safeguards that were designed to preserve the installation's material integrity. 32% were due to a failure to control the process parameters. In 29% of the incidents processes or activities were not started safely.
- **2nd LoD: recovery.** If incidents are to be prevented, any deviations that arise must promptly be discovered and remedied. Remarkably, many deviations went unnoticed due to a lack of suitable instruments and procedures for identifying abnormalities (in 48% of the incidents in question). Although in the other incidents there was certainly an indication of the deviation, there was a failure to detect it, to diagnose it correctly or to take adequate and prompt remedial action.
- **3rd LoD: emergency protection.** In 59% of the incidents, a failure to implement prompt recovery automatically led to the release of hazardous substances. In these incidents, it was not possible to implement any additional emergency measures. This concerned incidents in which the installation failed because of material degradation or loosened connections, and incidents in which a containment with a hazardous substance was actively opened or in which a process was initiated while valves were still open. In the other 41% of cases, additional protective measures could have prevented the incidents in question. These incidents mainly involved the failure of measures taken to prevent fires and explosions within an installation and of measures taken to protect the installation against high pressure. There were also 22 incidents (7%) in which the potential failure of the installation due to excessively high pressure was successfully prevented by venting or flaring hazardous substances.
- **4th, 5th and 6th LoD.** Even after an incident has started to develop, various measures can still be taken to limit its consequences. Some of these mitigating measures were more effective than others. In general, the deficiencies (387x) slightly outnumbered the successes (335x).

The Storybuilder MHC model also has a structure that is designed to show how and why safety measures fail. Safety measures mainly failed because they had been implemented incorrectly or had not been implemented at all (33%) or because they had not been used correctly or had not been used at all (28%). The former implies either a lack of the requisite safety instruments and procedures or that these safety instruments and procedures were insufficiently suitable. The latter case implies that, although the safety equipment was present, it was not used, operated or applied correctly. At the organisational level, the failure of safety measures was found to be mainly due to deficiencies in plans and procedures (26%). To a lesser extent, aspects such as poorly trained and insufficiently experienced staff (16%), unsuitable materials and equipment (14%), and a lack of alertness on the part of the staff (14%) were also involved. With regard to safety management, the primary deficiency was a failure to translate the awareness of hazards and risks into adequate measures and equipment (SMS element iii: Operational control).

Section 4 illustrates some common scenarios and underlying causes, in narrative form. These narratives are intended to make the incidents more tangible and to offer practical starting points from which to learn.

Trends over time
During the period analysed, the number of incidents investigated by the SZW Inspectorate has fallen. This trend started approximately ten years ago. It may reflect a genuine fall in the number of incidents involving hazardous substances throughout the industry. However, it may also simply mean that, relatively speaking, the SZW Inspectorate has been cutting down on the number of incidents it investigates. So far, there has been no verifiable reduction in the number of notifiable incidents that have been investigated. These are incidents with relatively serious consequences.

Between 2004 and 2018, the characteristics of the incidents remained substantially unchanged, as did their immediate and underlying causes.

Potential safety improvements
The analysis shows that safety management at major hazard chemical companies is a complicated task. The factors that could cause incidents are many and varied, and there are a plethora of measures for improving safety. The companies being investigated also differ from one another, as do their activities. As a result, safety improvements continue to involve a degree of customisation. Companies must analyse their individual situations to determine which measures might be most effective for them.

Nevertheless, it is possible to identify several similarities between these incidents. First and foremost, two immediate causes were together responsible for 56% of all incidents and 49% of all victims. These were errors in human actions and material degradation. Subsection 4.1 describes ways of improving safety in these two scenarios. Secondly, in 59% of the incidents, incident prevention depended on two pillars – safe process control, and prompt and adequate recovery from deviations. Therefore, strengthening these two pillars would deliver relatively significant safety benefits. Part of this involves a keen awareness of potential deviations beyond operational boundaries. Finally, with regard to the safety management system, the failures that occurred were mainly related to operational control. This means that, while there was a general awareness of the hazards and risks involved, there was also a deficiency in terms of translating this awareness into effective practical measures. Efforts to increase safety must focus more intensively on whether the instruments and procedures being implemented are indeed adequate in the light of the potential deviations. Checks must also be conducted in the work place to verify that these instruments and procedures are being used as intended.

Approach to the study
The analyses used information provided by the SZW Inspectorate and reports published by the Dutch Safety Board. The analyses were carried out using a scientifically underpinned model: Storybuilder MHC. This model was specifically developed for incidents involving hazardous substances at major hazard chemical companies. Following the initial phase of development, the analysis model was expanded and modified. Every incident was reviewed before performing the analyses for this report. The requirements for these analyses are laid down in a set of analysis instructions.

1 Introduction

What is the purpose of this study report?
In the Netherlands, incidents and accidents are investigated in a variety of ways, for a range of purposes. In many cases, investigations of this kind involve a single, specific incident. Companies and agencies primarily investigate incidents and accidents in order to learn from them. One purpose of these investigations is to identify the direct and underlying factors that played a part in the incident. Another is to identify the changes needed to reduce any risk of recurrence. Regulators, too, investigate specific incidents and accidents; to check whether any legislation and regulations were infringed. The main purpose of the investigations is to maximise compliance, but they can also help any victims involved to come to terms with what has happened.

Rather than focusing on a single incident, the present study has analysed 326 incidents and accidents at major hazard chemical companies. This large number of cases makes it possible to highlight any connecting threads between those incidents and to identify any underlying patterns. The lessons learned can be used to improve safety at these companies. Furthermore, the knowledge gained transcends the level of individual incidents and specific companies.

What methods were used?
The study was based on incidents at companies with large quantities of hazardous substances. These incidents were investigated by the SZW Inspectorate’s Major Hazard Control Department over the past fifteen years. The study also made use of Dutch Safety Board reports into accidents involving hazardous substances at major hazard chemical companies.

Based on the available information, the most important characteristics of each individual incident were identified, including the immediate and underlying causes. This involved a structured approach and the use of Storybuilder MHC [1], [2], which is a scientifically underpinned accident analysis model [3], [4], [5]. The Storybuilder MHC model was specifically developed for incidents involving hazardous substances at major hazard chemical companies. Details concerning more than 50 different aspects of each incident were recorded in a database [6]. A further 10 aspects were added in cases in which the incident in question involved victims. After the initial phase of development, the analysis model was expanded and modified. All the incidents were then re-examined before performing the analyses for this report. The requirements for these analyses are laid down in a set of analysis instructions [7].

Details of the information flow from incident to analysis are depicted in Figure 1.1. The detailed incident investigations in question were conducted either by the SZW Inspectorate's Major Hazard Control Department or by the Dutch Safety Board. The analyses were performed by RIVM, in cooperation with RPS, an engineering and consultancy firm.

Figure 1.1. Information flow from incident to analysis.

What will the study reveal?
The study will highlight and identify any characteristics that different incidents have in common. This study could provide answers to questions such as:

- Which types of companies and which items of equipment are most frequently involved in incidents?
- During which activities do incidents occur?
- What is the nature and severity of the victims' injuries? Which factors determine the severity of injuries?
- Are there any immediate or underlying causes that recur regularly?
- How can safety be further improved?

Scope
The analysis relates to 326 incidents involving hazardous substances at major hazard chemical companies, in particular Seveso companies.[1] This concerns incidents that were investigated between 2004 and 2018, either by the SZW Inspectorate's Major Hazard Control Department or by the Dutch Safety Board.

This comprehensive model offers many options for further analysis. This report presents the overarching characteristics. In addition, a number of characteristics were investigated to determine whether they had changed over time. Furthermore, several aspects of incidents were investigated in order to determine whether there was a connection with the severity of injuries involved. The database is public and can be obtained via RIVM's website. Any interested parties are free to use the data for further research, if they so wish.

Context
The present report is part of the "State of safety major hazard chemical companies 2018" reporting to Dutch Parliament. A separate report will be published – in parallel to this composite report – detailing the most important findings in the past investigative year [9]. A trend report covering the period from 2004 to 2013 was published in 2014 [10]. Appendix 5 describes the checks carried out to determine whether the conclusions drawn at the time are still valid.

[1] The Major Accident Hazards Decree (2015) [8] is the Dutch implementation of the EU Seveso III directive [14]. In the Netherlands, this covers more than 400 companies in the chemical industry, the refining industry, the waste processing industry, the wholesale sector, the storage sector, the metal manufacturing industry and the foodstuff production industry. The 'hazardous substances' referred to in this report are flammable, explosive, acutely toxic, or extremely harmful to health.

Reading guide
Section 2 describes the general characteristics of the 326 incidents. This concerns aspects such as the nature of the incidents, the number of victims and the injuries they sustained, as well as the companies, activities, substances and the items of equipment involved.

Section 3 describes the underlying causes of the incidents. The section reflects the structure of the analysis model (Storybuilder MHC), which is explained through analogies. The model identifies the specific safety measures needed to prevent incidents or to limit their severity.
Section 3 shows which measures failed in these incidents and why.

Section 4 illustrates some common scenarios and underlying causes, in narrative form. These narratives are intended to make the incidents more tangible and to offer practical starting points from which to learn.

In Section 5, statistical analyses are used to identify any trends over the course of time and to discover whether there are any correlations between the severity of injuries and other factors. Based on the developments that have been identified (or the absence thereof), government agencies can decide whether or not the regulations (or their enforcement) need to be amended.

In Section 6, a comparison is made with other industrial accidents. Any differences with regard to industrial accidents could serve as a useful lesson for MHC incidents.

Section 7 sets out the report’s main conclusions.

2 The incidents' main characteristics

2.1 Introduction

This section, which is intended for a general readership, covers the most important characteristics of the incidents in question. Unless otherwise stated, this section covers all 326 incidents that have been analysed since 2004.[2]

2.2 Number of incidents

Figure 2.1 provides details of the total number of registered incidents. It depicts the following data:

- A total of 326 incidents were investigated and analysed. In the case of 14 incidents, the incident investigation dated 31 December 2018 had not yet been completed. This could be related to ongoing criminal proceedings, for example. These 14 outstanding incidents have not yet been analysed.
- The number of incidents being investigated and analysed each year is falling.[3] This decline started around 2009. Between 2005 and 2010, 25 to 35 incidents were investigated each year. Five years later, the number of incidents investigated each year had fallen to approximately 15. In 2017 and 2018, fewer than 10 incidents were investigated (or are still being investigated).

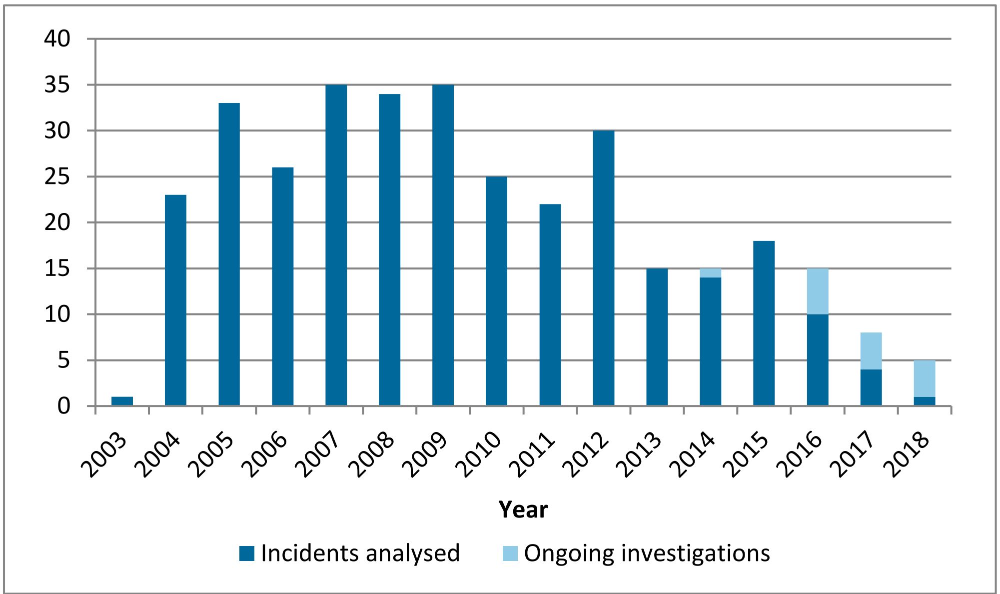


Figure 2.1. Incidents already analysed and ongoing investigations.

No clear-cut reason can be found for the decline in the number of incidents being investigated year on year. The most obvious explanation is that there has been a fall in the annual number of incidents at Seveso companies during the period in question. For instance, according to

[2] A single incident dating from 2003 was also analysed, in error.
[3] See Subsection 5.1 for the statistical validation and further details.

Veiligheid Voorop[4] (Safety First) the 'loss of primary containment' indicator has fallen every year since 2013 [11]. A second possible explanation is that, relatively speaking, the SZW Inspectorate has been cutting down on the number of incidents it investigates over the course of time.[5]

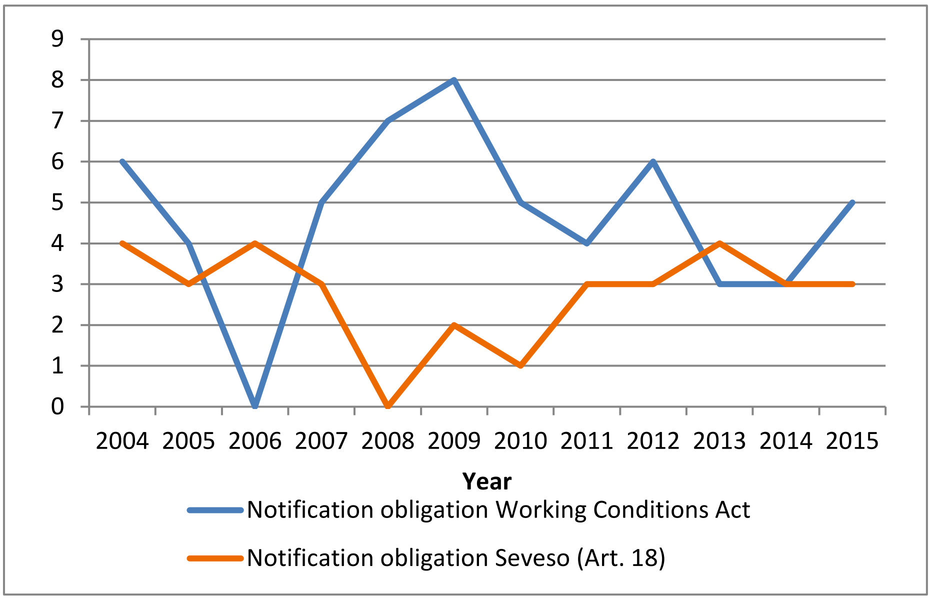


Figure 2.2. The notifiable incidents that took place between 2004 and 2015.

Figure 2.1 includes incidents with serious consequences and incidents with limited consequences. Figure 2.2 only illustrates incidents with relatively serious consequences. This concerns incidents that are notifiable pursuant to Article 9 of the Working Conditions Act [13] or pursuant to Article 18 of the European Seveso-III Directive [14]. In contrast to the incidents depicted in Figure 2.1, there has been no apparent increase or decrease in these 'notifiable incidents' over time.

- During the period in question, 56 incidents were registered that were notifiable under the Working Conditions Act. These were incidents that involved victims with severe injuries.[6]
- During the same period, 33 incidents had to be reported to the European Commission pursuant to Article 18 of the EU Seveso-III Directive (the eMARS reports).[7] These were primarily incidents that involved the release of large quantities of hazardous substances.

[4] Veiligheid Voorop is a partnership of sector organisations, see www.veiligheidvoorop.nl
[5] There has been an apparent decline in routine inspections. Between 2011 and 2015, the annual number of routine inspections conducted by the SZW Inspectorate's former Major Hazard Control Directorate fell from 612 to 350 [12]. However, different considerations applied in the case of incident investigations. It is not known whether, in relative terms, the Inspectorate began carrying out fewer incident investigations during the period in question.
[6] More specifically, these were incidents in which someone died as a result of the incident, sustained permanent injury or was admitted to hospital.
[7] Annex VI of the European Seveso III Directive gives details of the criteria that are used to determine whether incidents need to be reported to the European Commission or included in the European eMARS registration system. This concerns incidents in which considerable quantities of hazardous substances were released, incidents involving severe injury to persons or damage to property or the environment, and incidents involving transboundary damage.

- Data for the period running from 2016 to 2018 have not been included, as none are available for these years due to ongoing investigations. Nor was 2003 taken into account, as only one incident was analysed for that year (see Footnote 2).

2.3 Nature of the incident

This section examines how the incident started and how it subsequently developed. Unless otherwise stated, it concerns the entire data set of 326 incidents.

2.3.1 Type of incident: immediate effect

A total of 292 incidents initially involved the release of hazardous substances, 32 incidents started as a fire and 31 incidents started with an explosion (see Table 2.1). In three incidents, people were exposed to hazardous substances inside a containment. A single incident can have many effects, such as incidents in which both fire and explosion occurred (9x) or incidents in which a fire and/or an explosion was accompanied by the release of hazardous substances (19x). Subsection A2.2.1 of Appendix 2 describes the type of incident in greater detail.

Table 2.1. Type of incident: immediate effect.

Immediate effect	Number of incidents	% of incidents
Release of hazardous substances	292	90%
Immediate fire	32	10%
Immediate explosion	31	10%
Exposure within a containment	3	1%

Table 2.2. Way in which hazardous substances were released.

Way in which hazardous substances were released	Number of incidents	% of incidents
From an opening that is normally closed	93	32%
From a newly created hole (integrity failure) including weld seams	77	26%
Through a failing or loose connection	67	23%
From an opening normally open	23	8%
Due to a catastrophic rupture of the containment	20	7%
From an open containment	13	4%
Unknown	6	2%

In the 292 incidents that involved the release of hazardous substances, these were mainly released through openings that are normally closed (see Table 2.2), such as isolation valves, pressure relief valves, taps for liquid, vents and mistaken open pipe ends. Other incidents concerned new holes in the containment (such as corrosion leaks) and failing or loose connections. It should be noted that installations do not usually experience physical collapse. The percentages shown in Table 2.2 relate to the 292 incidents in which hazardous substances were released. In any given incident, hazardous substances can be released in a variety of ways. Subsection A2.6 of Appendix 2 describes the location of release in greater detail.

"Substances are not released by the physical failure of items of equipment, but rather because installations are open or opened or because connections become loose."

2.3.2 *Development of the incident*

An incident's subsequent course depends on factors such as the type of substance involved and the success of any measures taken to limit the consequences of the incident in question. Figure 2.3 shows details of this course.[8]

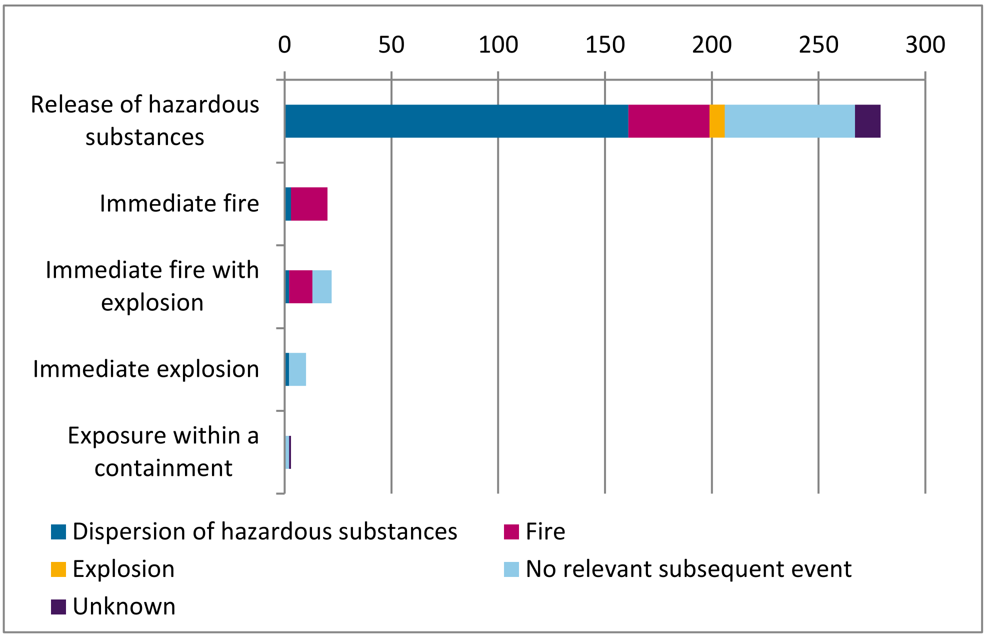


Figure 2.3. Type of incident: immediate effect and subsequent event[9] (number of incidents).

Release of hazardous substances

A total of 292 incidents involved the immediate release of hazardous substances (see Table 2.1). Nineteen of these incidents began as a combination of a release and a fire or an explosion. The other 273 incidents started as a release of hazardous substances only.

- In 59% of these 273 cases, this mainly resulted in a more widespread airborne dispersion of these substances.
- In 14% of these 273 cases, a fire started after the hazardous substances had been released.
- In 3% of these 273 cases, there was an explosion after the release of hazardous substances.
- In 22% of these incidents, there was no relevant subsequent event. The release stopped quickly, any liquids and powders were collected effectively, with no substantial evaporation.

[8] The layout of Figure 2.3 differs slightly from that of Table 2.1: here, the release of hazardous substances is without fire or an explosion. This concerns 273 of the 292 incidents.
[9] Here, the release of hazardous substances only relates to cases that did not involve a fire or explosion at the start of the incident in question.

Immediate fire and explosion
With regard to the 32 incidents that started as a fire, the fire persisted for a while in nine cases out of ten. There were various types of fire, see Subsection A2.2.2 of Appendix 2. In the case of immediate explosions (31 incidents), the incident usually ended shortly after the explosion.

2.3.3 Immediate effect and subsequent effect combined
If the direct effect and the subsequent effect are considered together, a total of 90 incidents (28%) involved a fire or explosion. There were 50 victims (23%) in those incidents. In 233 incidents (71%), hazardous substances were released without there being a fire or explosion. These incidents resulted in 160 victims (74%). The remaining three incidents, in which workers entered a containment with a hazardous substance, resulted in five victims.

2.4 Victims
The model defines a victim as a person who has sustained temporary or permanent physical injury as a result of the incident, a person who has been admitted to hospital or a person who has died [3]. One or more victims were involved in 111 of the 326 incidents. In all, there were 215 victims. Almost all of the victims were on the site of the company at which the incident occurred.

2.4.1 Severity of injuries
The severity of injuries is shown in Figure 2.4.

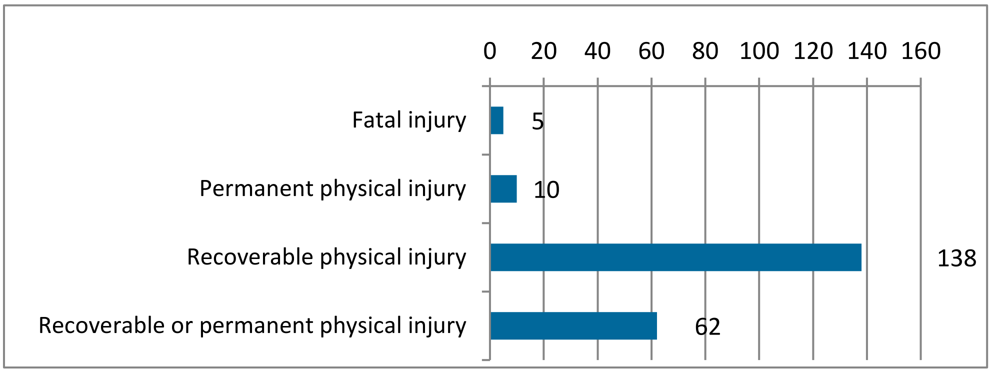


Figure 2.4. Victims and severity of injuries.

- Five people died as a result of accidents. Two accidents involved tank explosions. In total, three fatalities occurred in them. In a third accident, two people died when they entered a containment filled with inert gas.
- At least ten people sustained permanent physical injury.
- Most of the victims sustained recoverable physical injury (fortunately).
- In the cases involving more than a quarter of the victims, the analysts were unable to discover whether their physical injuries were permanent or recoverable in nature. This is partly because, at the time the interviews were held, it was not always clear whether the victim would make a full recovery and partly due to the protection of personal data (professional medical confidentiality).

The incident analyses did not address any long-term psychological problems (mental injury). Any trends over the course of time with regard to the severity of injuries are covered in Subsection 5.2. Any correlations between the severity of injuries and other factors are covered in Subsection 5.3.

2.4.2 *Type of injury*

The types of injury sustained by the victims are shown in Table 2.3. The most common types of injury are poisoning due to the inhalation of hazardous substances (81 victims) and burns (78 victims). These burns were mainly thermal burns resulting from flame contact, hot or cold substances or heat radiation (42 victims), and chemical burns caused by contact (or skin contact) with acidic or corrosive substances (32 victims). The most common type of burns in the thermal burns category were second-degree burns. The other injuries (27 victims) mainly involved contact (or skin contact) with irritating substances.

Table 2.3. Type of injury (ESAW classification).[10]

Type of injury	Number of victims	% of victims
010 Wounds and superficial injuries	5	2%
011 Superficial injuries	3	1%
020 Bone fractures	2	1%
030 Dislocations and strains	7	3%
050 Concussion and internal injuries	1	0%
060 Burns	78	36%
061 Thermal burns	42	20%
1st degree burns	13	6%
2nd degree burns	19	9%
3rd degree burns	4	2%
unknown	7	3%
062 chemical burns (corrosions)	32	15%
069 other burns	6	3%
070 Poisonings and infections	81	38%
071 acute poisonings	12	6%
079 other types of poisoning	18	8%
unknown	51	86%
080 Drowning and asphyxiation	2	1%
090 Effects of high and low pressure	3	1%
091 acute hearing loss	3	1%
120 Multiple injuries	2	1%
999 Other injuries	27	13%
Unknown type of injury	19	9%

Figure 2.5 shows how the severity of injuries (see Subsection 2.4.1) relates to the type of injury in question. The fatal accidents involved asphyxiation (a single accident involving two victims), multiple injuries (a single accident involving two victims), and unknown physical injury (a single accident involving one victim).[11] The permanent injuries mainly

[10] These are categorised using Eurostat's European Statistics for Accidents at Work (ESAW) classification system [19].

[11] The victim died as a result of an explosion in a filter. The nature of the injury he sustained is unknown.

involved burns (10 out of 13 victims): thermal burns caused by heat radiation, flame contact or contact with a hot product.

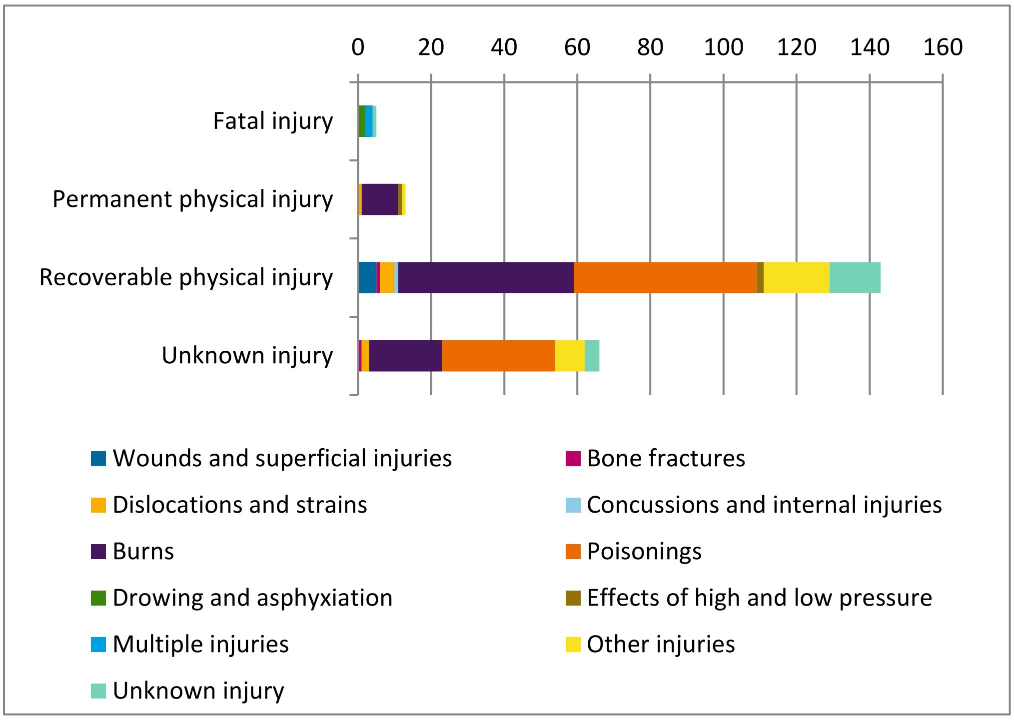


Figure 2.5. Nature and severity of injuries (number of victims).

2.4.3 *Other consequences*

At least one in every three victims was admitted to hospital for treatment, see Table 2.4. For some victims (15%), it was not known whether they were hospitalised or not. The duration of the victims' absence from work is often unknown (see subsection A2.4.3 of Appendix 2).

Table 2.4. Hospitalised.

Hospitalised	**Number of victims**	**% of victims**
Admitted to hospital	69	32%
Not admitted to hospital	113	53%
Hospitalisation unknown	33	15%

2.4.4 *Cause of injury*

The injury is a consequence of the direct effect of the incident (see Subsection 2.3.1) or of the subsequent effects of the incident (see Subsection 2.3.2) or a combination of both. Moreover, several direct effects and/or multiple subsequent effects may have occurred. Due to this complexity, it is not possible to clearly identify and illustrate the causes of the injury.

2.4.5 *Characteristics of the victims*

- **Job of the victim**. For 115 of the 215 victims, it is known which jobs they performed. Among these, victims were mainly process operators (41%) and maintenance workers (38%). The fatalities were also process operators (3x) and maintenance workers (2x).
- **Employment**. For 123 of the 215 victims, the type of employment is known. In half of all cases, they were contractors

or subcontractors. One-third of the victims were permanently employed by the company in question.
- **Third parties**. Four incidents reportedly included victims outside the establishment. All four cases appear to have involved limited exposure and light health effects.
- **Age**. The ages of only 59 victims are known. These appear to be evenly distributed across the various age groups. Of the fatalities, four of the five were over the age of 50.

"The victims were mainly maintenance workers and process operators. Half of the victims were contractors hired by the company in question, one-third were members of the company's staff."

The characteristics of the victims are presented in greater detail in Subsection A2.3.4 of Appendix 2, where they are categorised by the severity of their injuries.

2.5 The companies and activities

2.5.1 Legal regime

Ninety-seven percent of the incidents analysed occurred at Seveso companies. Given the field of operation of the SZW Inspectorate's Major Hazard Control Department, this is hardly surprising. To be more specific, these incidents mainly occurred at upper tier establishments. Three per cent of the incidents occurred at companies that did not fall under the Seveso III Directive. Those incidents involved relatively large numbers of victims. One possible explanation for this is that the SZW Inspectorate only investigates such incidents in exceptional cases, for instance when the incident involved is relatively severe.

Table 2.5. Seveso regime.

Seveso regime	**Incidents**		**Victims**	
	Number of	% of	Number of	% of
Upper tier establishment	278	85%	170	79%
Lower tier establishment	37	11%	26	12%
Not a Seveso company	11	3%	19	9%

2.5.2 Type of company

The types of companies involved were categorised using the Statistical classification of economic activities in the European Community (NACE) [15]. The incidents mainly occurred at sites for the manufacturing of chemicals and chemical products (code 20, see Figure 2.6). Far fewer incidents took place at refineries and petroleum processing plants (code 19) or involved warehousing and support activities for transportation (code 52). A comprehensive list of company types, including an additional level of detail, is included in Subsection A2.5.1 of Appendix 2.

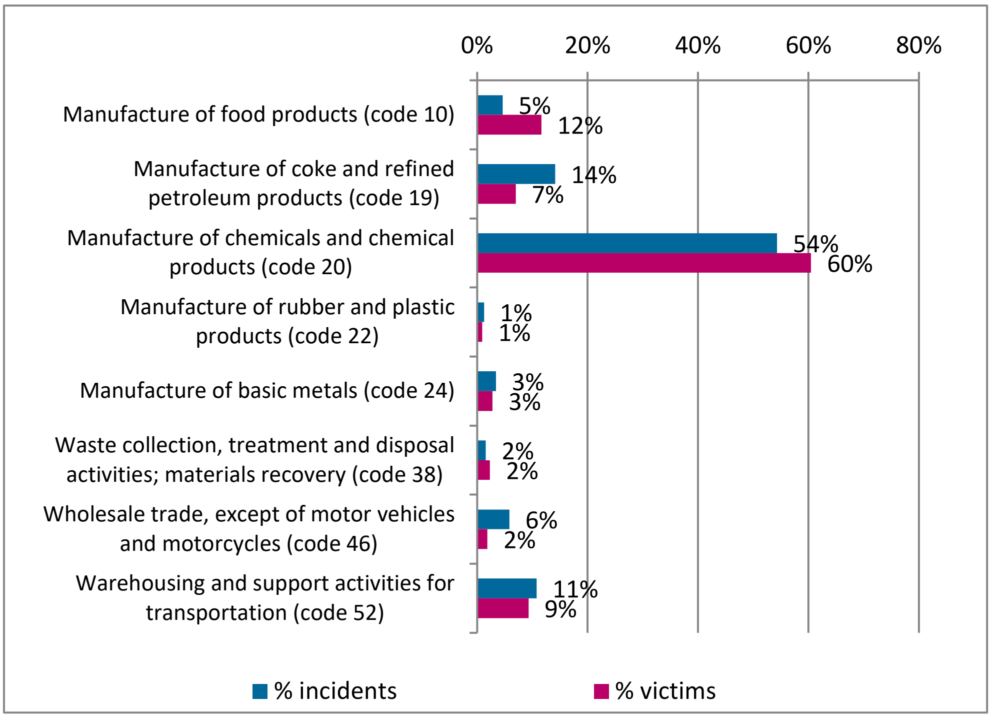


Figure 2.6. Company types (2-digit NACE code).

2.5.3 *Size of the company site*

The incidents occurred at both small and large sites, see Figure 2.7. In addition, the size of the site was measured in terms of its registered number of employees. Incidents at sites in the '250 to 1,000' registered employees category involved a relatively large number of victims, whereas those in the '1,000 or more' category involved relatively few. The reasons for this difference have not been investigated.

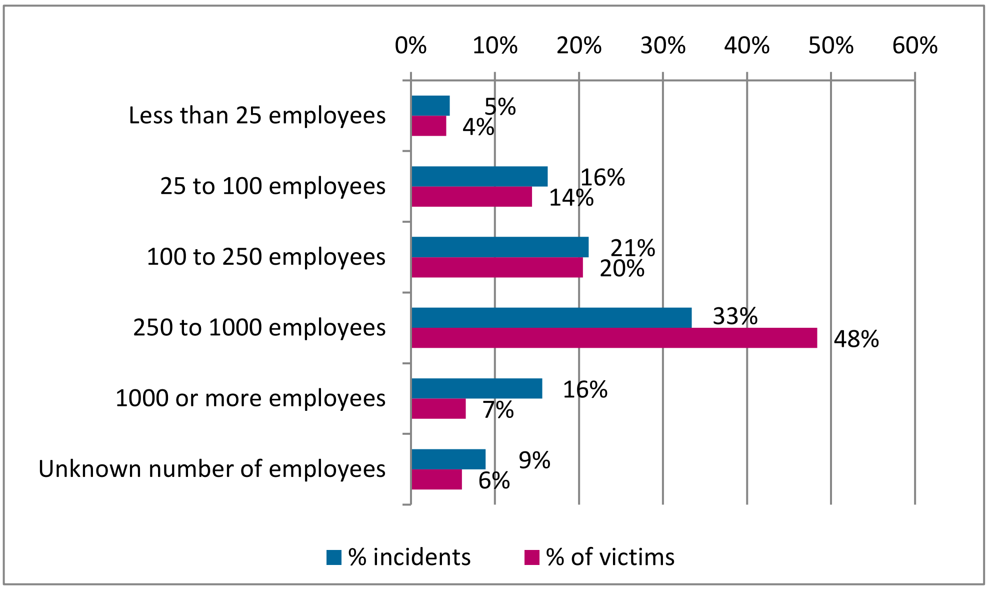


Figure 2.7. Size of the site (measured in terms of its registered number of employees).

2.5.4 *Process stage and activity prior to the incident*

Approximately 60% of incidents occurred during normal operation, 20% during maintenance, inspection and cleaning, and 13% during process start-up or when an installation was being commissioned. This picture conflicts with the commonly expressed view that most incidents occur during maintenance. However, for the incidents that occurred during maintenance, inspection and cleaning, there were more victims per incident. See also Subsection 5.3.

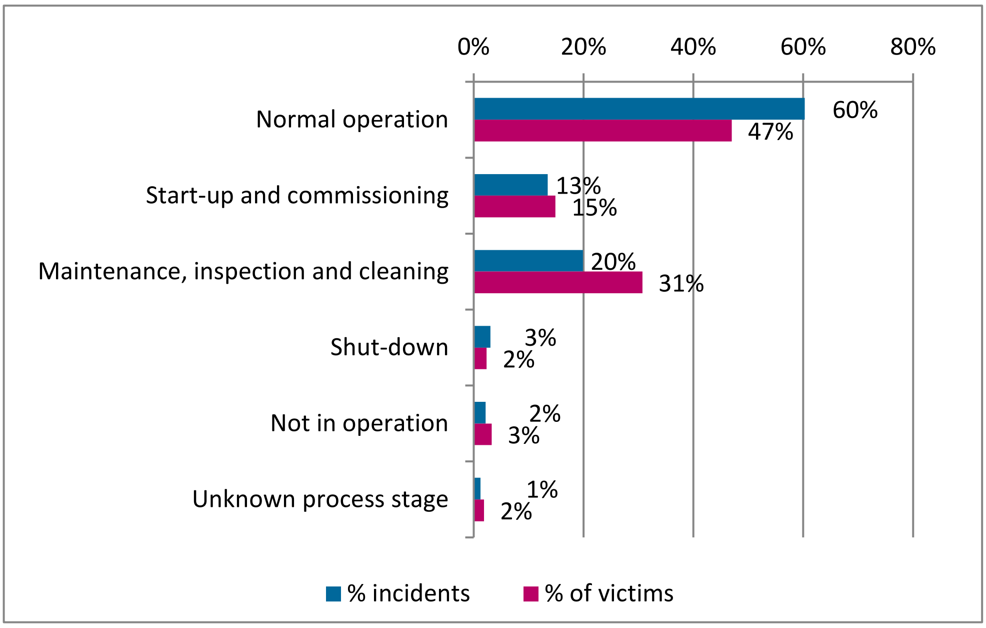


Figure 2.8. Process stage prior to the accident (percentages of total).

"60% of the incidents occurred during normal operation. Those incidents that occurred during maintenance, inspection and cleaning involved relatively larger numbers of victims per incident."

The activities carried out prior to the incident are described in Subsection A2.5.3 of Appendix 2. Most incidents involved 'adding/removing a substance'. This is in line with the previous finding that most incidents occur during normal operation (see Subsection 2.5.4).

2.6 The immediate causes

In these analyses, the immediate cause is defined as the failure mechanism that, chronologically speaking, directly precedes the incident. The immediate cause is not necessarily the reason why the incident arises in the first place (i.e. the underlying cause of failure). For example, if a faulty design leads to a corrosion leak, the immediate cause would be corrosion. If an installation fails as a result of high pressure caused by a dosing error, the immediate cause is high pressure. In exceptional cases, two immediate causes can be identified that jointly and inseparably lead to the incident.

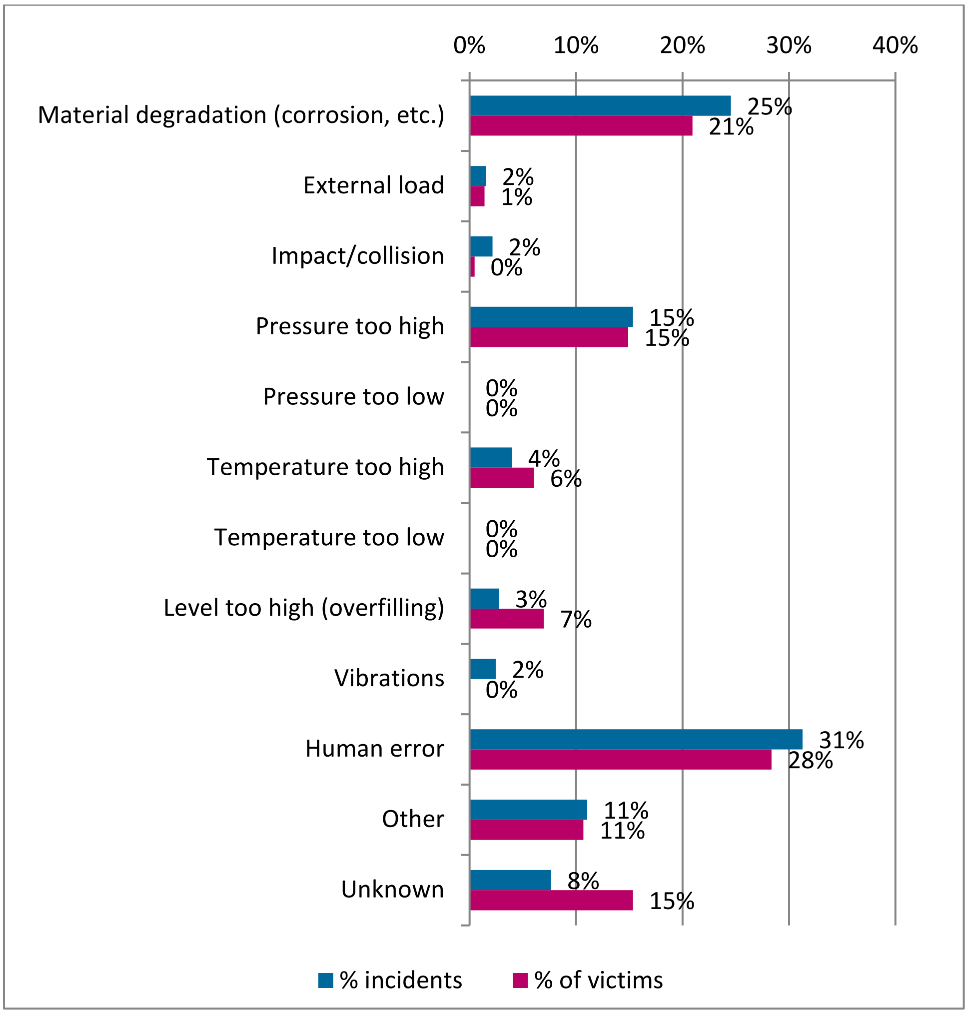


Figure 2.9. Immediate causes of the accident.

As shown in Figure 2.9, the most common immediate cause is human error. Here, 'human error' means 'error in human action'. In essence, an incorrect action or decision leads directly to the incident in question. It could also involve a failure to perform an action, such as not closing an opening to the outside air before starting up. Here, the term 'error' refers only to the consequences of the action and not to the underlying motivation. In particular, an 'erroneous' action could result from correctly following a given procedure (which could itself be substandard). In such cases, the 'human error' is, in fact, the fault of the organisation (or its staff).

After 'human error' (31% of incidents), the most common causes were material degradation (25%) and too high pressure (15%). Forty-four cases of material degradation involved corrosion and four involved erosion, while another 26 were due to other forms of material degradation, such as fatigue, fracturing, creep and wear. The category 'other' (36 incidents) concerns immediate causes that cannot be classified in any of the other categories. Because this category has not been analysed further, it is not possible to determine what other immediate causes might have been involved here.

> "Incidents are mainly the direct result of undesired human actions and material degradation."

Section 3 covers the causes of incidents in detail.

2.7 Substances and quantities

2.7.1 Substances and products involved

The registered information indicates that in the 326 incidents a total of 166 different substances or products were released. Table 2.6 lists 24 substances and products that were associated with six or more incidents or with incidents involving five or more victims. Most of the victims were involved in incidents with chlorine and hydrochloric acid (pure or in solution). Hydrogen was the substance involved in the highest number of incidents (21x), followed by chlorine (14x), ammonia (13x) and hydrochloric acid (11x). Subsection A2.4.1 of Appendix 2 contains a complete list of the substances involved.

Table 2.6. Substances involved (number of victims ≥ 5 or number of incidents ≥ 6).

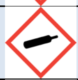
Substance, product or solution	Number of victims	Number of incidents
Chlorine	24	14
Hydrogen chloride (hydrochloric acid)	18	11
Hydrochloric acid (solution)	18	6
Oleum	9	1
Caustic soda (solution)	8	7
Ammonia	7	13
Phosphorus	7	5
Phosgene	7	2
Chloroacetaldehyde	7	1
Isoprene	7	1
Ethylidene norbornene	6	1
Hydrogen sulphide	5	9
Toluene	5	3
Acetyl chloride	5	1
Hydrogen	4	21
Ethylene oxide	4	10
Steam/Hot water	4	6
Gasoline	2	7
Ethanol	2	6
Naphtha	2	6
Benzene	1	10
Gasoline (diesel)	1	6
Propene (propylene)	1	6
Methane	0	6

2.7.2 Hazard categories

According to the European CLP Directive (Regulation 1272/2008), hazard statements must be assigned to specific substances. These hazard statements, also known as H phrases, indicate the main hazards associated with the substance. The CLP Directive lists a total of 78 different hazard statements. The CLP Directive also identifies the labels that apply to each of the various hazard statements. These labels indicate the hazard category to which a given hazard statement belongs. These labels also apply to substances that have been assigned one or more hazard statements within the group. The CLP Directive defines a total of nine different hazard categories. Some substances are assigned more than one label. Other substances are not assigned any label.

Table 2.7 indicates how often the various hazard categories were involved in an incident or, in other words, how often one or more substances belonging to the relevant hazard category were involved in an incident. Most incidents are associated with the category of flammable substances. Most of the victims are associated with the toxic category.

Table 2.7. Hazard categories according to the CLP Directive.

Label	Picto-gram	Summary of the hazard[12]	Number of incidents	Number of victims
GHS01		Explosive	1	1
GHS02		Flammable	133	49
GHS03		Oxidising	19	28
GHS04		Pressurised and cryogenic gas	7	3
GHS05		Corrosive	69	61
GHS06		Toxic	101	78
GHS07		Harmful	99	64
GHS08		Health hazard	120	50
GHS09		Environmental hazard	65	54
		No hazard category involved	18	14
		Unknown hazard categories involved	85	73

[12] This table uses the hazard pictograms that substances must carry, according to the European Regulation on the classification, labelling and packaging of substances and mixtures (the CLP Directive). These do not have catchy descriptions. An unofficial description has been added, for the reader's convenience.

Table 2.8 and Table 2.9 give further details for hazard statements related to flammability and toxicity.

Table 2.8. Incidents involving flammable substances: relevant H phrases.

H phrase	Description	Number of incidents	Number of victims
H220	Extremely flammable gas	73	17
H224	Extremely flammable liquid and vapour	8	8
H225	Highly flammable liquid and vapour	47	19
H226	Flammable liquid and vapour	11	5

Table 2.9. Incidents involving toxic substances: relevant H phrases.

H phrase	Description	Number of incidents	Number of victims
H300	Fatal if swallowed	3	1
H301	Toxic if swallowed	25	14
H311	Toxic in contact with skin	25	14
H330	Fatal if inhaled	26	26
H331	Toxic if inhaled	79	59

Disclaimer to the previous tables:
In the Netherlands, the CLP Directive came into force halfway through the period of analysis (2004-2018). The analysis model originally used the classification system stipulated by the former Environmentally Hazardous Substances Act. The CLP classification system was added to the model in 2017. For incidents that were analysed prior to 2017, the CLP classification of the substances involved was added in 2018. A database of the European Chemicals Agency (ECHA) with a reference date of 28 September 2018 [16] was used for this. This database only contained hazard statements that had already been assigned (harmonised entries). In September 2018, a number of proposed hazard statements (notified entries) had not yet been processed. This means that the database used is not complete in terms of hazard statements on substances. This is especially evident from the small number of incidents involving pressurised and cryogenic gases (GHS04). While the underlying hazard statement – H280 – is plausible for substances such as hydrogen and methane, it has not yet been officially assigned. Thus, with regard to hazard statement H280 and the associated GHS04 hazard label, some underreporting may very well have been involved.

2.7.3 Quantities involved

Figure 2.10 shows the amounts (mass) involved in the 326 incidents. The figure shows substantial variation in quantities. In 21 incidents, less than one kilogram of hazardous substance was involved. At the other end of the scale, 33 incidents involved the release of more than 10 tonnes of hazardous substances. In one-third of incidents, insufficient information was available to properly estimate the amount involved. None of these 102 incidents was notifiable with regard to the eMARS registration system (see Subsection 2.2); therefore, the quantities involved in these incidents would have been below the threshold value for this notification requirement.

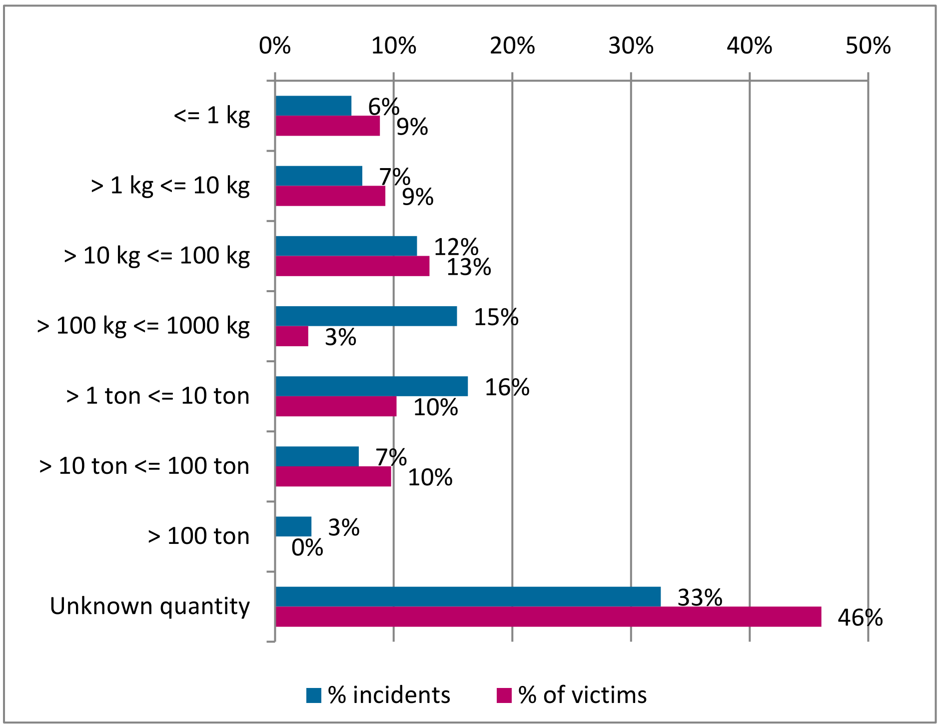


Figure 2.10. Amount (mass) of hazardous substances involved.

Subsection A2.4.3 of Appendix 2 shows the relationship between the quantities involved and the victims' severity of injuries. In Subsection 5.3, the possibility of a correlation between these two parameters is explored.

2.8 Items of equipment and location of release

Most incidents occurred in – or from – items of equipment in process installations (160x). In more specific terms, these were process piping (58x), reactor vessels (35x), and various types of product separators (31x). In addition, 36 of these incidents occurred in fixed storage tanks, 25 in piping at unloading areas and 21 in long pipelines for transport or unloading. See Subsection 2.6 of Appendix 2 for more details.

The release usually occurs from an open connection or valve, such as loose connections (39x) or couplings (19x), open valves/open isolation valves (23x), pressure relief valves (22x), taps for liquids (15x), piping (14x) and vents (11x). Eighty-four incidents involved a hole in the wall of a tank or pipe. See Subsection A2.6.2 of Appendix 2 for more details.

2.9 Material and ecological consequences

The identification of any material damage to installations is not the main objective of SZW Inspectorate investigations. Nevertheless, the information contained in their investigation reports is usually sufficient to determine whether the installations in question sustained any damage.

Installations were damaged in at least one out of every three incidents, while in at least half of all cases they suffered no damage (see Figure 2.11). This picture corresponds to the previous observation that, in the majority of incidents, hazardous substances were released through existing openings and loose connections. Once the opening was closed or the connection restored, the installation in question could resume normal operation. In 15% of the incidents, it was unclear or unknown whether any material damage had occurred.

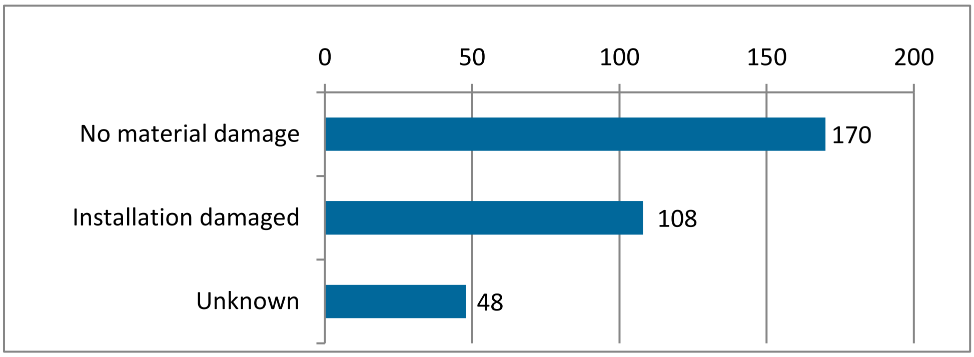


Figure 2.11. Material damage: number of incidents.

The identification of any environmental damage is not the main objective of SZW Inspectorate investigations. The investigation reports seldom go into any detail on this topic. Based on the available information, the analysts attempted to assess whether or not environmental damage had occurred. If there is any doubt, the situation is classified as 'unknown'.

One in twelve incidents resulted in environmental damage inside or outside the establishment (see Figure 2.12). In half of all incidents, the analysts were of the view that there had been no environmental damage. In 42% of incidents, based on the available information, it was not possible to determine whether any environmental damage had occurred.

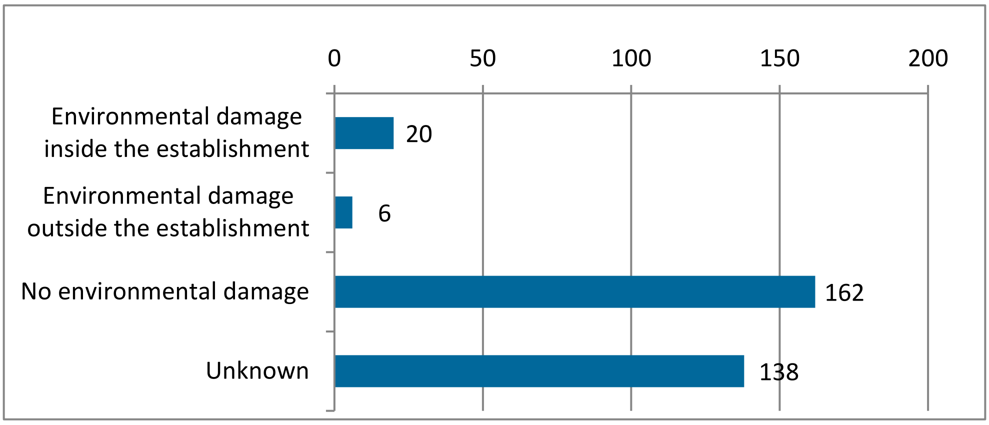


Figure 2.12. Environmental damage: number of incidents.

3 Ensuring safety: safety measures

3.1 Introduction

Safety measures are central to ensuring safety. Safety can be increased by taking (implementing) safety measures and by ensuring that these are – and continue to be – effective. Ideally, companies will have taken safety measures for dealing with all of the various ways in which incidents can occur (preventive measures). Companies must also take measures to limit the consequences of any incidents (mitigating measures).

Safety measures can be implemented through instruments, devices, procedures or a combination thereof. A face mask offers protection against the impact of a release of hazardous substances into someone's face, for example. However, face masks are only effective if people actually wear them. This calls for working instructions, procedures and supervision. The organisation must then identify specific circumstances in which face masks must be worn. Other types of safety measures include pressure control (sensors, signals, instructions and procedures), the prevention of corrosion (material and process specifications, regular monitoring of the material's condition), ignition prevention (design, procedures, working instructions) and fire repression (adequate facilities).

In practice, however, things sometimes go wrong – leading to incidents with undesired consequences. In such cases, specific safety measures will have failed. The necessity for such measures may not have been recognised or acknowledged, or perhaps the necessary measures had been taken but were not sufficiently effective.

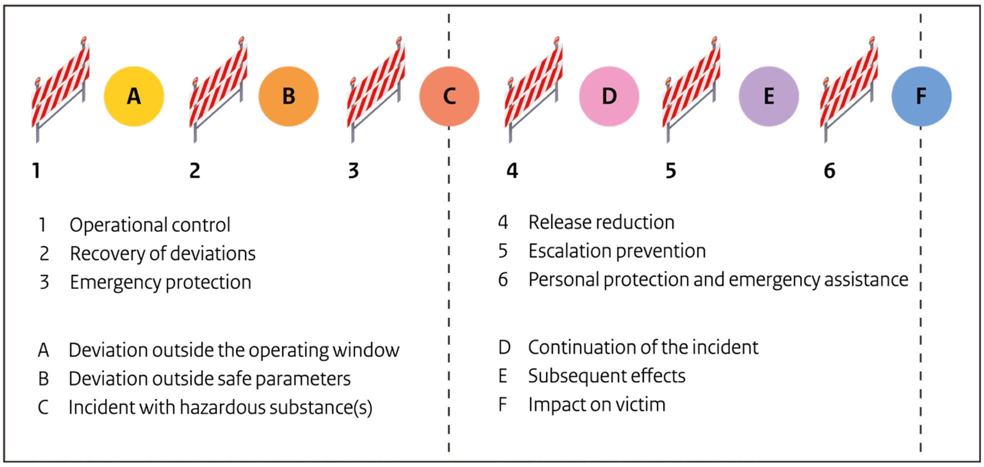


Figure 3.1. Lines of defence (represented by numbers) and the consequences of any failure (represented by letters) in the analysis model.

The Storybuilder MHC model identifies which safety measures are important for incidents involving hazardous substances. A total of 41 safety measures have been clustered into six groups of *lines of defence* (LoDs). Three of these are aimed at preventing incidents, while the purpose of the remaining three is to limit their consequences. Figure

3.1 is a graphic representation of the six LoDs and the consequences of their failure.

Analogy: preventing road accidents and limiting any injuries
An analogy is used to try to clarify the meaning of these LoDs: preventing road accidents and limiting any injuries. In the context of this analogy, the meaning of the six LoDs is as follows:

- Operational control. First, ensure that the road surface has markings to guide drivers. Next, ensure that you stay within the road markings.
- Recovery of deviations outside the operating window. Ensure that recovery is possible if, despite everything, you should come off the roadway. This could take the form of using a hard shoulder alongside the roadway, for example.
- Emergency protection. Prevent the vehicle from coming off the road, e.g. by installing a crash barrier.
- Release reduction (impact). If an incident should occur, ensure that its impact is as limited as possible, e.g. through crumple zones in the car, seatbelts and airbags.
- Escalation prevention. Prevent the incident from getting any worse. Extinguish any incipient fires quickly to stop them spreading. Prevent any other vehicles from becoming involved in the incident.
- Personal protective equipment and assistance. First aid and professional assistance. Treat victims as soon as possible to limit any consequences they might suffer.

This is the design of the analysis model. Companies are obliged to adequately protect their employees' safety, but how they do this is entirely up to them. Highway authorities may not always see the need for hard shoulders or crash barriers (in the case of minor roads, for example). In much the same way, companies are free to decide exactly how to guarantee safety and which measures are needed to serve this end. Instead of a hard shoulder or crash barrier, another option might be to reduce the maximum speed.

The classification described above is used when analysing incidents. The analysis model shows which lines of defence are possible and which were present during the incident.

Three questions are always asked during the analysis (see Figure 3.2):

- What went wrong?
- How did it go wrong?
- Why did it go wrong?

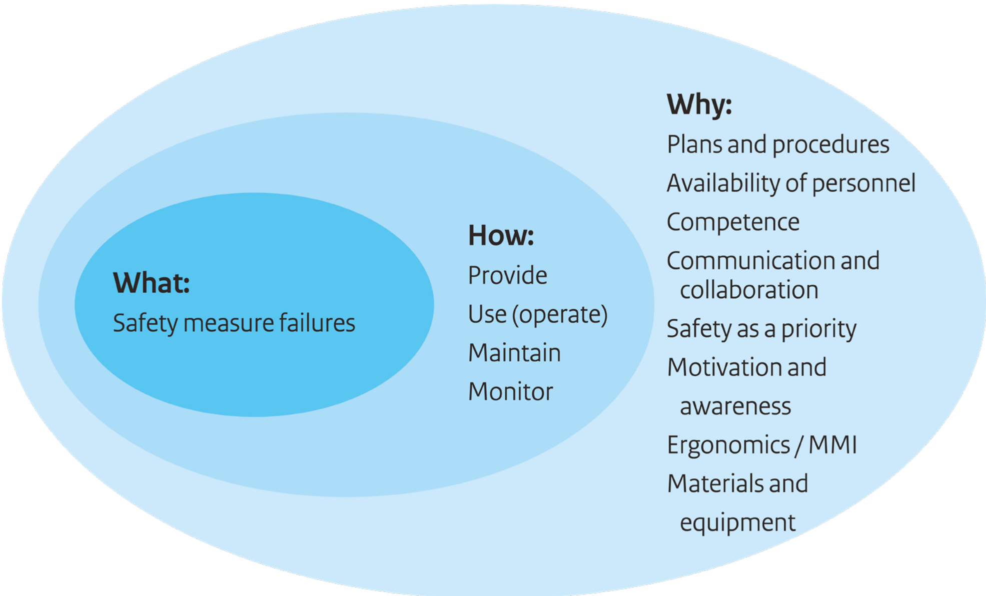


Figure 3.2. Structure of the analysis model for underlying factors.

What went wrong?
This concerns the safety measures that failed during the incident. Here, 'failure' means that, during the incident, the requisite protection was lacking. The required protection had either not been implemented or was ineffective. As stated, the model identifies 41 different safety measures distributed between six *lines of defence*. Details about which safety measures failed in the 326 incidents and the consequences are discussed in Subsections 3.2 to 3.5.

In some cases, the safety measures proved successful. This is also registered in the analysis model. The considerations involved in classifying a given measure as a 'failure' or a 'success' are described in Subsection A.1.4 of Appendix 1.

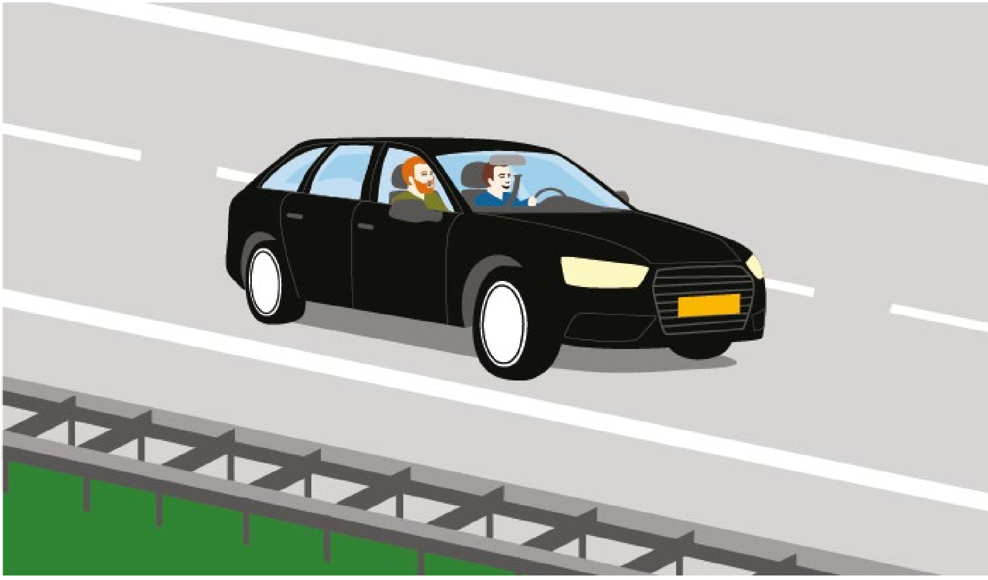
How did it go wrong?
Safety measures can only offer protection if they have actually been put in place and, moreover, function effectively. The analysis model translates this into four elements: safety measures must be Provided (implemented), Used, Maintained and Monitored. Subsection 3.6 addresses the issue of how safety measures in each of the various *lines of defence* failed.

Why did it go wrong?
The organisation must ensure that safety measures are put in place, that they continue to function effectively and that they are correctly used. Companies operate safety management systems for this purpose. For the analyses, the elements of these systems are classified in two different ways. Both are discussed in Subsection 3.7, as are the findings for the 326 incidents.

Section 3 is probably the most technical section of this report. For those who are only interested in the main points of the analysis, the findings are summarised in Subsection 3.8.

3.2 1st LoD: operational control

The first *line of defence* involves operational control. In terms of the road accident analogy, this means: (i) ensure that the road surface has markings to guide drivers and (ii) ensure that you stay within the road markings. Towards this end, various requirements must be satisfied. For instance, the driver must be sufficiently fit and alert, the vehicle must be in good condition and it must be travelling at a speed that is suited to the prevailing conditions.



With regard to incidents involving hazardous substances, this means:

i. **Safe start or start-up**: ensuring that you can safely perform any actions involved.
ii. **Ensuring the integrity of the installation**: ensuring that the items of equipment in the installation and the connections are in good condition ('asset integrity') and that they stay that way.
iii. **Controlling process parameters**: ensuring that the process parameters remain within predefined suitable operating windows.
iv. **Site/environment control**: preventing external factors from causing an incident.

In terms of safety measures, this LoD includes 18 different measures, divided into four groups. A comprehensive overview of these measures and how they are subdivided into groups is included in Subsection A#.2 of Appendix 3. The measures are independent of each other – several measures can fail in any given incident.

3.2.1 Which operational control elements failed?

Figure 3.3 shows which groups of operational control safety measures fail most frequently.[13] Three groups have a similar record in this regard: ensuring the integrity of the installation, controlling process parameters, and safe start or start-up. In their efforts to improve safety, inspectorates and companies cannot focus solely on a single measure that has a major effect.

[13] Several safety measures can fail in any given incident.

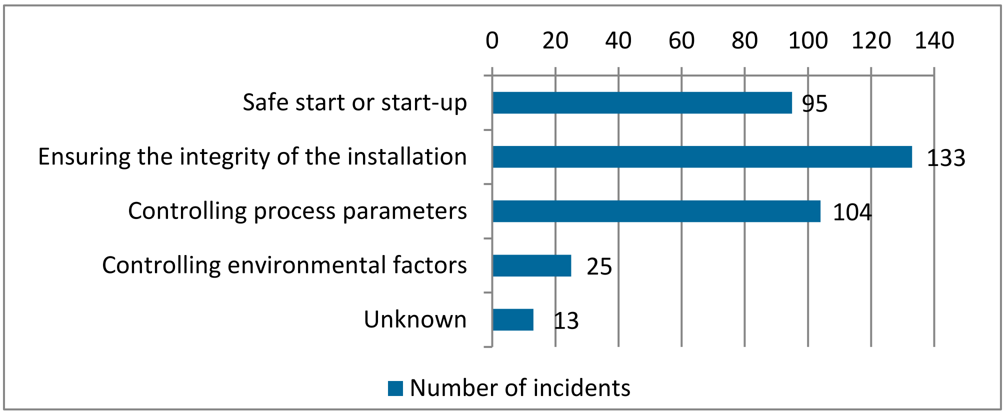


Figure 3.3. Failure of groups of safety measures in operational control.

"No dominant cause is responsible for the occurrence of incidents. Therefore, in attempting to improve safety, companies and inspectorates cannot focus solely on a single group of measures that have a major effect."

Ensuring the integrity of the installation:
In 133 incidents (41%), one or more of the measures taken to safeguard the material integrity of the installation failed.

- In 48 incidents, insufficient measures were taken to prevent material ageing. Most cases (30x) involved corrosion.
- In 38 incidents, insufficient consideration was given to the material's suitability and to its protection. For instance, unsuitable materials had been used or the material was insufficiently protected against material degradation.
- In 35 incidents, loose or detached connections were involved. In most cases, this was due to incorrect assembly of the connections.
- In 21 incidents, deficiencies in the design of the installation were involved.
- In 17 incidents, various items of equipment in the installation were either missing or had been installed/assembled incorrectly.

Controlling process parameters:
In 104 incidents (32%), process parameters were poorly controlled.

- In 53 incidents, the flow was poorly controlled. This involved factors such as too much feed/flow (16x), blockage (12x) and insufficient discharge – or none at all (10x).
- In 26 incidents, the pressure (or process pressure) in installations had not been adequately controlled. The vast majority of cases involved the prevention of excessive pressure.
- In 23 incidents, undesired chemical reactions occurred during the normal process.
- In 13 incidents, the temperature was not under control – seven of these involved cooling failures, while the remaining six were due to heating failures.

Safe start or start-up:
Ninety-five incidents involved the failure of safe start or start-up measures (29%).

- In 83 incidents, few – if any – precautionary measures had been taken to ensure that processes or activities could be started safely. In 39 cases, an item of equipment in the installation had not been properly emptied and cleaned in advance. In 36 cases, an item of equipment in the installation that was not effectively isolated (e.g. due to leaking valves or wrongly positioned valves) had been opened. In 13 cases, an installation was being filled while part of it had unintentionally been left open.
- In 13 incidents, work was being carried out on the wrong containment.

Example of a safe start or start-up failure
In one case, an operator was asked to purge a pump in the process pipework by adding demineralised water. The operator was not familiar with the installation. The operator assumed that the pipework was product-free and that the demineralised water had to be added via a connection that was sealed with a blind flange. When loosening the bolts on the blind flange, a spray of liquid squirted out. Instead of being product-free, the pipework contained a hydrochloric acid solution at a pressure of 6 bar.

The operator had not been properly instructed in advance on how to carry out the work. As a result, the operator mistakenly believed that the blind flange needed to be opened and that the pipework was product free. No additional checks were carried out before the bolts on the flange were loosened. As a result, the act of loosening the bolts on the flange led to the irrevocable release of product.

Controlling environmental factors:
Twenty-five incidents (8%) involved an environmental deviation against which the installation was insufficiently protected.

- Ten incidents involved protection against collisions with vehicles.
- Eight incidents involved protection against heat from external heat sources.
- Four incidents involved a disruption to the power supply.

3.2.2 *What were the consequences of the failure of operational control?*

The failure of safety measures results in deviations in the work or in the installation itself. These 'deviations outside the operating window'[14] are comparable to a vehicle coming off the roadway.[15] They mainly involve (i) the unsafe starting of actions, (ii) material deviations outside operational limits and (iii) process deviations outside operational limits (see Figure 3.4). The deviations are, more or less, the mirror images of the safety measure failures shown in Figure 3.3.

See also Subsection A#.2.4 of Appendix 3.

[14] Any given incident may involve several deviations outside the operating windows.
[15] After all, the primary goal of safety management is to set operating windows and to remain within them.

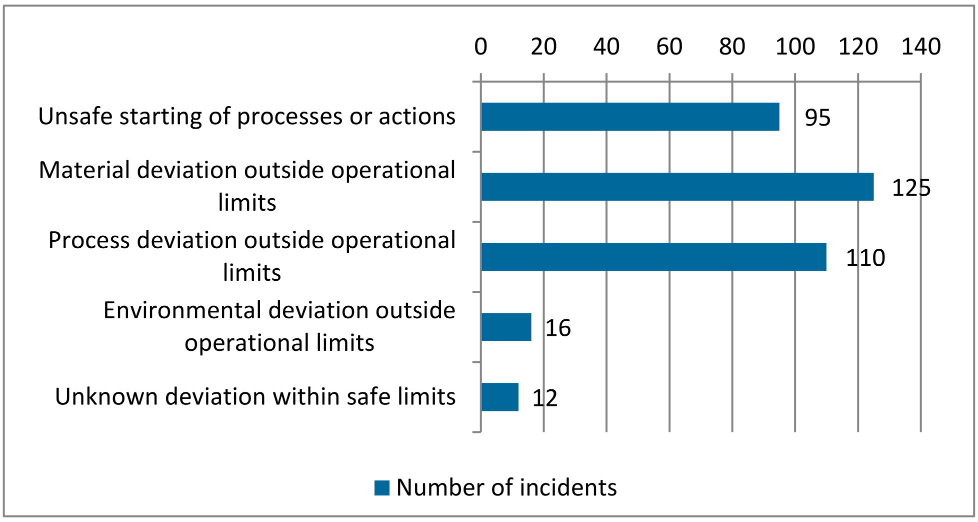
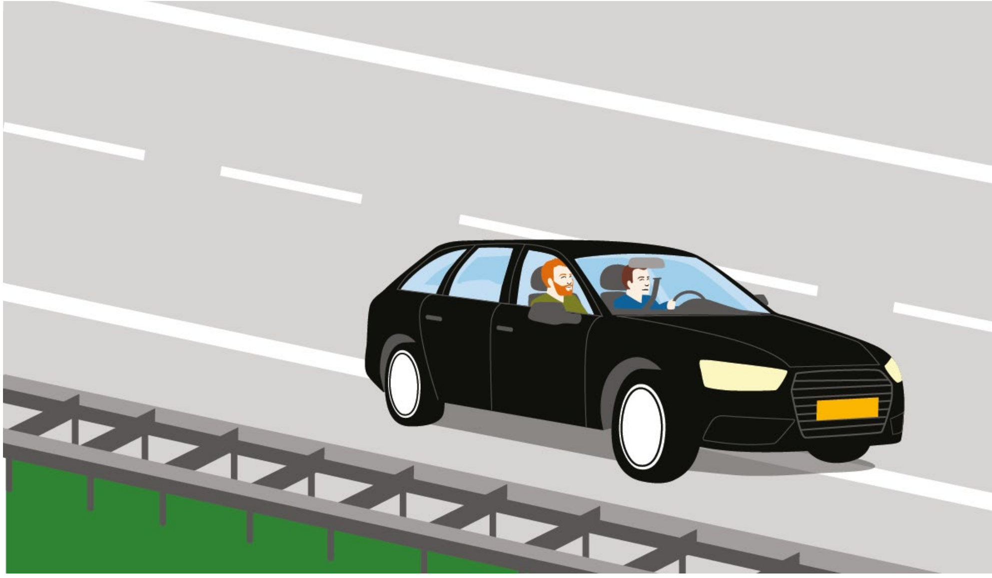


Figure 3.4. Deviations outside the operating window.

3.3 2nd LoD: recovery of deviations outside the operating window

The second *line of defence* involves measures taken for the prompt detection and correction of any deviations outside the operating windows.

In terms of the road accident analogy, this means: ensuring that recovery is possible if, despite everything, you should come off the roadway. This could take the form of a hard shoulder alongside the roadway, for example. Measures can be taken to enhance the additional protection offered by the hard shoulder. If physical markings (rumble strips) are added to hard shoulders, motorists will quickly be alerted to the fact that they have strayed onto the hard shoulder. Automatic detection systems can also fulfil this function. It is also possible to diminish the protection offered by the hard shoulder. This could involve placing obstacles on the hard shoulder or tolerating their presence there. In addition, if the hard shoulder is used as an extra driving lane, it will lose its function as an additional form of protection.



3.3.1 *Which elements of the 'recovery outside the operating window' failed?*

In the case of incidents involving hazardous substances, this LoD contains just a single safety measure that applies generically to all incidents – the 'recovery of deviations outside the operating window'. The analysis model distinguishes four elements that are needed for a successful 'recovery of deviations outside the operating window'. These are explained through the hard shoulder analogy. One of these elements is selected for each incident.

i. **Indication**: the presence of a road marking between the main roadway and the hard shoulder, making it possible for drivers to identify that their vehicle has come off the roadway.
ii. **Detection**: the awareness that the vehicle is veering onto the hard shoulder. Rumble strips on the hard shoulder or automatic line detection can enhance detection.
iii. **Diagnosis**: the realisation that driving on the hard shoulder is undesirable.
iv. **Recovery**: a prompt return to the main roadway.

Recovery of deviations; the four elements of the analysis model

- **Indication**. Presence of an operational instrument, system or procedure that can be used to promptly identify any deviations.
- **Detection**. The indication of the deviation triggers a visible or audible signal, or an alternative. More specifically, such signals must be clear (strong) enough to be detectable against any background noise. While human observers could be involved in detection, automatic systems (such as an automatic protection system) could perform the same function. The outcome (detection of the signal) is all that counts here.
- **Diagnosis**. Correct interpretation of the nature and seriousness of the observed deviation. While human observers could be involved in diagnosis, automatic systems could perform the same function. The outcome (correct diagnosis) is all that counts here.
- **Remedial action**. Correct diagnosis of the deviation leads to measures that enable the prompt and adequate resolution of the (potentially) unsafe situation. Corrective actions return the system to a safe operating window. Any activities may be temporarily suspended or terminated. In addition, remedial actions can either be performed by humans or by automatic systems. What counts is the correct action.

Figure 3.5 shows how often each of the elements involved in the recovery of deviations failed. In almost half of all incidents (156 incidents, or 48%), the indication of the deviation failed. This means that the companies involved had no suitable and effective instruments or procedures that would have enabled them to promptly identify any deviations. As a result, any deviations that developed were undetectable. Safety can be improved by increased monitoring, more extensive inspections and by performing additional final checks before starting any actions.

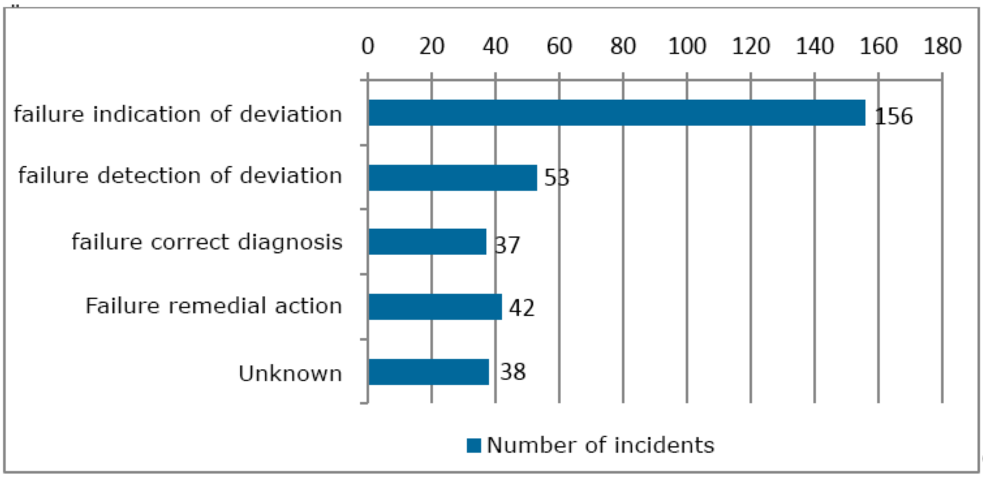


Figure 3.5. Ways in which recovery of deviations fails.

Example of an indication of deviation failure
Hot steam was being transported through a pipeline. Sustained high pressure in the pipeline had caused the metal to deform ('creep'). This deviation in the pipeline material was not picked up during the inspection programme. As a result, the material continued to weaken until the pipeline finally burst. A fragment of pipe weighing about 300 kg was launched into the air and ended up in a workplace 60 metres below the pipeline. The high-pressure jet of steam that was released punched a hole through the front of the building.

The pipeline failed due to the ageing of the material as a result of creep. The phenomenon of creep had been identified during inspection and maintenance activities and had been monitored through non-destructive testing (NDT). However, rather than being carried out at the most critical point, these inspections were performed elsewhere, in a more accessible area. Therefore, the non-destructive testing was unable to identify any deviation at the most critical point. Unclear guidelines for determining which points should be tested for creep were also a factor in play.

3.3.2 *What were the consequences of the failure of recovery?*

Unsuccessful recovery leads to deviations outside safe parameters.[16] The most common deviations are:

- physical failure of the containment or the connections;
- the active opening of a containment that, undesirably, still contains product;
- pressure, temperature or level outside safe parameters;
- flammable conditions in a containment or its immediate vicinity.[17]

The first two types of deviation usually result in the immediate release of product. Thus, in the case of these deviations, few if any further preventive measures are possible. In total, 59% of incidents involved situations of this kind. The other deviations (41%) do not immediately and inevitably result in the release of product, fire or explosion. In these

[16] Any given incident may involve several deviations outside safe parameters.
[17] The phrase 'flammable conditions in the vicinity of a containment' refers to incidents in which hot work activities are performed in an environment that is contaminated with flammable product. Hot work activities can cause this product to evaporate and, possibly, ignite.

cases, further preventive measures can often be taken. These are discussed in the following subsection.

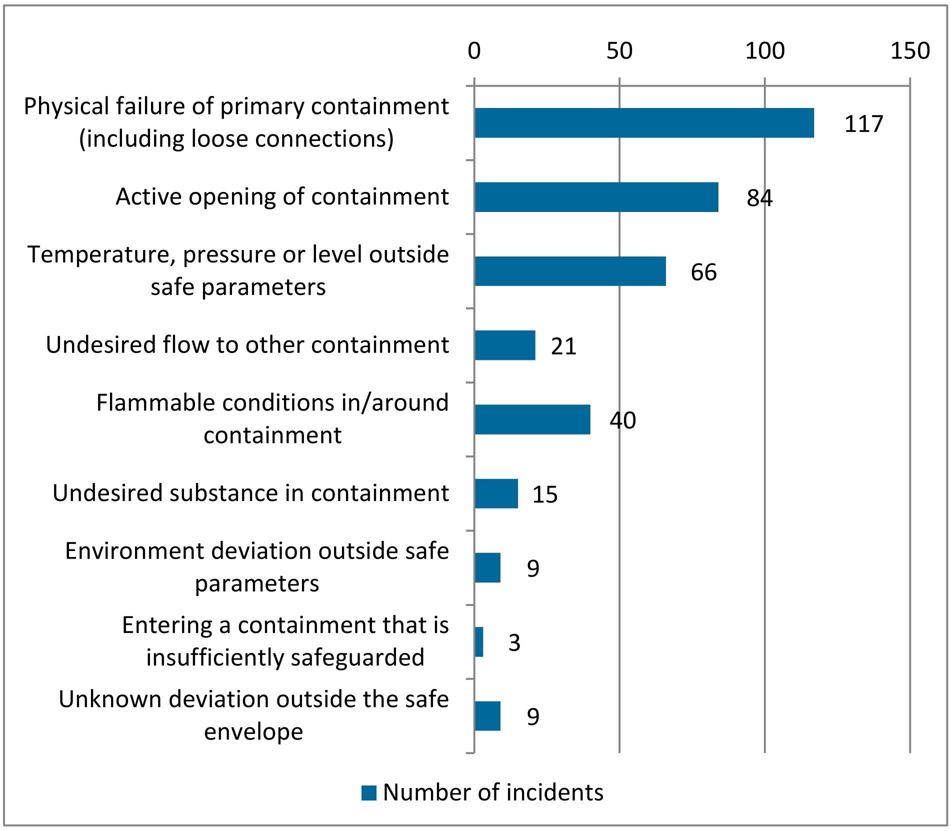
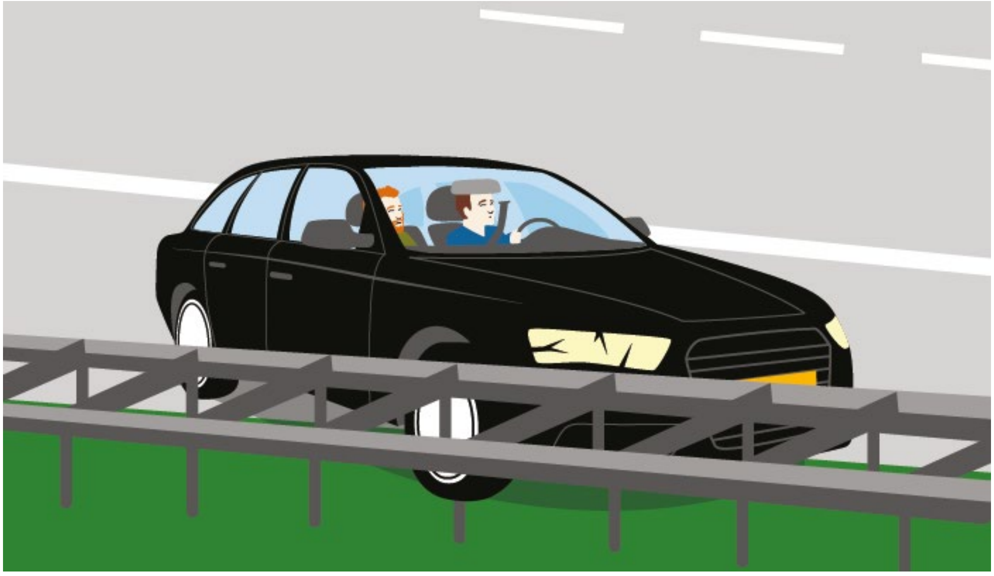


Figure 3.6. Deviations outside safe parameters.

See also Subsection A#.3.4 of Appendix 3.

3.4 3rd LoD: emergency protection

The third *line of defence* concerns emergency measures to prevent an incident or accident involving hazardous substances. In terms of the road accident analogy, this would be a crash barrier. Crash barriers prevent vehicles from crashing into the roadside verge. The vehicles involved may still sustain a moderate amount of damage. It is not always possible (or reasonably achievable) to install a crash barrier. One example would be roads in urban environments, which have crossing points where cyclists and pedestrians can cross.



In the case of incidents involving hazardous substances, these would be the most extreme measures to prevent serious incidents if a deviation occurs for which there is no adequate recovery. This could involve, for instance, venting or flaring hazardous substances into the environment in order to prevent an item of equipment in the installation from failing completely due to excessive pressure. As a result of this measure, instead of a serious incident (failure of an item of equipment in the installation), a less serious incident occurs.

Table 3.1. Emergency protection options.

Emergency protection options	Number of incidents
Emergency protection possible	135 (41%)
Emergency protection not possible/unrealistic	191 (59%)

Firstly, while for many types of incidents special emergency measures exist to prevent the incidents from occurring if there has been no recovery, certain exceptions apply. In 59% of incidents (see Table 3.1), it is difficult to imagine what emergency measures could have been taken given the nature of the deviation (see Section 3.3.2). These were primarily incidents that involved failing installations due to material degradation or weak connections, and incidents in which installations were actively opened.

- For example, if corrosion develops (failure of operational control) and is not promptly detected by corrosion inspections (remedial action failure), a corrosion leak will occur. This will cause the immediate release of hazardous substances. No emergency protection measures are in place for the stage between the failure of the corrosion inspection and the occurrence of the corrosion leak.
- If an installation has to be opened for work but is not properly rendered product-free beforehand (failure of operational control) and if that failure was not detected (remedial action failure), then hazardous substances will immediately be released when the installation is opened. In most cases, there is nothing to be done, aside from limiting the duration or amount of the release, which

is a mitigative measure. Only in some cases could a release still be prevented, for example by using an interlock system. For details, see the end of the following subsection.

"No emergency measures were reasonably achievable for 59% of the incidents investigated. For these incidents, safety was based on two pillars – safe operational control and prompt recovery of deviations."

3.4.1 *Which elements of the emergency protection failed or succeeded?*

Figure 3.7 shows which emergency protection measures failed or succeeded. [18] This figure only relates to the 135 incidents in which emergency measures were possible (see Table 3.1). The measures are taken independent of each other – several measures can fail or succeed in any given incident.

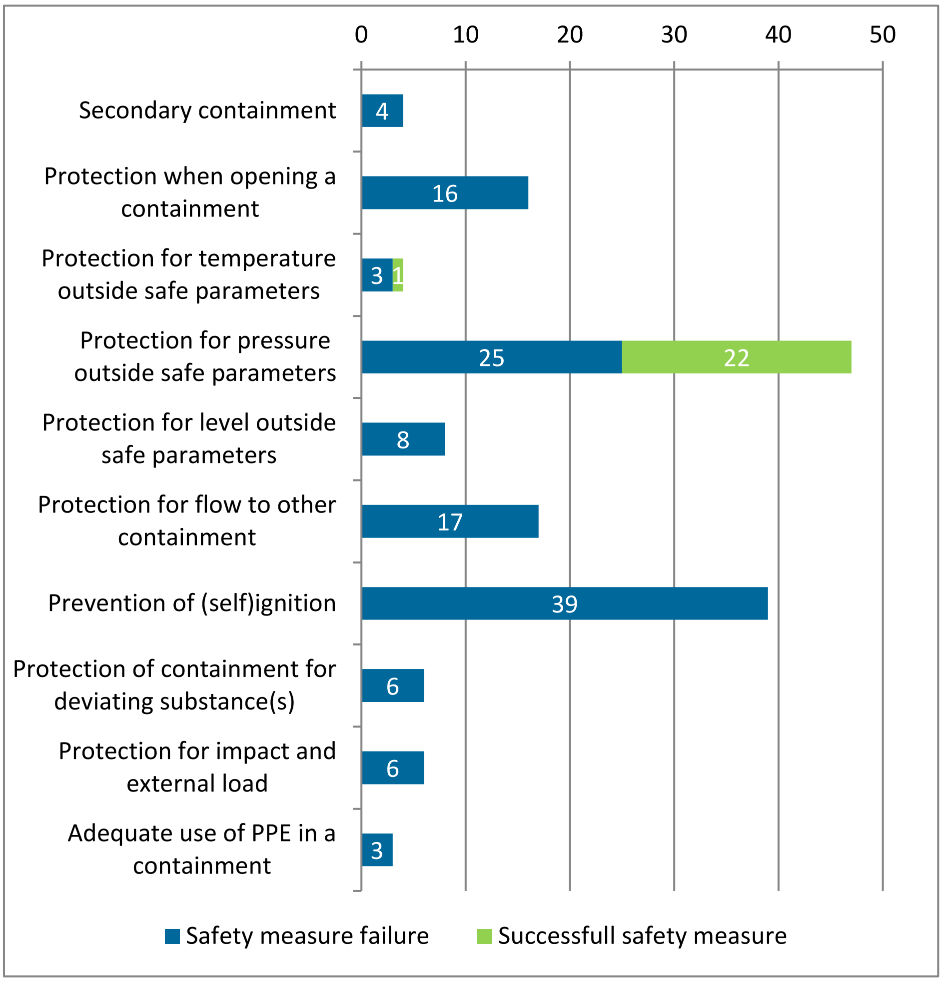


Figure 3.7. Safety measures with regard to emergency protection: number of times that the safety measure failed or succeeded. Note: the 3rd LoD was only relevant for 41% of all incidents.

Measures are deemed to have been 'successful' if they actually (and effectively) fulfilled the required safety function. The emergency protection against pressure outside safe parameters serves to prevent

[18] The terms 'failure' and 'success' are defined in Subsection A1.4.

an item of equipment in the installation from failing due to excessive pressure. This measure proved to be effective in 22 incidents. Nonetheless, product was vented or flared, leading to a classification as 'incidents'. To continue the road accident analogy: crash barriers are there to prevent serious accidents, not to bring cars to a halt without causing any damage whatsoever.

Preventing ignition or self-ignition
Fires start when a flammable mixture comes into contact with an ignition source.[19] In flammable mixtures, ignition prevention is a preventive measure taken to prevent immediate fire or explosion (preceding the release of hazardous substances) and a repressive measure to prevent delayed fire or explosion (following the release of hazardous substances). The preventive measure, which is included in the 3rd LoD failed on 39 occasions. In 16 cases, an ignition source was present in a containment. Five cases involved static electricity, while two concerned hotspots. Self-ignition of a mixture was involved in 11 cases. The repressive measure is included in the 5th LoD, see Subsection 3.5.

Protection against pressure outside safe parameters
The function of this emergency protection is to prevent equipment items in the installation from failing due to excessive pressure. This includes emergency shutdown systems (ESD), rupture discs, emergency venting systems and explosion hatches. The measure failed on 25 occasions and succeeded on 22 occasions.[20]

Example of a pressure protection system failure
A process installation was being recommissioned after maintenance. This involved the use of a heating fluid to heat two reactors in the installation. Because this heating process was initially too slow, the heat feed was increased. Chemical reactions in the installation then led to deviations in level, pressure and temperature. The causes of these process parameter deviations were not promptly identified and eliminated. This created an excessive pressure outside safe parameters in the installation.

The installation's design included an off-gas system and pressure relief valves to relieve pressure in the event of excessively high pressure. However, due to previous level deviations in the installation, the off-gas system had already been closed. The pressure relief valves had insufficient capacity to compensate for the rapid increase in pressure caused by the above-mentioned chemical reactions. As a result, a reactor vessel and a separator vessel in the installation failed due to excessive pressure.

Protection when opening a containment
If a containment that has not been properly rendered product-free is opened, there are generally no further measures that might prevent the release of these hazardous substances. The model lists three exceptions:

- Some installations contain (inter)lock systems: automatic or procedural protection systems that prevent the opening of any

[19] When their self-ignition temperature is exceeded, substances can ignite without an ignition source.
[20] See text at the top of this page regarding the meaning of 'successful'.

items of equipment that are insufficiently isolated from the rest of the installation. Accident investigations revealed that, in seven incidents, release could have been prevented if an effective (inter)lock system had been used.
- Any openings to the environment that are not in use or that are only used incidentally can be sealed with an additional blind flange or blind plate. In six incidents, release could have been prevented in this way.
- Procedures for resolving blockages. In the event of blockages in a containment, the system has to be opened to resolve the blockage. The safe resolving of blockages is also included in this 3rd *Line of Defence,* and requires safe working practices.[21] Three incidents involved blockages that were resolved by means of unsafe working practices, inasmuch as the cause of the blockage was not taken fully into account.

3.4.2 What were the consequences of the failure of emergency protection?

Incidents occurred due to the failure of the various safety measures in the first three LoDs. The model distinguishes between the release of hazardous substances, fire, explosion and exposure to hazardous substances in a containment. Combinations of the above are also possible. The nature of these incidents was discussed in Subsection 2.3.1 of this report. Further details are available in Subsection A#.4.4 of Appendix 3.

3.5 Mitigating measures (4th, 5th and 6th LoDs)

Once incidents have occurred, companies must act to limit the consequences as quickly and effectively as possible. The model identifies three different *lines of defence* that can mitigate the consequences of an incident.

[21] Blockages are usually caused by incorrect flows (failure of operational control). If this cause is not sufficiently remedied, blockage will occur. Resolving blockages is an emergency measure.

4th LoD: release reduction
In the road accident analogy, this involves limiting the impact of the incident through crumple zones in the car, seatbelts and airbags, for example.

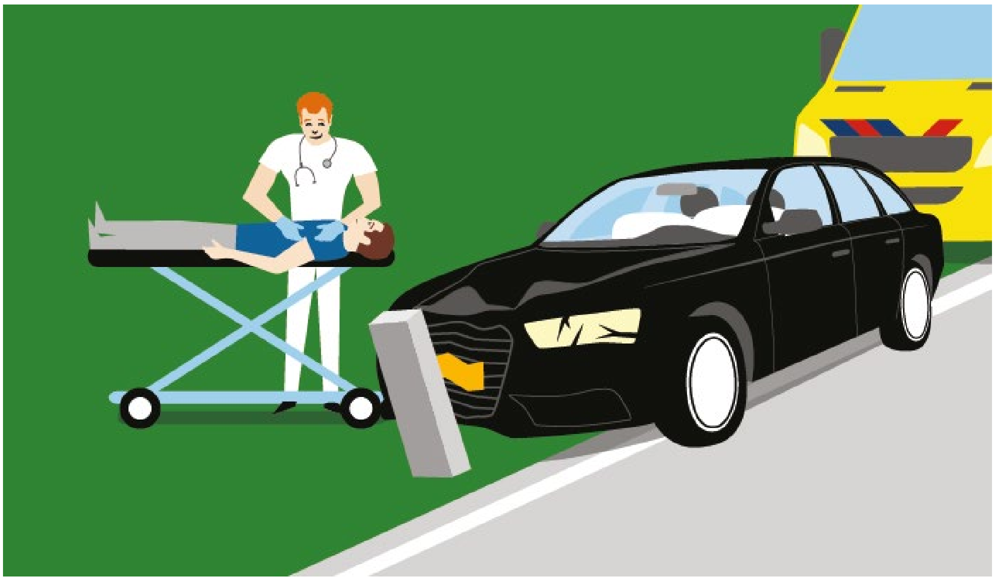
In the case of incidents involving hazardous substances, this concerns measures to close the containment, to limit the feed/flow, or to reduce the pressure in the system.

5th LoD: escalation prevention
In terms of the road accident analogy, this concerns measures to restrict the incident (stop it escalating). This could include displaying a warning triangle to prevent additional vehicles from becoming involved in the incident and extinguishing fires in or around the car.

In the case of incidents involving hazardous substances, this would involve:

- emergency containment for released liquids;
- limiting further evaporation, using a layer of foam, for example;
- limiting dispersion by creating a water curtain, for example;
- preventing flammable substances from igniting;
- extinguishing fires to prevent flashover to other items of equipment or other installations;
- positioning installations sufficiently far apart to prevent a domino effect with respect to other installations.

6th LoD: personal protection and assistance
In the road accident analogy, this mainly involves assistance (by fellow passengers, bystanders and professionals).



In the case of incidents involving hazardous substances, this would involve:

- the use of personal protective equipment (PPE);
- helping victims escape;
- evacuating others within the impact area;
- maintaining a safe distance from the accident location (or not approaching it without adequate protection);
- offering medical assistance on site, in a medical assistance centre or hospital.

3.5.1 *Which mitigating measures failed or succeeded?*

The analysis model contains a total of twelve measures to limit the severity of the consequences. Figure 3.8 shows how often these measures failed or succeeded.[22] The measures are independent of each other – several measures can fail and/or succeed in any given incident. Furthermore, no measure is universally applicable to every single incident. In the 326 incidents, a total of 385 safety measure failures were identified, while 335 measures succeeded.

[22] The terms 'failure' and 'success' are defined in Subsection A1.4.

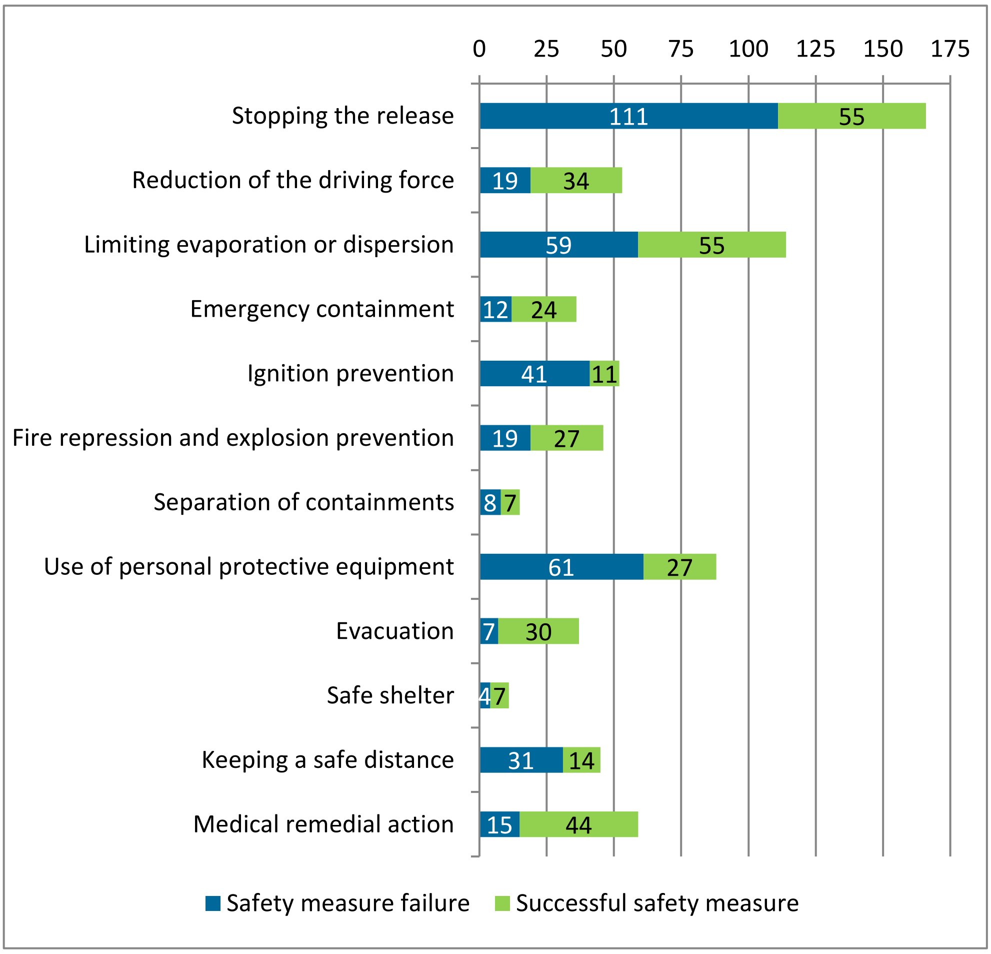


Figure 3.8. Mitigating safety measures: number of times these measures failed or were successful.

Stopping the release
Stopping the release was relevant in the majority of cases (166 of the 326 incidents). This measure failed in two-thirds of these incidents (111x). This concerns issues such as open valves that were not or could not be closed, loose connections that could not be restored and holes in items of equipment that could not be promptly sealed with a plug or clamp. In 55 incidents, it was possible to stop the release quickly by retightening the bolts on the flange, for example, or by closing a feed valve near the release location.

Limiting evaporation and dispersion
Layers of foam, water curtains and comparable measures can limit the evaporation and dispersion of hazardous substances. In 59 incidents these measures either failed or were only partially successful. In 55 incidents they were successful. Frequent use was made of water curtains (32x).

Preventing ignition
Forty-one incidents involved flammable substances that ignited after being released. These events resulted in a fire or explosion. The mechanism of ignition was identified in twenty of these incidents. Eleven cases involved spontaneous ignition immediately on release,

another four cases concerned nearby hot work activities, two involved nearby ignition sources and another two were related to static electricity.

The use of personal protective equipment (PPE)
In 61 incidents, deficiencies were identified in the use of personal protective equipment. This means that the injuries sustained might have been less severe if those workers had been equipped with – and had used – suitable personal protective equipment. The incidents occurred during maintenance, cleaning and inspection (31x), during normal operation (26x), and during start-up (4x). In 26 of these incidents, a containment was actively opened. Personal protective equipment was used (properly) in 27 incidents, which limited the injuries that were sustained.

Evacuation and company emergency response
Measures involving evacuation and company emergency response were successful relatively often.

3.5.2 What were the consequences of a failure of mitigating measures?
The analysis model first specifies the subsequent physical effects of the incident (Figure 3.9) and, subsequently, how anyone involved was exposed (Table 3.2).

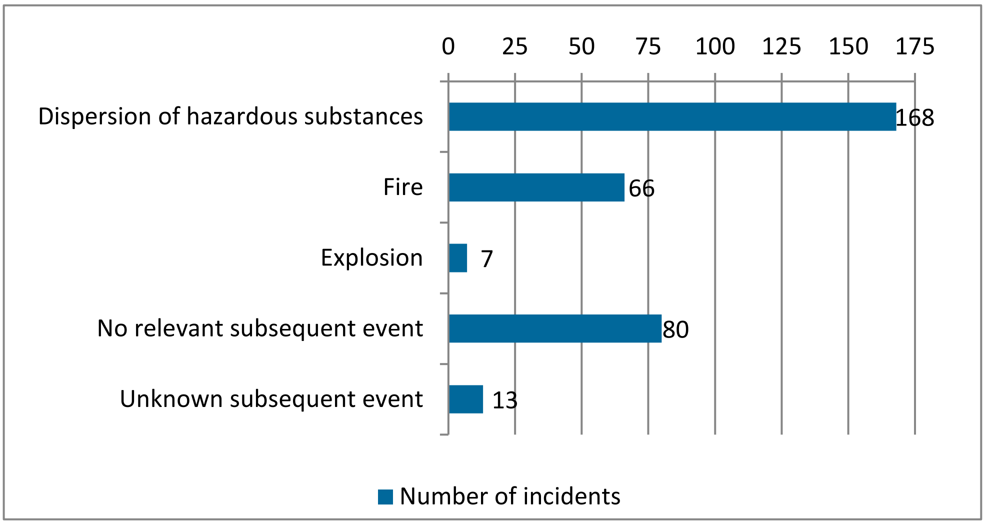


Figure 3.9. Type of consequence resulting from the incident. A single incident may trigger several types of consequences.

Figure 3.9 shows the physical effects that arise or occur after the start of the incident. The subsequent physical effects depend on the success and/or failure of the various mitigating measures.

- In 168 incidents (52%), the incident resulted in airborne dispersion of hazardous substances. An unknown percentage of these instances occurred from a 'safe release location' – in other words, an emission point at the top of a tall structure that was intended to limit exposure to hazardous substances at ground level.
- In 66 incidents, some type of fire was involved, while seven incidents led to an explosion.
- Eighty incidents were short-lived and had no relevant subsequent effects. These were incidents in which no hazardous substances

were released and incidents in which the released substances were effectively captured, thus keeping evaporation and dispersion of these substances to a minimum. Essentially, the hazard stopped shortly after the initial occurrence of the accident.

Subsection A#.5.4 of Appendix 3 provides a detailed specification of the subsequent physical effects. An incident's total physical effects are a combination of the immediate effects and the subsequent effects. That combination is described in Subsection 2.3.3.

In 120 incidents, one or more people were exposed. A total of 224 people were involved.[23] Details of the type of exposure concerned are shown in Table 3.2. Most cases involved exposure to a substance with toxic effects (91x) or to a substance with acidic, corrosive or irritating effects (76x).[24] In any given incident, the victims involved can be exposed to more than one type of hazard. For example, people can be exposed to multiple substances or to a combination of fire and explosion effects.

Table 3.2. Type of exposure and number of people involved.

Type of exposure	Number of people
Exposure to a substance with toxic effects	91
Exposure to a substance with acidic, corrosive or irritating effects	76
Exposure to smoke products or combustion products	5
Exposure to toxic decomposition products	3
Exposure to asphyxiating substance	3
Exposure to hot or cold product	25
Exposure to heat (radiation)/flames	22
Exposure to overpressure/blast wave	16
Impact caused by fall of person	3
Impact caused by ejected, falling or collapsing objects	1
Unknown type of impact/exposure	5

Exposure results in injury. These injuries are discussed in Subsection 2.4.2.

3.6 How did the safety measures fail?

Safety measures can offer protection only if they have actually been put in place and, moreover, if they function effectively. The generic Storybuilder accident analysis model contains four elements ('barrier tasks') to capture how safety measures failed. The most applicable element for each safety measure failure is identified.

[23] In nine incidents that involved a total of nine people, the exposures were so low that the model did not register these individuals as 'victims'. As a result, there are 111 incidents in total involving 215 victims.
[24] The descriptions given in the analyses were the same as those used in the incident investigations. Many substances with toxic effects are not formally classified as toxic substances and many substances with acidic, corrosive or irritating effects are not officially classified as acidic substances, corrosive substances or irritants.

How did it go wrong? The analysis model's four elements ('barrier tasks').

- **Provide**. The safety measure must have been present/provided/implemented, and its design and realisation must be such that it can indeed provide the intended protection. First and foremost, this means that the organisation has acknowledged the necessity for the measure and that it subsequently took the appropriate action by putting it into effect. This means that specific instruments, devices or procedures have been put in place that are capable of fulfilling the intended safety function.
- **Use (operate)**. The organisation and its staff must actually and adequately use the instruments, devices and procedures involved in the safety function. For example, a procedure is only effective if it is followed properly and a safety helmet only works if it is actually worn.
- **Maintain**. Once implemented, safety measures must continue to work. In other words, the effect of the safety measure must not be undermined by changes in processes, materials or working practices. An alarm that has been temporarily disabled is one example of a safety measure that has not been maintained. Another example would be a materials inspection programme whose scope or inspection frequency has been reduced over time.
- **Monitor (supervise)**. The management of the organisation is specifically tasked with ensuring full compliance with rules and procedures. In case of a systematic failure to adhere to rules and procedures, this failure is identified as a failure of supervision. This differs from use and maintenance in that it involves systematic deviations.

Figure 3.10 shows how safety measures fail, on average. One-third (33%) of all safety measure failures occurred because the measures had not been provided/implemented effectively, if at all. The instruments or procedures required to ensure safety were either substandard or non-existent. These failures involved, for example, incomplete start-up procedures, insufficiently sensitive material inspections (or none at all) and emergency venting systems with insufficient capacity.

Deficiencies in the operation/use of safety provisions are also fairly common. 28% of all safety measure failures involved an available measure that had been used or applied incorrectly. This means that the organisation had implemented suitable instruments or procedures to ensure safety, but that these were not used/applied effectively – if at all – by the organisation's employees. This may have been due to a lack of familiarity with company regulations and procedures or a failure to comply with them. The nature of underlying human errors is described in greater detail in Subsection 4.3.

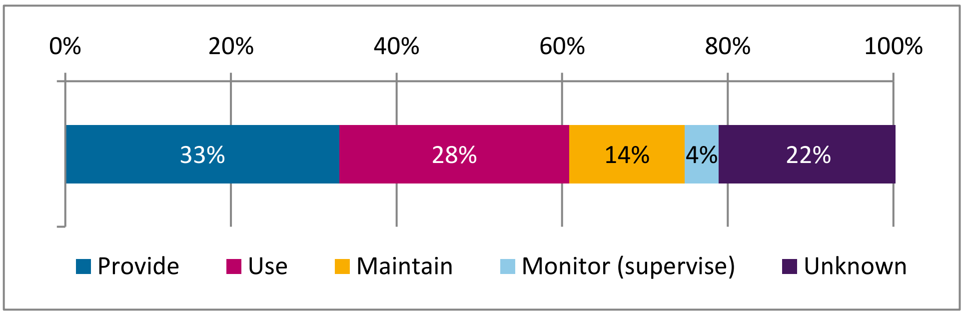


Figure 3.10. Manner in which safety measures fail. Average incidence per safety measure failure.

The way in which safety measures failed revealed minor differences between the different *lines of defence* in the model. In terms of the first *line of defence*, maintaining the safety function was also relevant. Appendix 3 presents the data per *line of defence*.

3.7 Why did safety measures fail?

This concerns the underlying causes for why the required protection was not delivered or removed. These are causes at the organisational level. The analysis model uses two different formats. One is a generic Storybuilder model format that is used in all incident analyses with Storybuilder (see Subsection 3.7.1), the other applies specifically to Seveso companies (see Subsection 3.7.2).

3.7.1 Management factors (Storybuilder model)

The process of implementing safety measures and ensuring that they remain effective depends on a number of distinct management factors. For example, staff must have sufficient knowledge and experience, and people must be alert to any malpractices, as well as cooperate and communicate effectively. The organisation must ensure that all work scheduling, working procedures, materials and equipment are fit for purpose.

The generic Storybuilder accident analysis model identifies eight different elements or management factors[25] that, together, are intended to ensure that safety is adequately guaranteed. Whenever there is a safety measure failure, checks are made to determine which elements were involved (in an adverse sense) in the failure. A maximum of three elements may be selected.

[25] In the model, this part is labelled the 'Management Delivery Systems', see Annex 1. To avoid jargon, these elements are sometimes referred to as 'management factors'.

Why did it go wrong? The eight elements of the analysis model.

- **Plans and procedures**: company regulations, work instructions, manuals, checklists, maintenance schedules, etc. A written record of the way in which the company desires to operate.
- **Availability of personnel**: ensuring that sufficient staff are available to perform the different tasks related to ensuring safety.
- **Competence**: ensuring that staff have sufficient knowledge, experience and skills to perform the tasks.
- **Communication and collaboration**: mutual coordination, communicating about how the work should be performed, informing each other if something does not go as planned or if technical disruptions or deviations were observed.
- **Motivation and awareness**: concentrating when working, following the rules, being aware of potential risks and acting proactively to ensure safety.
- **Safety as a priority**: an adequate focus on safety at the organisational level, not subordinating the interests of safety to financial or other interests.
- **Ergonomics/MMI**: ensuring that the resources to be used are convenient and workable, and that suboptimal design does not lead to incorrect decisions or assessments.
- **Materials and equipment**: ensuring the material used in the construction of installations is of suitable quality, instruments can perform their function and the right maintenance tools are available.

Figure 3.11 shows why safety measures in each of the various *lines of defence* failed. 26% of safety measure failures involved deficiencies in company plans and procedures, followed by deficiencies in competence (16%), materials and equipment (14%), and motivation and awareness (12%). Furthermore, there is a large proportion of 'unknown' deficiencies – in 43% of safety measure failures, it was not possible to determine which underlying management factors were involved in the failure.

Deficiencies in company plans and procedures may be associated with a general lack of company regulations, work scheduling and procedures. More often, rules and procedures have been put in place to some extent, but these are either unclear or incomplete/substandard. Examples of safety measure failures in the various *lines of defence* are given in Appendix 3.

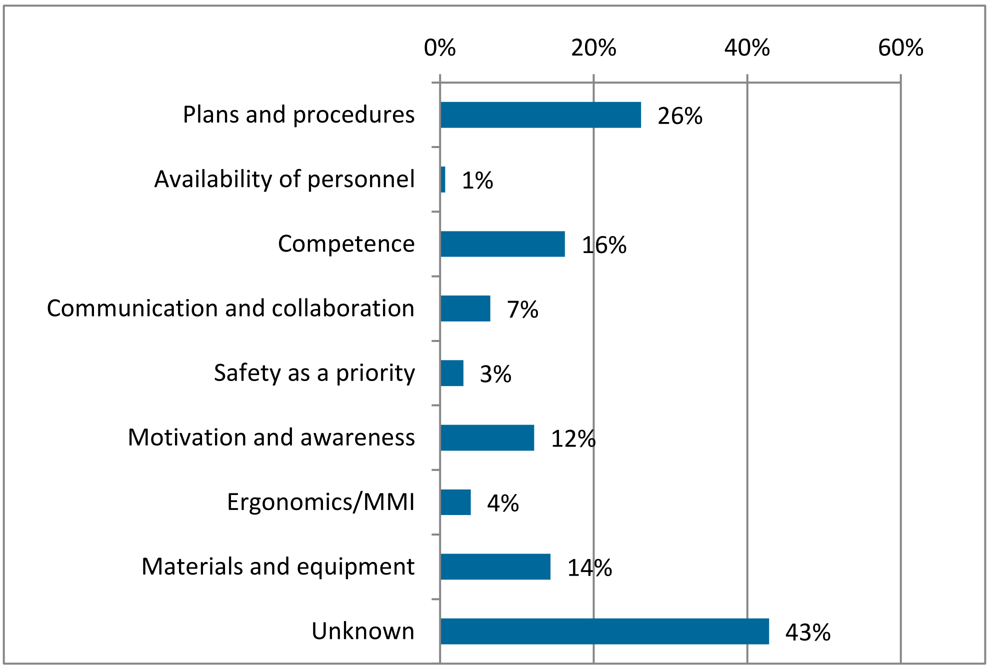


Figure 3.11. Why do safety measures fail? Average incidence of management factors per safety measure failure.

3.7.2 *Elements of the Safety Management System (EU Seveso Directive)*

The European Seveso III Directive [14] (formerly Seveso II) stipulates that establishments that are subject to this Directive must implement a safety management system (SMS). Annex III of the Directive specifies seven elements that must be included in the SMS. In the Storybuilder MHC model, these seven elements have been added to the analytical structure. This is an alternative classification of management factors (alternative to those discussed in the previous subsection). Each safety measure failure was investigated to determine which SMS elements of the safety management system had played a role (in an adverse sense) in the failure.

The seven elements of the Safety Management System (SMS)

- i. Organisation and personnel.
- ii. Identification of hazards and evaluation of the risks of major accidents.
- iii. Operational control.
- iv. Management of change.
- v. Planning for emergencies.
- vi. Monitoring performance.
- vii. Audit and review.

These elements of safety management systems are defined in Annex III of the Seveso Directive.

Figure 3.12 shows which SMS deficiencies played a role in the failure of safety measures in each of the various *lines of defence*. 38% of safety measure failures involved deficiencies in operational control (element iii). 18% of safety measure failures involved deficiencies concerning the identification of hazards and the evaluation of risks (element ii).

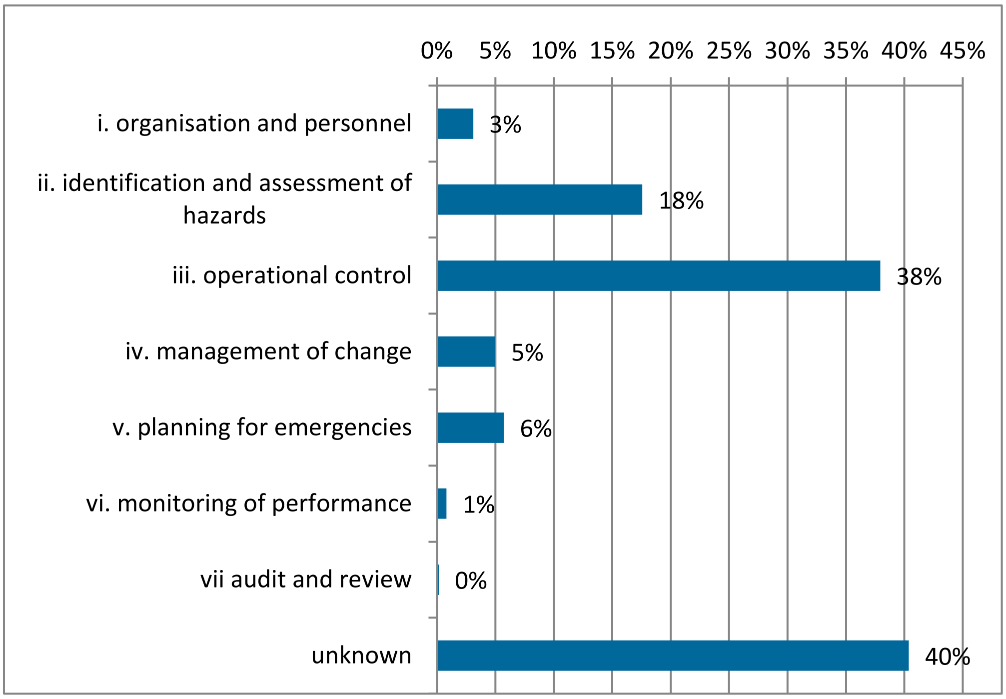


Figure 3.12. Deficiencies in the SMS related to safety measure failures. The average incidence of deficiencies in the SMS per safety measure failure.

In Subsection 4.2, the deficiencies in SMS elements ii, iii and iv are discussed in greater detail. Appendix 3 specifies the relevant deficiencies in the SMS per *line of defence*.

3.8 Summary

The analysis model presents a structured insight into the immediate and underlying causes of incidents. The model includes 41 safety measures for preventing the occurrence of incidents or for limiting the severity of their consequences. These measures are distributed over six *lines of defence* (LoDs), three of which are aimed at preventing incidents and the other three at limiting the consequences of any incidents that do occur.

In every incident, at least one safety measure in the 1st LoD failed, as did at least one measure in the 2nd LoD. In the other LoDs, safety measures may have been successful or may have failed.

All safety measure failures were investigated in order to establish how and why they failed. For each failure, the same elements are used to analyse underlying causes.

In the 1st LoD – operational control – one notable fact is that no single group of safety measures stands out from the rest (in an adverse sense). Incidents occur due to deficiencies in (i) guaranteeing the integrity of installations, (ii) controlling process parameters and (iii) starting or starting-up processes and operations safely.
In the 2nd LoD – recovery of deviations – it is notable that in almost half of all incidents there is no reliable indication of the deviation involved. Deviations therefore remain out of view and no remedial action is taken. Safety can be improved by increased monitoring, more extensive

inspections and by performing additional final checks before starting any operations.

In the 3rd LoD – emergency measures – it is notable that emergency measures would only have been useful in a limited number of incidents (41%). Those cases were mainly about protecting installations against excessive pressure and preventing the ignition of flammable mixtures within installations. In the other 59% of incidents, it was not possible to implement any further emergency measures. For these incidents, safety depended on two pillars – safe operational control and prompt recovery of any deviations.

In the mitigating LoDs (4th, 5th and 6th) in the 326 incidents, a total of 385 safety measure failures were identified, while 335 measures succeeded. This means that further improvements could be made in terms of limiting the consequences of incidents.

With regard to the underlying causes, it is noteworthy that incidents are mainly due to a failure to implement the required safety measures effectively, if at all (33%), or to use/apply them effectively (28%). The former can be improved by a greater focus on risk identification and assessment, and by prudently translating these into suitable safety measures. The latter aspect requires an increased awareness of company procedures and regulations among staff and contractors. Efforts should also be made to ensure that these procedures and regulations are correctly applied and followed up.

The analyses show that deficiencies in terms of work plans and procedures occur fairly often – they are either absent, unclear or incomplete. Deficiencies in plans and procedures are involved in 26% of all safety measure failures and in 60% of all incidents.

With regard to the safety management system (SMS), the main deficiencies involve operational control – the safe performance of normal operations and maintenance activities. The translation of existing knowledge about hazards and risks into adequate safety measures has a part to play here.

In terms of underlying causes, the 'unknown' factor is often quite substantial (around 40%). This may be because, by the time the incident investigation took place, it was no longer possible to clearly identify or determine some of the aspects involved. Another contributing factor is that – in incident investigations – some aspects of the incident are investigated in greater detail than others. If incident investigations were more extensive, more lessons could be learned from incidents.

4 Frequently occurring scenarios and underlying causes

The preceding sections have presented the general characteristics of incidents (see Section 2) and described their underlying causes (see Section 3). In this section, the aim is to make more sense of the data. Subsection 4.1 describes three common incident scenarios. These are scenarios in which the same safety measures failed. Subsection 4.2 and Subsection 4.3 illustrate some frequent underlying causes through examples. In this respect, Subsection 4.2 explores the organisational perspective, while Subsection 4.3 examines the human factor.

4.1 Frequently occurring scenarios

The Storybuilder model has three *lines of defence* (LoDs) with safety measures for preventing incidents (see Subsection 3.1). Each incident was examined to determine which safety measures had failed and to identify the consequences. Some combinations occurred more often than others. The most frequently observed combinations were the 'common threads' in the database or, in other words, the commonest incident scenarios. The three most frequent scenarios are explained in detail in the following subsections. Together, these accounted for 45% of all incidents. They are:

i. Physical failure of the containment as a result of material degradation.
ii. Failure to safeguard a containment before opening it.
iii. High pressure in a containment.

4.1.1 Physical failure of the containment as a result of material degradation

This scenario involves the degradation of the containment material, such as the wall of a pipe, a gasket or a coupling. At first, the integrity of the installation is insufficiently safeguarded by normal operational control measures. If the weakening of the installation is not noticed in time, the containment may suffer a physical failure. Without an additional shell/body around the primary containment[26], hazardous substances will be released to the environment. A total of 69 incidents (21% of the total) occurred in this way. They resulted in 42 victims (20%).[27]

The fact that material degradation is an important cause was also shown by the analysis of immediate causes (Subsection 2.6). In a quarter of all cases, material degradation was identified as the immediate cause of the incident. Half of these incidents involved corrosion. The other incidents involved fatigue, wear, embrittlement, erosion or other forms of material degradation.

[26] An additional shell/body (secondary containment) is generally a measure to prevent release following a primary containment failure. Additional shells/bodies are only used to a limited extent. They also introduce new risks in terms of operational safety. Therefore, in the analyses, an additional shell/body is not treated as a standard accident prevention measure. In the analyses, the secondary containment safety measure is only considered to have failed if the incident investigation produces evidence to support this. In the other cases, it is assumed that the release of hazardous substances that followed the failure of the primary containment could not have been prevented by an additional measure in the 3rd LoD.

[27] The search criteria are described in more detail in Appendix 4. Although there is a range of similar incidents, they do not share all of these characteristics.

This material degradation was initially caused by an incorrect material specification (18x), the failure of measures to protect the material – such as a damaged coating or the failure of cathodic protection (9x), or defective welds (4x). Another primary cause that is not directly related to the material or its protective layers is when the process conditions or the duration of use deviate from the material's design specifications. Examples of this include conditions in which the medium is too corrosive (27x), erosive/abrasive conditions – such as an excessive velocity of flow (6x) – or corrosion under insulation (5x).

These deviations were often not noticed (54x) because there was no effective system – such as periodic inspections – for identifying the deviation. This is not simply a matter of the existence of instruments and procedures. It is also about their effectiveness, so that material degradation can, at critical points, be indicated in time (see example on page 43). Furthermore, any deviations that are being monitored must also be detected, interpreted and followed up in time.

In the absence of an extra protective safety measure, such as an additional shell/body, the deviations mentioned above result directly in the failure of the containment and the release of hazardous substances. This could be leakage from a newly created hole in the shell/body (48x), for example, or from a connection (12x) and sometimes (6x) from a catastrophic rupture of the containment.

An example of material degradation
A gasket in a production column sprung a leak. This was because the original asbestos gasket had been replaced by another type of gasket that was not sufficiently resistant to the medium and the prevailing process temperature (phenol at a temperature in excess of 200°C). This substance has a low odour threshold, so the operators discovered the leak reasonably quickly. The company stopped the pump, isolated the pipeline, and set up a water curtain. Next, the installation was shut down to find the cause of the leak. The faulty gasket was replaced by a different type of gasket – one that was able to withstand the prevailing process conditions. A programme has been drawn up to replace any gaskets that come into contact with phenol.

The potential measures for boosting safety are as follows:
- Improving checks on material specifications to establish that they are correct and, if necessary, providing additional protection for the material.
- Preventing undesirable process conditions from weakening the material. This includes factors such as flow (excessive flow, too little flow, or undesired substances or particles in the product flows) or pressure and temperature (too high or too low or too many fluctuations). This requires careful consideration of whether such widely deviating process conditions can occur and whether the design of the installation should take this into account.
- Monitoring maximum operational life for all elements of the containment material.
- Adequate material inspection programmes, i.e. sufficiently frequent, sufficiently extensive (at all potentially critical locations) and sufficiently sensitive.

- The use of containments with a double shell/body, including a system for indicating when the primary shell/body fails.

4.1.2 *The failure to safeguard a containment before opening it*

This scenario involves the active opening of a containment that has not yet been adequately safeguarded or an installation start-up while various items of equipment have accidentally been left open. The term 'active opening' is used here to mean opening an isolation valve, a manhole lid, etc. If there is no extra protective safety measure, such as an (inter)lock system[28], the actions mentioned above will result directly in the release of hazardous substances. This involved a total of 42 incidents (13% of the total), with 33 victims (15%).[29]

In these incidents, the contents of the containment to be opened were not (or not properly) rendered product-free or were not (or not sufficiently) depressurised (22x), the section to be opened was not sufficiently isolated from the rest of the installation (16x), and/or the installation was started up while certain isolation valves had accidentally been left open (9x). Insufficient isolation may point to leaking valves in the installation or to a failure to use spectacle blinds or spades prior to opening pipes.

Prior to the planned action (opening or start-up), these deviations must be indicated (indication), noticed (detection), interpreted (diagnosis) and followed up (remedial action). Otherwise, the action will lead to a release of a hazardous substance, assuming that no additional protection – such as an (inter)lock system – has been fitted. In many cases, there is no indication (22x), such as an instrument on the spot or an additional check prior to the planned action. In these situations people merely trust that previous actions taken to make the system safe were carried out correctly and that the system has no defects (such as leaking valves).

Example of a failure to secure a containment prior to opening
When commissioning an installation after a brief period of maintenance work, methane, cyclohexanone and hydrogen gas were released through an open exhaust. During normal operation the exhaust is connected to the flare. During maintenance work, the exhaust is open to the outside air. During installation start-up, no-one was aware of this exhaust setting. As a result, around 6,000 kg of flammable gas flowed out through the open connection over a period of 20 hours.

The potential measures for improving safety are as follows:
- Prudent procedures for rendering items of equipment in installations product-free prior to operations on, at, in or near the installations.
- Sufficient knowledge of the installation, of the physical condition of its isolation valves and of their setting/position.
- The use of spectacle blinds or spades to safeguard the isolation of the item of equipment in the installation that is to be opened.

[28] An (inter)lock system is a protective device that prevents items of equipment in process installations from being opened in undesirable circumstances (pressure, certain isolation valve settings). See also Subsection 3.4.1.
[29] The criteria are described in greater detail in Appendix 4. Although there is a range of similar incidents, they do not share all of these characteristics.

Checking whether these measures have been removed before the installation is restarted.

- Additional procedures and instruments to effectively verify, just prior to opening the containment, that the system is product-free and/or depressurised and does not have any undesired openings, leaking valves or valve settings.
- The use of (inter)lock systems to prevent containments from being opened in undesirable circumstances.

4.1.3 *High pressure in a containment*

This scenario concerns incidents involving insufficient control of operational process parameters (pressure, temperature, flow), following which – due to the absence of effective remedial action – high pressure develops in the installation. This either causes the installation to fail or results in products having to be discharged into the atmosphere via an emergency relief system. This involved a total of 36 incidents (11% of the total), with 20 victims (9%).[30]

There was no recovery of the initial deviations in the process conditions because there was no indication that these deviations existed (10x), because indications were displayed but not noticed (5x) or were not adequately diagnosed (4x), or because the correct remedial measures were not taken in time (11x). In six incidents, the reasons for the failure to implement a prompt recovery were unknown.

The term ‘emergency protection against high pressure’ refers to systems that are intended to prevent items of equipment in installations from failing due to excessively high pressure. These items include emergency pressure relief valves, rupture discs, or emergency shutdown systems (ESD).

Often, installations are depressurised by venting gases or vapours into the outside air. Sometimes flare/torch systems or scrubbers are installed to prevent the release of hazardous substances into the environment. In the 36 incidents involved, the installation’s high-pressure emergency protection system failed on 19 occasions, while it succeeded in protecting the installation (but not in preventing a release) on 15 occasions. In the remaining two incidents, insufficient details were available to classify its performance as being successful or not.

On 13 of the 19 occasions when the pressure protection system failed, this safety provision had not been provided correctly, if at all. This means that this protection was either entirely lacking or that the design capacity was inadequate to cope with the scenario that occurred (see example below).

Example of high pressure in a containment
Biogas was being produced in digesters. More foaming than usual occurred during the production process. This foaming was countered by adding an anti-foaming agent. At a certain point, the stock of anti-foaming agent ran out. The foaming caused the pressure in the digesters

[30] The criteria are described in greater detail in Appendix 4. Although there is a range of similar incidents, they do not share all of these characteristics.

to rise and the digesters' pressure relief valves opened. This resulted in the release of biogas and foam. It was decided to transfer part of the contents of the digesters to the post-digester. Foaming then occurred in the post-digester as well. The discharge pipeline became contaminated with foam and was sealed. This caused the pressure in the post-digester to rise. This increase in pressure caused the pressure protection system in the post-digester to open. Due to the foaming effect, the pressure protection system had insufficient capacity to prevent a build-up of pressure in the post-digester. A 12-metre tear opened at the junction between the wall of the post-digester and the membrane roof, resulting in the release of approximately 24 tonnes of biogas.

The potential measures for improving safety are as follows:
- Minimising process deviations by improving the control and monitoring of normal processes, including start-up.
- Understanding the potential consequences of process deviations and implementing recovery systems for process deviations outside safe operating windows, in accordance with the principle of indication, detection, diagnosis and response.
- Ensure that items of equipment in installations are fitted with effective pressure protection systems (or emergency pressure protection systems) with sufficient capacity to handle deviating process conditions (including deviating flows).

4.2 Common causes from an organisational perspective

The elements of a safety management system (SMS) are examined from an organisational perspective. The three elements that failed most often according to the incident analysis are discussed.

4.2.1 Operational control management

Incident analysis shows that this element of the safety management system fails the most often (74% of incidents). The operational control element covers all stages of the process, such as:
- normal operation (failed 145x);
- recommissioning after maintenance (failed 29x);
- maintenance or inspection (failed 48x);
- shut-down (failed 9x).

Example of inadequate operational control
Crude benzene was released into a tank pit due to a missing adapter in the pipeline leading to the tank. The tank inspection should have been more thorough, as no-one noticed that the adaptor (an intermediate piece) in the tank pipeline was missing. During the investigation, it emerged that people had different ideas about what constituted "a thorough inspection" and about who should perform this inspection; the work preparation department or the operations department.

4.2.2 Identification of the hazards and assessment of the risks involved

There was inadequate identification and assessment of the hazards in approximately half of the incidents (44%). This mainly concerned process safety analyses or task risk analyses.

The following points of interest for the implementation of process safety analyses emerged from the incident analyses:

- Identifying the mechanisms that lead to material degradation. See also Subsection 4.1.1.
- Assessing the risk of undesired hazardous substances ending up in an item of equipment in the installation that is neither intended nor designed for that purpose.
- Correctly assessing the requisite reliability and effectiveness of safeguards designed to handle process deviations (such as high pressure, high level, etc.). This includes issues such as the correct Safety Integrity Level (SIL) for the safety systems used.

A point of interest for task risk analyses:

- Opening items of equipment in installations that are not entirely product-free of fully depressurised and insufficiently isolating items of equipment prior to starting operations (e.g. not using spectacle blinds when isolation valves may be leaking). See also Subsection 4.1.2.

Example of inadequate hazard identification and risk assessment
To resolve a process malfunction, an operator switched off the steam feed to a stripper. However, it was the wrong stripper. This was partly because many alarms were triggered in a short space of time. The continuous steam/heat feed raised the temperature in the stripper, causing more benzene to evaporate than had been anticipated. This benzene then flowed into adjoining installations and a storage tank. The benzene subsequently flowed out through a vent in the storage tank.

The tank vent contained a high temperature sensor that sent a signal (alarm) to the control room. Numerous alarms were going off in the control room, so the significance of this particular alarm was not recognised. As a result, the duty operator did not take any action to stop the release.

Insufficient control measures had been implemented to prevent flow from the stripper to connected items of equipment. The potential hazards of such a flow had not been properly identified prior to the incident.

4.2.3 *Management of Change*

In 51 (16%) of the 326 incidents, one or more safety measure failures were considered to involve an inadequate management of change.

This quite often (29x) concerned the condition of the equipment. This condition was adequate before, but not after, the change. Examples of common safety measure failures are:

- Material failure (for example, replacing gaskets with different gaskets made of the wrong material).
- A change in process conditions with regard to material degradation (for example, changes in product flows that might cause corrosion).
- Inadequately designed changes (by expansion of production, for example, or changes in the installation related to environmental requirements).

- Connection failures (e.g. due to connections being incorrectly assembled when carrying out the modification).

Example of a management of change failure
A dust explosion occurred in a gluten dryer containing wheat gluten six hours after start-up. Two modifications to the gluten dryer were probably responsible for this incident. First of all, a baffle had been installed in the dryer to make the flow more turbulent. This had the unforeseen effect that large chunks of gluten formed on this baffle. An investigation showed that these chunks accumulated charges of static electricity large enough to ignite the wheat gluten in the gluten flow. Secondly, the gas mixture in the installation had been changed. The original gas mixture contained 16% oxygen. However, this gas mixture facilitated the production of nitrites, so the installation was switched to fresh air (21% oxygen). In an atmosphere containing 21% oxygen, the minimum ignition energy of gluten is lower (by a factor of 7 to 10) than it is in a gas mixture containing 16% oxygen. After the modification, the combined effect of these changes increased the ignition risk considerably compared with the original process design.

4.3 Common causes from the perspective of the human factor

The preceding sections and subsections contain various examples of the effect of undesired human actions. Firstly, Subsection 2.6 showed that almost one-third of all the incidents (31%) were the direct result of someone performing an undesired action.[31] Incorrect actions or decisions were also a significant factor with regard to the underlying causes. Subsection 3.6 showed that safety measures failed in at least 28% of the cases because well-implemented systems were either not used or not used properly.

The analyses of the 326 incidents explored the nature of any human errors that occurred prior to or following the release. In this context, Storybuilder distinguishes between violations, mistakes and slips/lapses. In total, there were 254 situations in which people performed incorrect actions that could be classified into one of these three categories. 20% of these human errors were violations, 60% were mistakes, while 17% were slips/lapses (see also Subsection A3.6 in Appendix 3).

4.3.1 Violations

In these cases, people deliberately deviate from the applicable procedure. Within organisations, deviations may involve several people and may occur so often that they can be defined as ‘routine violations’. However, they can also occur incidentally due to specific circumstances, such as being under pressure to complete a given task. The latter is an example of a ‘situational violation’.

[31] This is also known as ‘human error’, see Subsection 2.6. Here, ‘human error’ means that it was the direct result of an incorrect human action. That undesired action could have been prompted by a procedure or by an approach commonly used within the company. Accordingly, it cannot always be attributed to the culpable behaviour of a specific individual.

An example of a situational violation
Tanker wagons were to be filled with methanol. However, a control system disruption occurred that could not be immediately corrected. The shipment was highly time-critical for the customer, so the decision was taken to deviate from the applicable internal procedures and to fill the tanker wagons using hoses inserted into their manhole opening. However, the filling process was not stopped in time, causing the methanol to overflow through the manhole opening. The methanol then flowed into the basement, which acted as an overflow container. This overflow resulted in a high concentration of vapour and an increased risk of explosion. When the concentration reached 40% of the lower explosion limit, the power was automatically shut off. Under normal circumstances this would cause loading to stop automatically. However, due to the deviation from the normal loading procedure, the automatic stop was no longer functioning. A total of five tonnes of methanol overflowed.

4.3.2 *Mistakes*

The incident analyses show that mistakes are the most common type of human error. Mistakes involve incorrect assumptions. In such cases, the plan to act or not to act is incorrect. Mistakes can relate to a person's level of expertise, i.e. they are insufficiently competent or skilled to deal with new problems or actions. This is also reflected in failures involving the management of competence (44% of the incidents investigated).

Mistakes can also occur at the level of procedures or rules. Such cases can involve the improper application of everyday routines (that are often carried out on automatic pilot).

An example of a mistake
Two workers were filling a tank container with methylene diphenyl diisocyanate (MDI), a toxic and corrosive liquid. A vapour return line fitted with an isolation valve was located beside the loading arm/loading pipe. The vapour return connection had to be open during loading and uncoupling. The workers twisted the isolation valve with the intention of opening it a bit. This would typically result in a hissing sound, due to escaping air, but nothing was heard on this occasion. As a result, the workers assumed that the pipeline was not pressurised. This assumption was incorrect. It later emerged that the valve was defective and that it did not open when it was rotated. Due to this defect, no hissing sound occurred.

During loading, the pressure in the tank container increased. After loading, the installation's loading pipe was flushed out with nitrogen to ensure that it was empty before it was disconnected. This was based on the assumption that the isolation valve to the vapour handling unit was open. This led to a further increase in pressure.

The loading operators then attempted to disconnect the loading pipe from the tank container's loading valve. The loading arm was subsequently ejected by the sudden release of product. Both operators were then covered in MDI. In total, 10 tons of product was released.

4.3.3 *Lapses and slips*

In this case, the intention (the plan) is good, but the implementation is not. This is either because something was forgotten (lapse) or because of a loss of concentration (slip) while performing a task. One example of a lapse is forgetting to close a valve (even though the person had intended to do so). A rather literal example of a slip is shown below.

A (rather literal) example of a slip
An operator was doing preparatory work before coupling a loading arm to a tanker wagon. The blind flange, the locking pin and the tie-wraps (which fix the position of the handwheel) were removed. The operator was squatting down. He lost his balance. By reflex, he grabbed the side valve's handwheel for support, partially opening that valve in the process. It seems that a small amount of ammonia had collected between the bottom valve and the side valve of the gas return line. A jet of ammonia was released, some of which was blown under the victim's face mask. He sustained minor facial burns from drops of ammonia in the gas jet. He also inhaled some ammonia. The victim spent two days in hospital for observation.

5 Trends and patterns

This section examines trends and patterns in the analysis data. The trends relate to changes over time, that being from 2004 to 2018. The patterns relate to correlations between data other than time. In total, three series of tests were performed:

1. Did any changes occur in the annual number of incidents or the annual number of victims during that period?
2. Did any changes occur in the incidents' characteristics and underlying causes during that period?
3. Which facets of incidents correlate with the severity of injury?

The statistical analysis consists of three steps (see text box). Firstly, the hypotheses to be tested are specified for each series. To limit the risk of nonsensical outcomes, it is important to be critical when deciding on the number of tests to be included in the statistical analysis.[32] A p-value is then calculated for each tested hypothesis. Finally, a multiple test correction is carried out. The guiding principle here is that the proportion of false positives in the selection should not exceed 10%.[33] The multiple test correction generates a list of hypotheses that are likely to produce a genuine effect (trend or correlation).

Explanation of/justification for the statistical approach used

The analysis of trends and patterns in the data consists of three steps.

1. Firstly, the hypotheses to be subjected to the statistical test are specified. The more hypotheses included, the lower the statistical power of the test. For that reason, you must first carefully consider which hypotheses you do – or do not – wish to test.
2. A p-value is then calculated for each tested hypothesis.
   - The basic assumption behind the test (the null hypothesis) is that the parameter under consideration is constant in the selected data set. Any mutual differences will then be the result of random fluctuations. For example, if the parameter under consideration is the number of incidents per year and the data set is the range of years, then the null hypothesis is that the expected value for the number of incidents will be identical year on year.
   - The p-value is calculated using a chi-squared test.[34]
   - The calculated p-value indicates the (im)probability of the data, given the null hypothesis. The smaller the p-value, the more reason to reject the null hypothesis.
3. The more hypotheses tested, the higher the chance of finding low p-values. In other words, the more tests performed, the higher the chance of finding a trend or pattern that does not actually exist (a false positive).[35] That is why the statistical test is supplemented with a multiple test correction. After the

[32] The more tests you perform, the higher the chance of a false positive. If you correct for this with a multiple test correction, then the more tests you perform, the lower the statistical power.
[33] Ergo: a false discovery rate (FDR) of 0.1.
[34] https://www.rdocumentation.org/packages/stats/versions/3.6.0/topics/chisq.test.
[35] For a more detailed explanation, see https://en.wikipedia.org/wiki/False_discovery_rate

multiple test correction, only those tests with the smallest p-values are selected, such that the proportion of false positives within the selection does not exceed a given (self-selected) value.

- The Benjamini-Hochberg procedure was used for multiple test correction [17].
- A value of 0.1 was selected for the proportion of false positives within the selection.

The statistical test only shows whether model elements are correlated, not how they are correlated. For example, the test may show that the expected value for incidents is not constant over time. However, the test does not indicate whether this expected value increases or decreases over the years. There may also be no regular pattern at all (the data for years 1, 3, 4, 8 and 11 show a statistically significant deviation from the data for years 2, 5, 6, 7, 9, 10, 12 and 13). An additional (visual) observation was used to check the data for chronological coherence (a trend over time).

5.1 Trends over time

Figure 5.1 shows six developments over time in terms of the number of incidents and the number of victims. The number of incidents is known for the entire period; the other parameters are only known for the period running from 2004 to 2015 (see Subsection 2.2).

Table 5.1 shows the results of the statistical analysis. These results relate to the parameters and their values, which are shown in Figure 5.1. The p-value for the test is shown in the second column of Table 5.1. The third column indicates whether or not the test was selected after the multiple test correction (MTC). For the selected tests, a deviation from the null hypothesis is plausible. Accordingly, these parameters have changed over time. The other parameters show no visible changes over time.

According to the analysis, two parameters are likely to involve deviations from the null hypothesis. These are:

- the annual number of incidents;
- the annual number of victims.

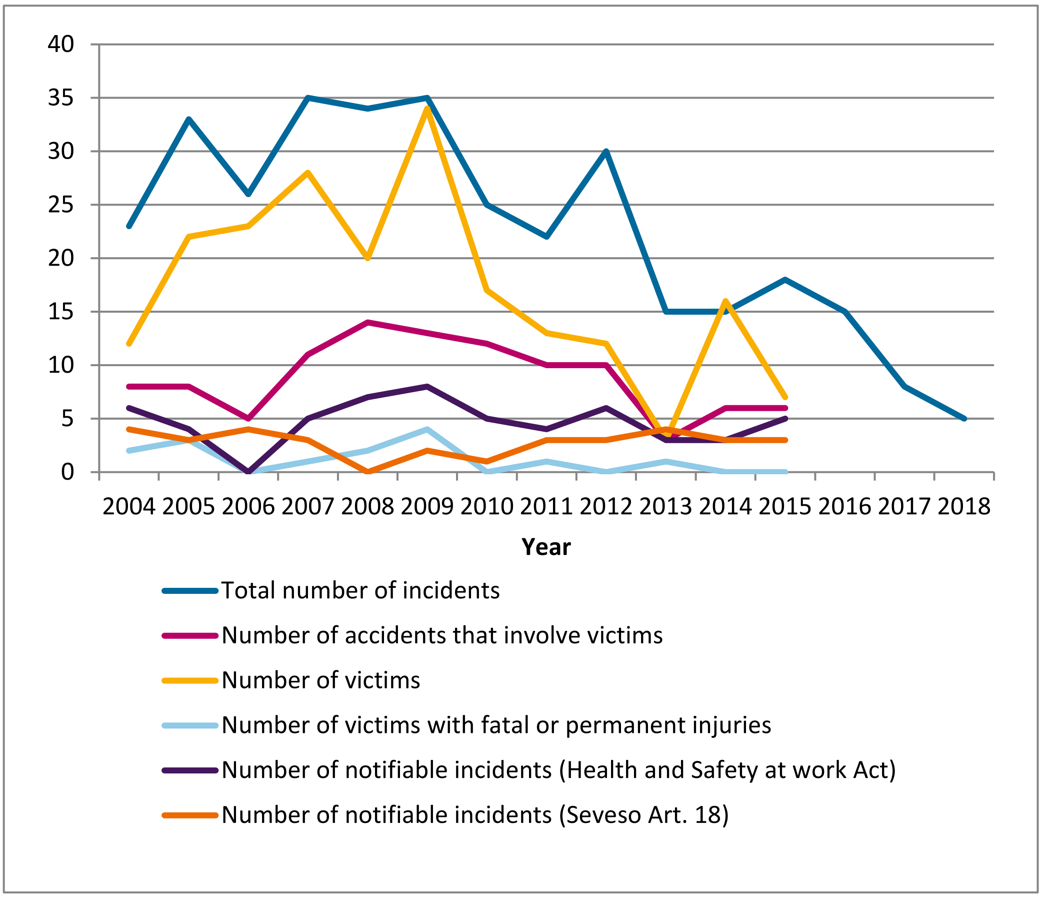


Figure 5.1. Trends in numbers of incidents and numbers of victims.

Table 5.1. Trends in numbers of incidents and numbers of victims.

Parameter	**Null-hypothesis**	**P-value**	**Null-hypothesis rejected after MTC**
Annual number of incidents	Constant between 2004 and 2018	<0.001	yes
Annual number of incidents that involved victims (one or more)	Constant between 2004 and 2015	0.21	no
Annual number of victims	Constant between 2004 and 2015	<0.001	yes
Annual number of victims with fatal or permanent injuries	Constant between 2004 and 2015	0.11	no
Annual number of notifiable incidents (Working Conditions Act)	Constant between 2004 and 2015	0.49	no
Annual number of notifiable incidents (Seveso)	Constant between 2004 and 2015	0.88	no

The two selected parameters were further investigated to identify any visible changes over time. Both showed a decline over the years. This decline appears to have started around ten years ago.

No clear-cut reason was found for the decline. The most obvious explanation is a fall in the annual number of incidents at Seveso companies during the period. For instance, according to Veiligheid Voorop (Safety First), the 'loss of primary containment' indicator has fallen every year since 2013 [11]. Another possible explanation is that, relatively speaking, the SZW Inspectorate cut down on the number of incidents it investigated during this period.[36] Furthermore, other factors unknown to RIVM may also be involved.

The other four parameters showed no demonstrable changes, if any, during the period. These parameters are:
- the annual number of incidents with victims (one or more);
- the annual number of incidents with one or more victims with fatal or permanent injuries;
- the annual number of incidents that were notifiable under the Working Conditions Act;
- the annual number of incidents with a mandatory notification of the European Commission, under the European Seveso III Directive.

The data do not explain why two parameters are visibly decreasing, while four others are not. *Possible* explanations include:
- The observed decrease in the annual number of incidents (see above) mainly involved relatively minor incidents. This may be related to the suspicion that the SZW Inspectorate's capacity to investigate incidents has been reduced over the years. As time progressed, relatively minor incidents were no longer investigated, while notifiable accidents were. As a result, the trend with regard to notifiable incidents is different from the trend for incidents in general.
- The number of notifiable incidents is relatively small, making it more difficult to identify any patterns.

5.2 Changes in causes and consequences over time

The second step was to check whether the causes or consequences of incidents changed during the period. Specifically, this concerns the underlying causes (what, how and why, see Subsections 3.6 and 3.7), the immediate cause (see Subsection 2.6), the immediate effect (see Subsection 2.3.1) and the subsequent effect (see Subsection 2.3.2) of the incident. In total, this amounts to eleven tests (see Table 5.2).

Each of the different parameters tested consists of a range of elements.[37] Tests are carried out to determine whether the relative contributions of

[36] See Footnote 5.
[37] For example, the safety measures in the 1st LoD are subdivided into five groups, as follows: safe start or start-up, ensuring the integrity of the installation, controlling the process parameters, controlling environmental factors, and unknown. See Subsection 3.2.1. The safety measures in the 2nd LoD are also subdivided into five groups, as follows: indication of the deviation, detection of the deviation, correct diagnosis of the deviation, correct remedial action, and unknown. See Subsection 3.3.1. There are also twelve possible immediate causes, five ways in which measures can fail, ten reasons why safety measures can fail, etc.

these elements differ from one year to another; for example, whether the immediate causes in one year are significantly different to those in another year. For all parameters, 'unknown' is also included in the analysis. This makes it possible to see whether the quality of the information has changed over the years.

Table 5.2. Description of the tests with regard to changes in causes and consequences over time.

Test	Null-hypothesis
Safety measure failures in the 1st LoD	The relative contributions of the safety measure failures in the 1st LoD were constant between 2004 and 2018. These failures are aggregated at group level: (i) safe start or start-up failure; (ii) failure to ensure the integrity of the installation; (iii) failure to control the process parameters; (iv) failure to control the site/environment; (v) unknown failure. See also Subsection 3.2.1.
Safety measure failures in the 2nd LoD	The relative contributions of the different types of recovery failures in the 2nd LoD were constant between 2004 and 2018. As discussed in Subsection 3.3.1, the following types of recovery failures are considered: (i) indication failure; (ii) detection failure; (iii) diagnosis failure; (iv) failure of remedial action; (v) unknown type of failure.
Safety measure failures in the 3rd LoD	The relative contributions of the different safety measure failures in the 3rd LoD were constant between 2004 and 2018. For more information, see Subsection 3.4.1.
Safety measure failures in the mitigating LoDs	The relative contributions of the different safety measure failures in the 4th, 5th or 6th LoD were constant between 2004 and 2018. For more information, see Subsection 3.5.1.
Successful safety measures	The relative contributions of the different safety measure successes were constant between 2004 and 2018. For more information, see Subsection 3.4.1 and 3.5.1.
Immediate causes of the incident	The relative contributions of the ten distinct types of immediate causes and unknown were constant between 2004 and 2018. For more information, see Subsection 2.6.
Type of incident: immediate effect	The relative contributions of the four types of immediate effects (release, fire, explosion, exposure within containment) were constant between 2004 and 2018. For more information, see Subsection 2.3.1.

Test	Null-hypothesis
Type of incident: subsequent effect	The relative contributions of the four main types of subsequent effects (airborne dispersion, fire, explosion and none) and unknown were constant between 2004 and 2018. For more information, see Subsection 2.3.2.
Manner in which safety measures fail (barrier task failures)	The relative contributions of the four distinct types of barrier task failures and unknown were constant between 2004 and 2018. For more information, see Subsection 3.6.
The reasons why safety measures fail (Management Delivery System failures)	The relative contributions of the eight distinct types of Management Delivery System failures and unknown were constant between 2004 and 2018. For more information, see Subsection 3.7.1.
Identified deficiencies in the SMS	The relative contributions of the seven distinct SMS elements and unknown were constant between 2004 and 2018. For more information, see Subsection 3.7.2.

Table 5.3 shows the results of the statistical analysis. The p-value for the test is shown in the second column. The third column contains the result of the multiple test correction (MTC).

Table 5.3. Changes in causes and consequences over time.

Test	P-value	Null-hypothesis rejected after MTC
Safety measure failures in the 1st LoD	0.67	no
Safety measure failures in the 2nd LoD	0.35	no
Safety measure failures in the 3rd LoD	0.36	no
Safety measure failures in the mitigating LoDs	0.63	no
Successful safety measures	0.30	no
Immediate causes of the incident	0.87	no
Type of incident: immediate effect	0.79	no
Type of incident: subsequent effect	0.37	no
Manner in which safety measures fail (barrier task failures)	0.002	yes
The reasons why safety measures fail (Management Delivery System failures)	0.01	yes
Identified deficiencies in the SMS	0.004	yes

Table 5.3 shows that, for eight of the eleven parameters subjected to the statistical test, no demonstrable changes/shifts were observed over time. For these parameters, the relative contributions of the different parameter elements remained largely the same during the period investigated (2003-2018). This applies to the various safety measure failures, the successful safety measures, the immediate causes of incidents and the nature of the incidents (immediate effect and subsequent effect).

"The nature of the incidents does not seem to have changed in the period running from 2003 to 2018. The causes of the incidents also seem to have remained the same during this period."

Three of the parameters tested did show statistically significant changes between the individual years in the period under consideration. This concerns the manner in which safety measures fail (barrier task failures), the reasons why safety measures fail (Management Delivery System failures) and the identified deficiencies in the Safety Management System. The changes in these parameters during the period are shown in Figure 5.2, Figure 5.3 and Figure 5.4.

The figures referred to above show that the relative contributions of the various parameter elements, such as the relative contributions of the various types of barrier task failures (see Figure 5.2), at the start of the period under investigation are not substantially different to those at the end of this period. Accordingly, no ongoing trends are observed over time. However, large differences can be seen between individual years and these are larger than might be expected based on natural (stochastic) variations of random processes.[38]

This appears to be an artefact, as the changes occur on a yearly basis and not continuously over time. The most likely explanation is that the incident analyses contain 'biases'. This means that, in some years, the analysts may have preferred specific factors. In the following years, these preferences faded away. On the other hand, each incident was examined by two analysts, with the express purpose of reducing the effect of any 'biases'. Furthermore, incidents from several years were generally analysed per analysis year. For this reason, the above explanation is not entirely satisfactory.

[38] For instance, between 2010 and 2012, the number of safety measure failures that resulted from maintaining the measures changed from 19 to 4 to 15. For the 'Operate (use)' element between 2012 and 2014, the number changed from 35 to 9 to 18.

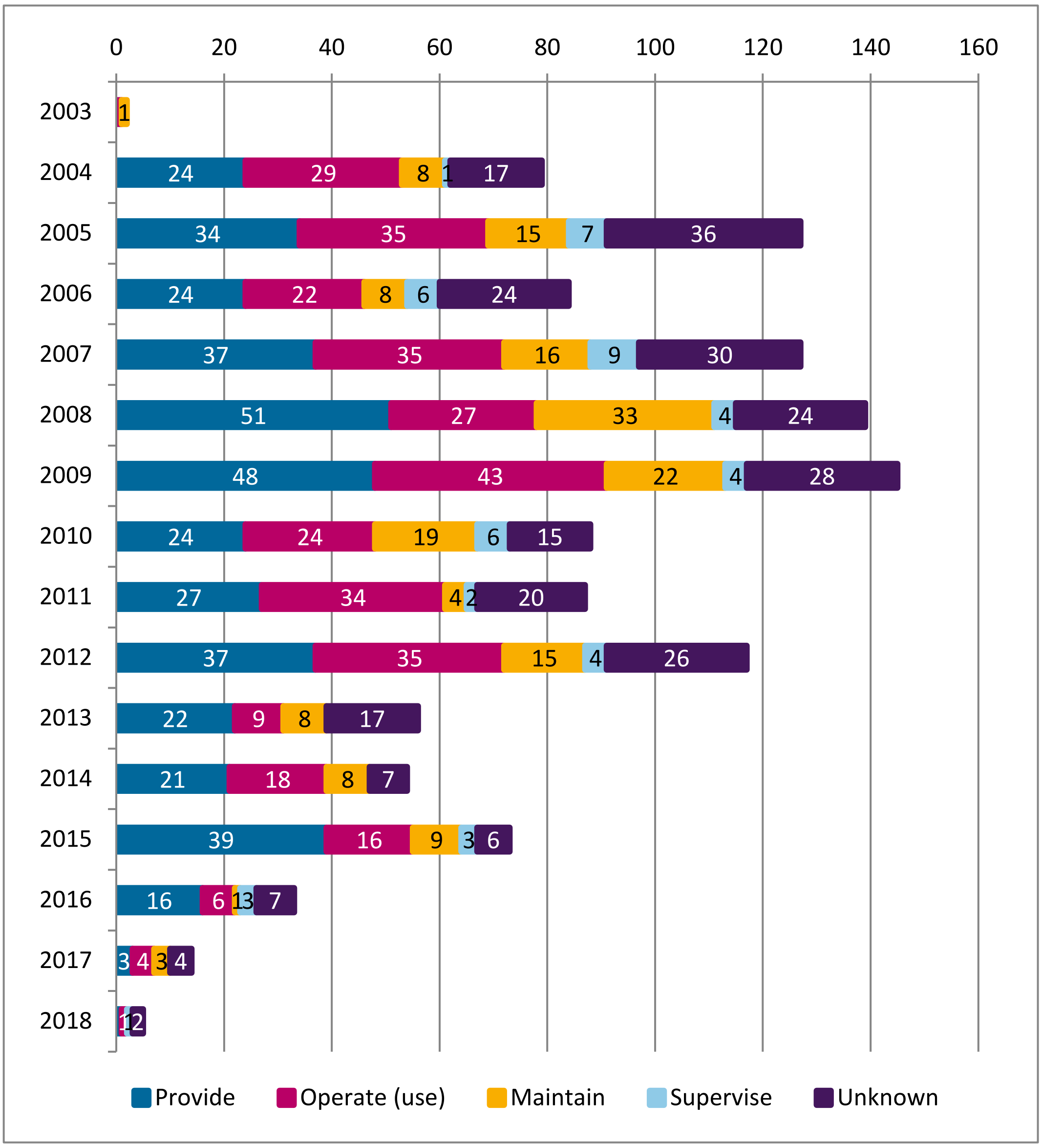


Figure 5.2. Manner in which the safety measures failed (number of barrier task failures).

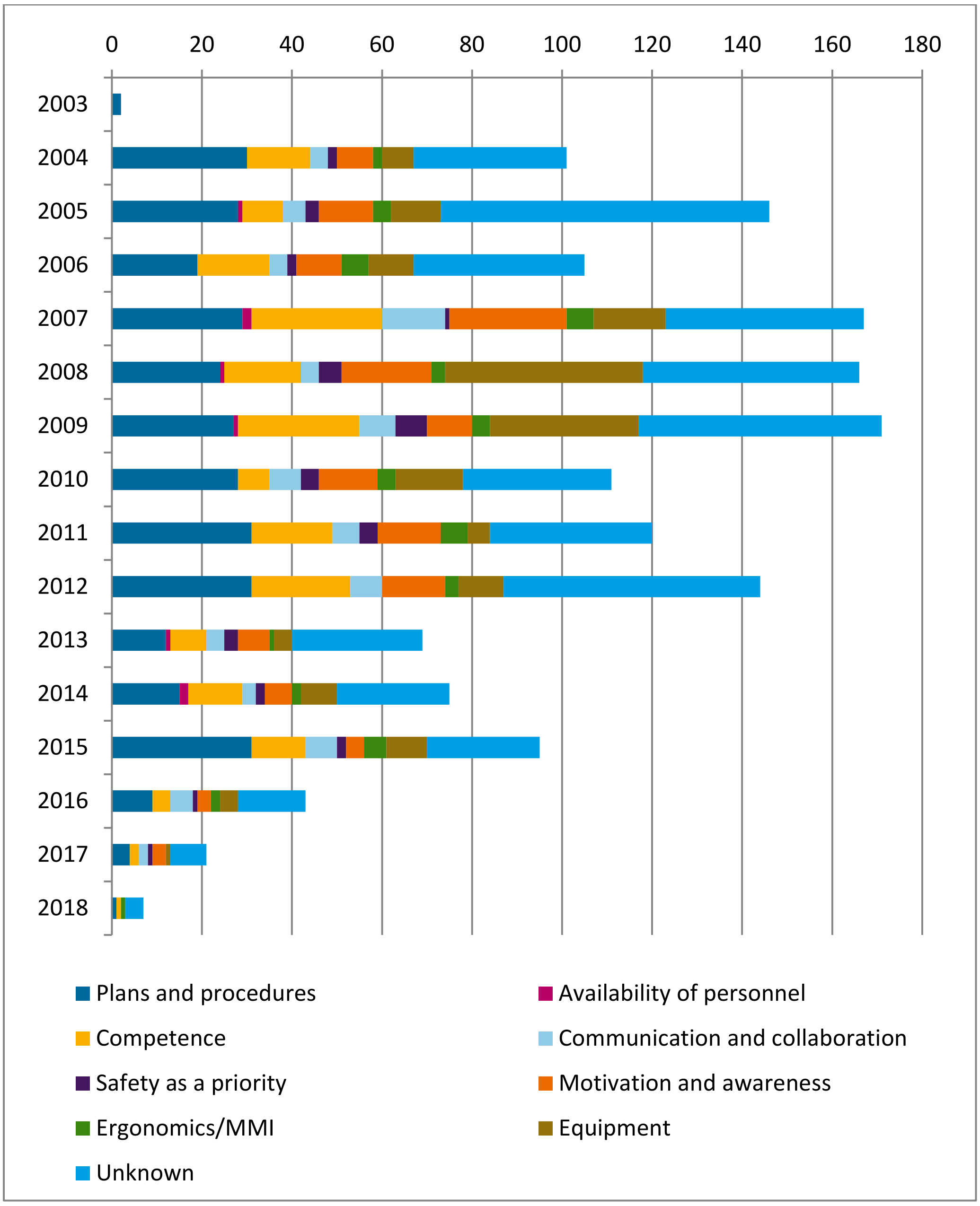


Figure 5.3. Underlying causes of safety measure failures (number of Management Delivery System failures).

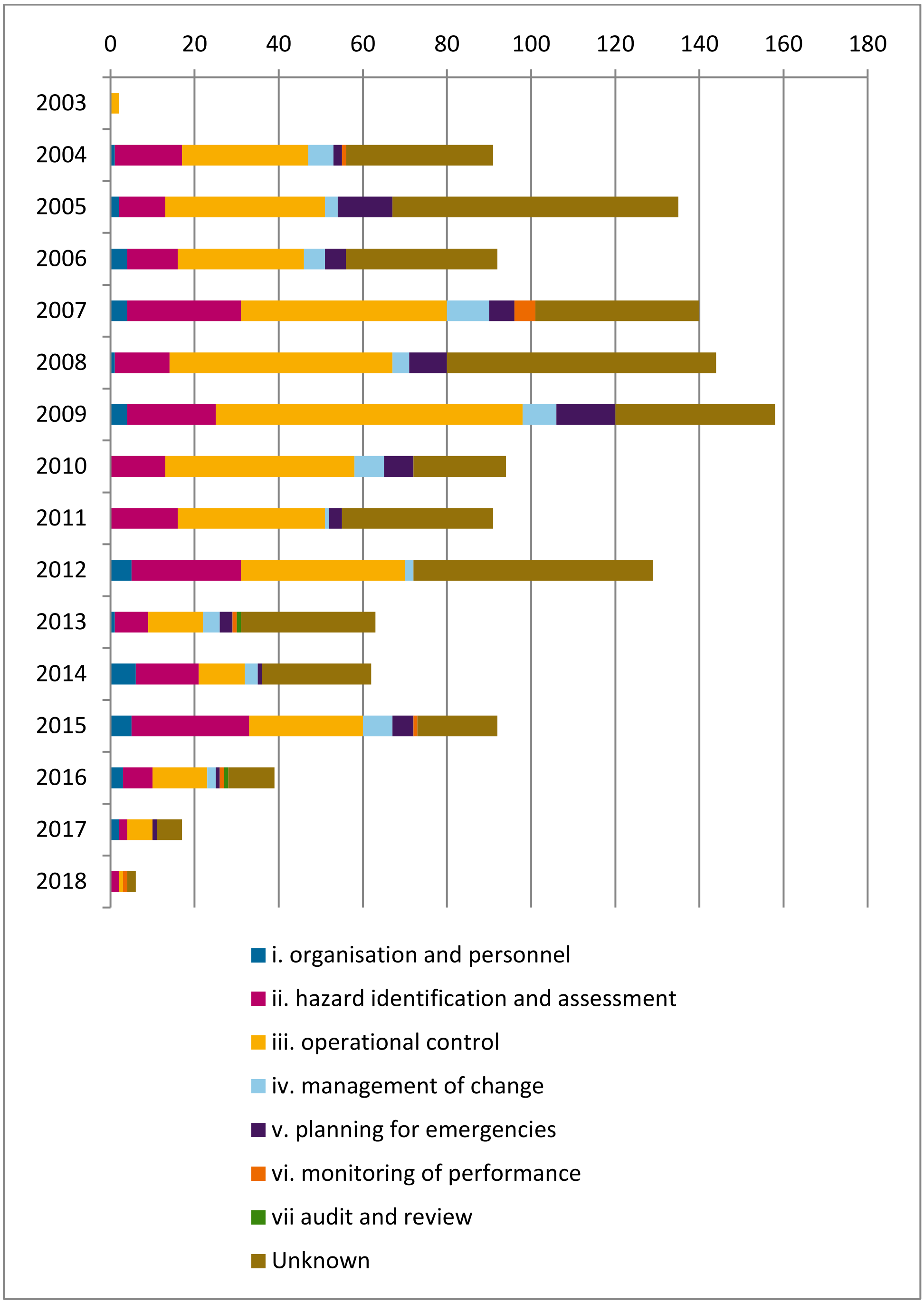


Figure 5.4. Deficiencies in the Safety Management Systems (number of SMS deficiencies).

5.3 Correlations with severity of injury

Finally, an investigation was carried out to determine which characteristics of the incidents or the victims correlate with the severity of injury. The severity of injury has four distinct elements, namely fatal injury, permanent injury, recoverable injury, and unknown (permanent or recoverable) injury. The tested parameters, such as the type of company, also involve distinct numbers of elements. Each parameter (for example, type of company) was examined to determine whether the severity of injury differs between the different parameter elements. For instance, were there relatively more victims with permanent injury at one type of company than there were at another?

Table 5.4 shows the results of the statistical analysis. The p-value for the tests is shown in the third column. The fourth column contains the result of the multiple test correction (MTC).

Table 5.4. Existence of correlations (associations) with the severity of injury.

Parameter	Null-hypothesis	P-value	Null-hypothesis rejected after MTC
Type of company (two-digit NACE code, see Subsection 2.5.2)	Severity of injury constant between different types of industry	0.0001	yes
Size of the company site (Subsection 2.5.3)	Severity of injury constant between different site sizes	0.006	yes
Process stage prior to the incident (Subsection 2.5.4)	Severity of injury constant between different process stages	0.01	yes
Method of task and process control (Subsection A2.5.3 of Appendix 2)	Severity of injury constant between different types of control	0.04	yes
Immediate cause of the incident (Subsection 2.6)	Severity of injury constant between different immediate causes	0.07	no
Type of incident: immediate effect (Subsection 2.3.1)	Severity of injury constant between different types of immediate effects	0.001	yes
Type of incident: subsequent effect (Subsection 2.3.2)	Severity of injury constant between different types of subsequent effects	0.0005	yes
Amounts of hazardous substance involved (Subsection 2.7.3)	Severity of injury constant between different amounts	0.15	no
Hazard category of the hazardous substance (or substances) (Subsection 2.7.2)	Severity of injury constant between different hazard categories	0.08	no
Victim's job (Subsection 2.4.5)	Severity of injury constant between different professions	0.89	no
Type of employment victim (Subsection 2.4.5)	Severity of injury constant between different types of employment	0.50	no
Age of victim (Subsection 2.4.5)	Severity of injury constant between different ages	0.08	no

Finally, Table 5.4 shows that, with regard to six specific characteristics of incidents or victims, no correlation with the severity of injury could be demonstrated. This means that there were no clear differences between the various categories within the parameter in terms of the severity of injury (fatal injury, permanent injury, recoverable injury, or permanent or recoverable injury). These six characteristics are:

- The **immediate cause** of the incident. The severity of injury does not appear to be significantly different for material degradation, high pressure, human error and other immediate causes.
- The **amount of hazardous substance involved**. The severity of injury for incidents that involved small amounts does not appear to be significantly different from the severity of injury for incidents involving large amounts.
- **Hazard category of the hazardous substances**. In particular, incidents involving flammable substances do not differ demonstrably from incidents involving toxic substances in terms of severity of injury.
- The **victim's job.** In cases in which the job of the victim is known, most of the victims are maintenance workers or process operators. The severity of injury appears to be comparable between the two groups.
- **Type of employment of the victim**. They were mostly contractors and the company's staff. In terms of the severity of injury, there is no significant difference between these two employment categories.
- **Age of the victim**. The ages of the victims were not of significance in terms of the severity of injury.

"The immediate cause of the incident does not (demonstrably) correlate with the severity of injury. Furthermore, there is no indication that either the amount of hazardous substance involved or its hazard category has any significant influence on the severity of injury."

In the case of six other characteristics, however, a correlation with the severity of injury does seem likely. These characteristics are:

- the type of company (see Figure 5.5);
- the size of the company site (see Figure 5.6);
- the process stage prior to the incident (see Figure 5.7);
- the method of task or process control (see Figure 5.8);
- the immediate effect of the incident (see Figure 5.9);
- the subsequent effect of the incident (see Figure 5.10).

Figure 5.5 shows the severity of injury for the different types of companies (two-digit NACE code). In the processing industry category (code 20: manufacture of chemicals and chemical products), the large number of victims with an unknown injury is particularly noticeable. This deviation (which is statistically significant) was mainly due to a single incident in which 15 people were exposed to chlorine fumes, with unknown consequences. The interrelationship in the extraction of crude petroleum and natural gas category (code 6) also shows an apparent deviation – in this business category, two of the three victims died.

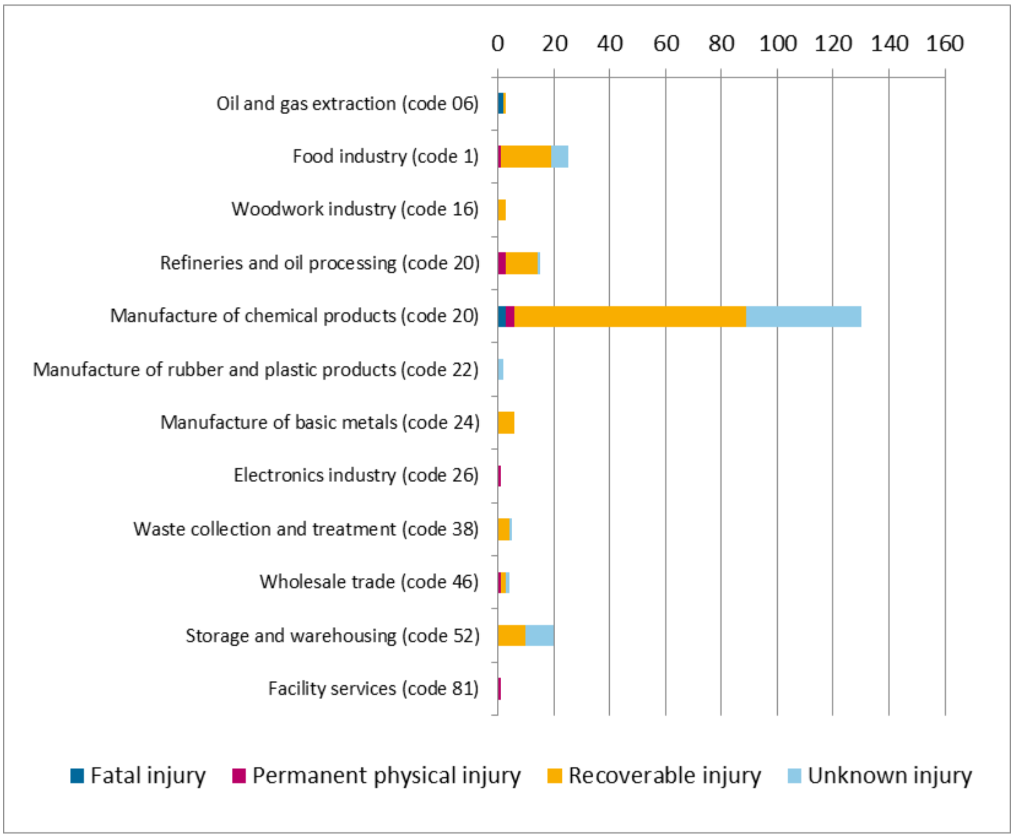


Figure 5.5. Type of company (two-digit NACE code) and severity of injury.

Figure 5.6 shows the severity of injury for sites of different sizes, measured in terms of the registered number of employees at that company site. The most striking deviation is the exceptionally large number of victims with an unknown type of injury at sites with 250 to 1,000 employees. This deviation (which is statistically significant) was mainly due to a single incident in which 15 people were exposed to chlorine fumes, with unknown consequences.

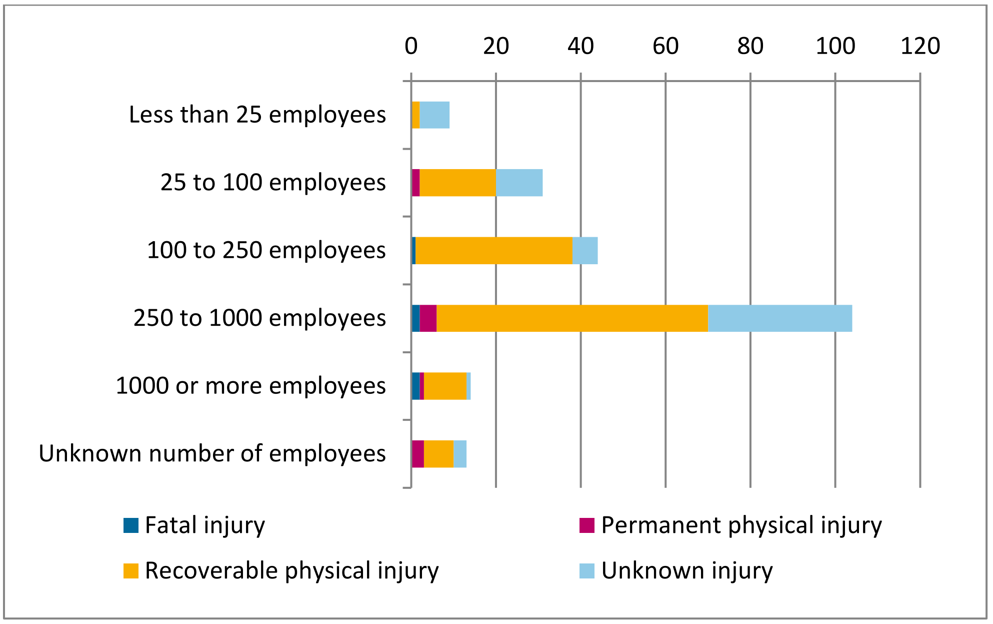


Figure 5.6. Size of the company site and severity of injury.

Figure 5.7 shows the severity of injury for the process stage prior to the incident. Particularly striking in the figure is the fact that four of the five fatalities were associated with incidents that occurred during maintenance, cleaning and inspection. As pointed out in Subsection 2.5.4, the number of victims associated with this process phase is relatively large. Figure 5.7 shows that the risk of fatal injury during this process phase is also relatively high.

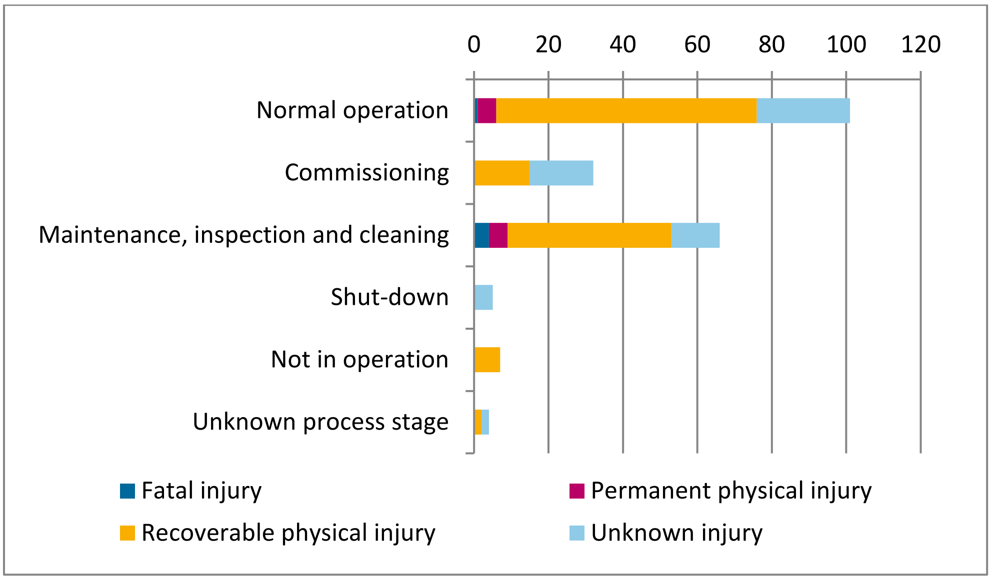


Figure 5.7. Process stage and severity of injury.

"Four of the five fatalities occurred during maintenance work. The number of victims with a permanent injury sustained during maintenance work is also relatively high."

Figure 5.8 shows the severity of injury for the method of task or process control. It is striking that a relatively large number of victims sustained fatal or permanent injuries during manual tasks and processes in particular. This concerns incidents in which maintenance work was being carried out on an installation (three victims), in which hot work activities (such as welding) were being performed on or next to an installation (two victims), or in which items of equipment in installations were actively opened (six victims).

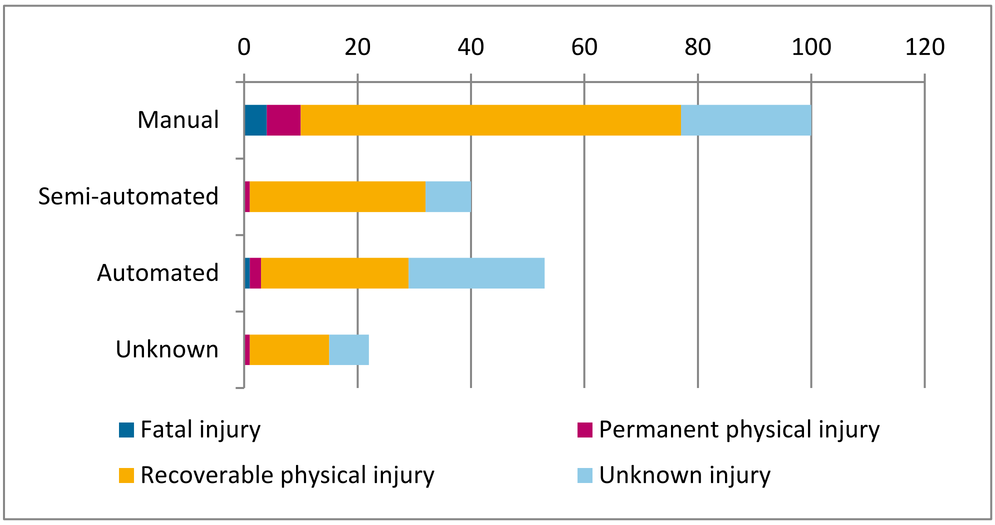


Figure 5.8. Method of task or process automation and severity of injury.

Figure 5.9 shows the severity of injury for the immediate effect of the incident. As a side note to the figure, the sustained injury is a combination of the immediate effect and the subsequent effect (see Figure 5.10). The most striking (deviating) category is exposure in a containment. While this only involved three incidents, these did involve two fatalities.

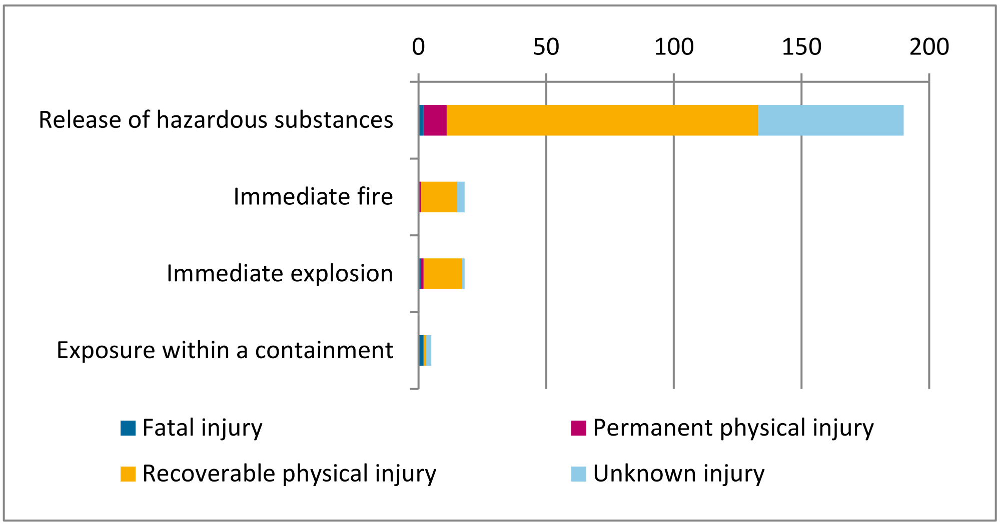


Figure 5.9. Immediate effect of the incident and severity of injury.

Finally, Figure 5.10 shows the severity of injury for the subsequent effect of the incident. The side note stating the injury is a combination of the immediate effect (see Figure 5.9) and the subsequent effect also applies in this case. The 'airborne dispersion' category is the most prominent. Strikingly, there were no fatalities and relatively few victims with a permanent injury. On the other hand, there was an exceptionally large number of victims with unknown injuries. In cases involving the inhalation of hazardous substances, it seems to be more difficult to determine whether the injury is of a permanent or recoverable nature.

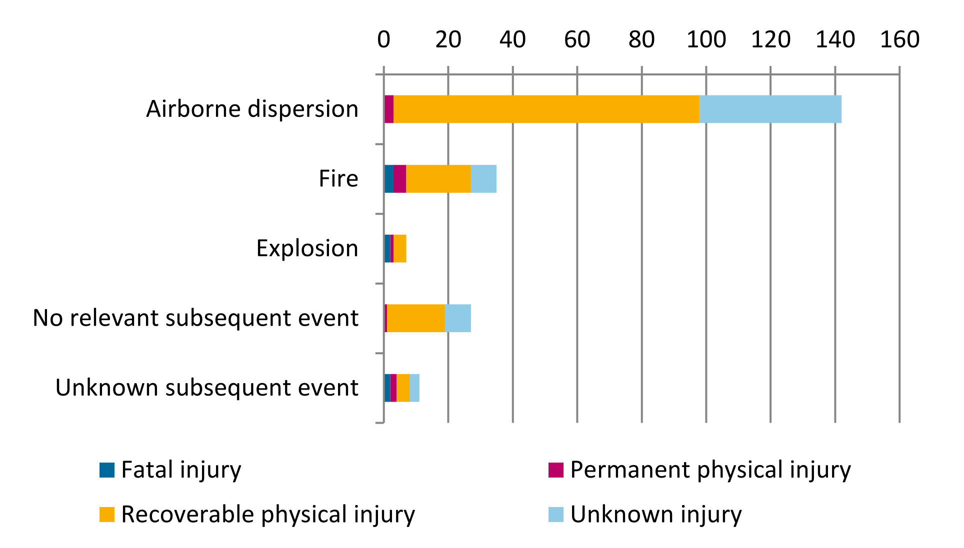


Figure 5.10. Subsequent effect of the incident and severity of injury.

6 Comparison with other occupational accidents

This investigation studied the 326 incidents involving hazardous substances that mainly took place at Seveso companies (see Subsection 2.5.1). This section examines how these incidents relate to incidents at other types of companies and to other types of incidents. Towards this end, a comparison is made with data in the generic Storybuilder occupational accident database, which includes the details of 31,156 occupational accidents with 32,111 victims [18]. This concerns accidents with severe consequences that occurred in the Netherlands between 1998 and 2014, that were reported to and investigated by the SZW Inspectorate, and that were analysed by RIVM.

The characteristics of occupational accidents versus MHC incidents are:

1. The generic Storybuilder database shows an average of 1.06 victims per accident.[39] The number of victims per accident in the MHC database, 0.66, is significantly lower.[40]
2. Both datasets contain details of the severity of injury. The data are shown in Figure 6.1. Thirty-eight percent of the victims involved in occupational accidents sustained permanent or fatal injuries. In the case of MHC incidents, the figure is 7%.

Both differences can be explained by the selection criteria used to trigger incident investigations. MHC incidents can be investigated if there is a potential hazard for employees or local residents. These do not necessarily involve victims nor, logically, severe injury. Occupational accidents are only investigated if they result in permanent or fatal injury, if a person is admitted to hospital or if the injury leads to absence from work for at least three working days.

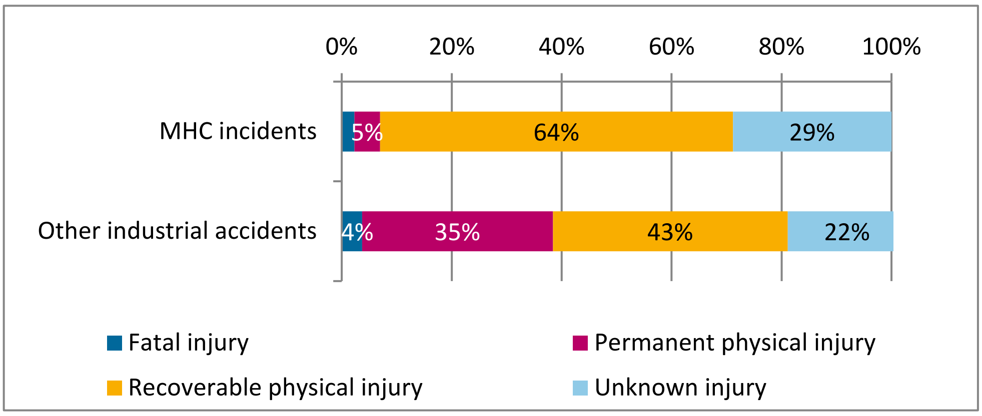


Figure 6.1. Severity of injury in MHC incidents and occupational accidents.

The investigation then focuses on how safety measures failed and why. Results are shown in Figure 6.2 and Figure 6.3.

[39] 32,111 victims in 31,156 accidents.
[40] 215 victims in 326 accidents.

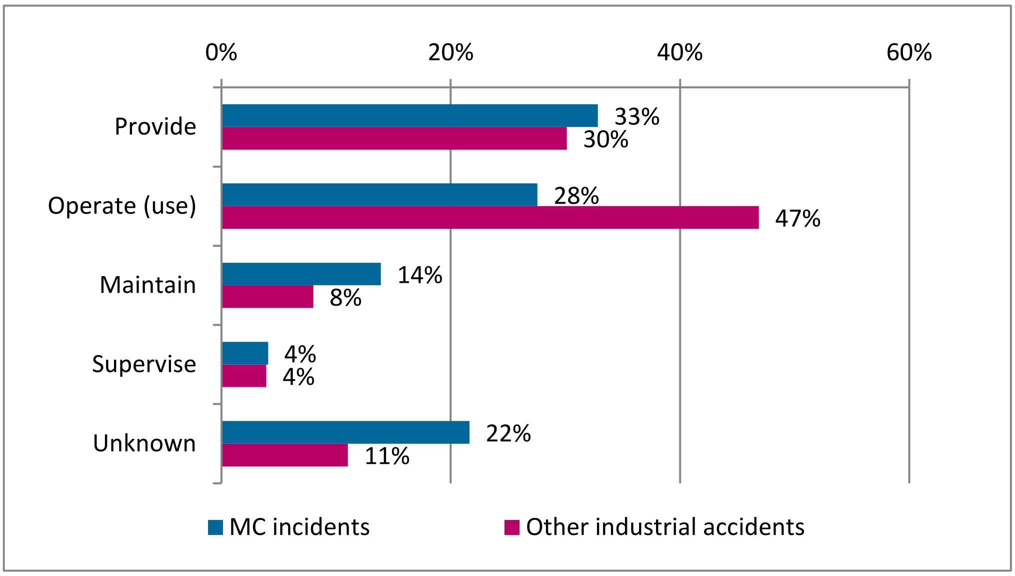


Figure 6.2. How do safety measures fail? MHC incidents compared to other occupational accidents.

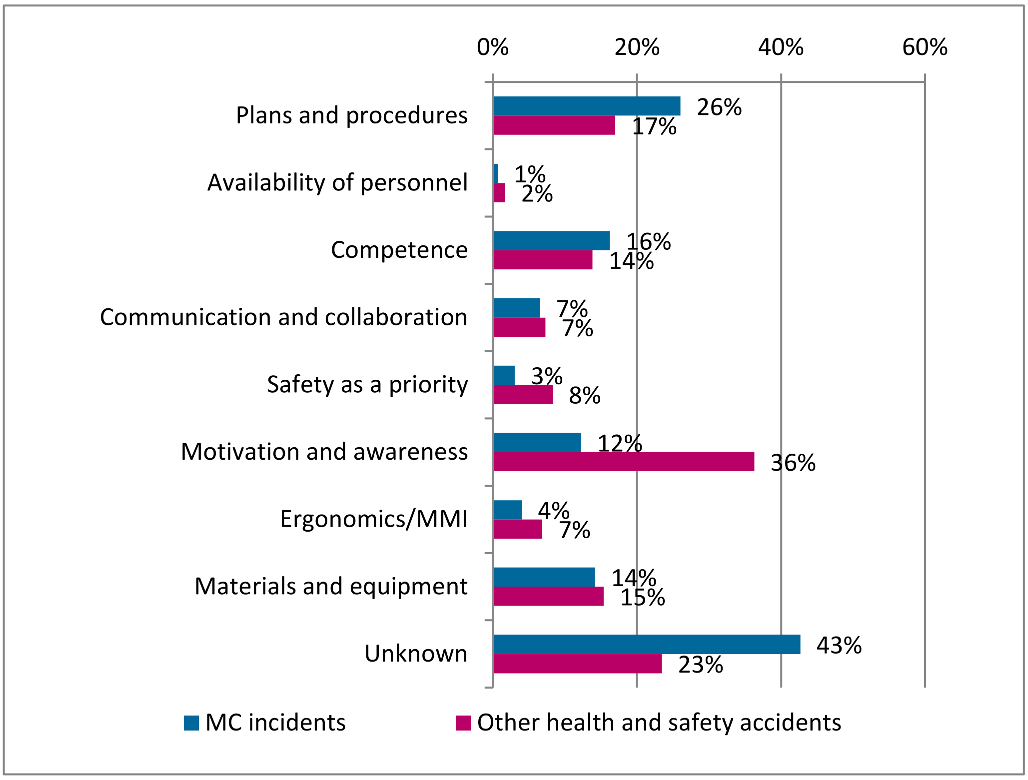


Figure 6.3. Why do safety measures fail? MHC incidents compared to other occupational accidents.

Figure 6.2 and Figure 6.3 show the following differences:

- In MHC incidents, safety measures fail mainly because they have not been provided (33%) or have not been used/applied correctly (28%). In the case of other occupational accidents, safety measures fail mainly because they have not been used correctly (47%). See Figure 6.2.

- In MHC incidents, failure is mainly due to the lack of quality and completeness of plans and procedures (26%). In other occupational accidents, this is mainly due to lack of motivation and awareness (36%) (see Figure 6.3). There is also a striking difference in terms of the 'safety as priority' factor (3% for MHC incidents versus 8% for occupational accidents).

One possible explanation for these differences is that the control of safety at major hazard chemical companies is more complex. There are more potential causes of incidents, some of which are related to each other in more complex ways. It is therefore more difficult to foresee every potential route to an incident and to manage them with measures that are applicable in everyday practice. This would account for the relatively large number of deficiencies in plans and procedures in MHC incidents, and the relatively large number of safety measures that were not or not adequately, provided.

In the other occupational accidents, human actions from individual employees play a more significant role. Quite often, safety measures are not used. In a relatively large number of cases, the fundamental reason for this is a lack of awareness among employees. In the case of other occupational accidents, safety can be enhanced by increased efforts to encourage safe working practices among the staff. In the case of MHC incidents, this delivers fewer benefits and a further improvement of plans and procedures is also necessary.

7 Conclusions

The SZW Inspectorate's Major Hazard Control Department investigated 326 incidents involving hazardous substances between 2004 and 2018. These 326 incidents resulted in 215 victims. The numbers are significant enough to draw the following statistically substantiated conclusions:

1. The majority of incidents occurred at upper-tier establishments that fall under the EU Seveso III Directive. This mainly concerned establishments that manufacture chemical products (the chemical processing industry).
2. Fortunately, the victims' injuries were usually temporary. Nevertheless, three incidents resulted in fatalities (a total of five) and nine incidents resulted in ten victims with a permanent injury.
3. The victims were mainly maintenance workers and process operators. Half of the victims were contractors hired by the company; one-third were members of the company's staff.
4. Most incidents (60% of the total) occurred during normal operation. The maintenance-related incidents involved a relatively large number of victims. The severity of injury in the victims of maintenance-related incidents was also greater.
5. During the period analysed, the number of incidents investigated by the SZW Inspectorate fell. This trend started approximately ten years ago and may reflect a genuine fall in the number of incidents involving hazardous substances throughout the industry. However, it can also mean that, in relative terms, the SZW Inspectorate has been reducing the number of incidents it investigates. No demonstrable reduction was observed in the number of notifiable incidents that were investigated during this period.
6. During the period under investigation, the nature of such incidents remained substantially unchanged, as did their immediate and underlying causes.
7. In most incidents, there was initially a release of hazardous substances. Fifteen per cent of incidents started with a fire or explosion or a combination of the two. The hazardous substances were mainly released from loose connections and couplings, open valves, pressure relief valves, taps for liquids, vents and piping.
8. If hazardous substances are released, this is usually followed by airborne dispersion. In one case in seven, the release of hazardous substances was followed by a fire or explosion. A quarter of the incidents were either short-lived or were quickly brought under control.
9. The most common immediate causes of incidents were human error and material degradation. Together, these two immediate causes were responsible for 56% of all incidents.
10. The analysis model identifies several safety measures that could be used to prevent incidents. These are grouped into three layers of protection (lines of defence): operational control, recovery and emergency protection:
    a. The safety measures for effective operational control are clustered into four groups. Three of these were decisive with respect to the occurrence of incidents. The incidents occurred due to deficiencies in ensuring the integrity (or material

integrity) of the installation, in controlling process parameters and in safe start-up. Accordingly, no single dominant cause was responsible for the occurrence of the incidents.

b. A failure in providing effective operational control will trigger deviations outside the operating windows. In the incidents, recovery was neither prompt nor adequate. In approximately half of all incidents, this was because there was no indication of the deviation. The deviation was not identified because no resources or procedures were in place that might have detected the deviations in time or because these resources or procedures were not functioning properly.
c. Sometimes, if no remedial action is taken, it may still be possible to take emergency measures to prevent an incident. According to the analysis, this was the case in 41% of the incidents. This mainly concerned the prevention of fire and explosion inside a containment and measures to protect installations against high pressure. In the remaining 59% of incidents, the analysis shows that – after a failure to identify and recover deviations – no further emergency measures to prevent the incident were possible. In those incidents, safety was entirely dependent on effective operational control (point a) and on timely and adequate recovery (point b). This included, for example, scenarios involving material degradation or the active opening of a containment.

11. The analysis model includes a range of measures for limiting the consequences of an incident. For any given incident, some measures are more effective than others. In general, the failures (387x) slightly outnumbered the successes (335x). This means that further improvements could be made with regard to combating the incident and preventing or reducing injury.
12. Safety measures mainly failed because they had been provided incorrectly or not at all (33%) or because they had been used incorrectly or not at all (28%). The former implies that the requisite safety instruments and safety procedures were either lacking or inadequate. The latter implies that the available resources were not operated, used or applied correctly.
13. At the organisational level, the failure of safety measures was mainly due to deficiencies in plans and procedures (26%). To a lesser extent, aspects such as poorly trained and insufficiently experienced staff (16%), unsuitable materials and equipment (14%) and a lack of alertness on the part of the staff (14%) were also involved.
14. With regard to the safety management system, in 38% of the cases, the failure of safety measures was related to deficiencies in operational control (SMS element iii). In 18% of cases, the failure of the measure was related to errors in identifying hazards and assessing risks (element ii). Other elements of the SMS were less often judged to have critical deviations.
15. Safety improvements involve a degree of customisation. Companies must analyse their own situations to determine which measures might be most effective for them. Nevertheless, it is possible to identify several similarities in the occurrence of these incidents. First and foremost, two immediate causes were collectively responsible for 56% of all incidents and 49% of all

victims. These were human error and material degradation. Subsection 4.1 describes ways of improving safety in these two scenarios. Secondly, in 59% of the incidents, two pillars of safety were identified – safe operational control and prompt and adequate recovery. Therefore, strengthening these two pillars would deliver relatively significant safety benefits. Part of this is a keen awareness of potential deviations outside the operating windows. Finally, with regard to the safety management system, the failures that occurred were mainly in terms of operational control. This means that, while there was a general awareness of the hazards and risks involved, there was also a deficiency in translating this awareness into effective practical measures. Efforts to increase safety must focus more intensively on whether the implemented instruments and procedures are indeed adequate in the light of the potential deviations. Checks must also be conducted in the workplace to verify that these instruments and procedures are being used and followed as intended.

Glossary

Accident	In an accident, one or more preventive barriers fail, leading to deviations from normal operation for which recovery is neither prompt nor adequate. This results in the release of hazardous substances, in fire or explosion, or in people entering spaces that contain hazardous substances.
Barrier (definition cf. Storybuilder)	Barriers are obstacles in the incident path that are intended to prevent incidents or to mitigate their consequences. Barriers therefore fulfil a specific safety function. The safety function can be implemented in various ways. Barriers must be managed by means of a management cycle to ensure that they function adequately. The Storybuilder MHC model comprises six groups of barriers (see 'line of defence'), three of which are situated to the left of the central event (preventive barriers) and three to the right (mitigating barriers).
Barrier task	See task.
Brzo	Major Accident Hazards Decree (in Dutch: Besluit Risico's Zware Ongevallen). Brzo 2015 (previously Brzo 1999) is the Dutch implementation of the EU Seveso III Directive (previously Seveso II Directive). The Brzo integrates legislation and regulations in the areas of occupational safety, external safety and disaster response into a single legal framework. The objective is to prevent or control major accidents involving hazardous substances. Towards this end, Brzo imposes requirements on major-hazard companies in the Netherlands. In addition, the decree stipulates how the government must supervise these companies. The current version (Brzo 2015) came into effect on 8 July 2015.
Central event	A central event is the centre of what is known as a 'bow-tie'. It is the point at which the hazardous substance or agent is released. The Storybuilder MHC model distinguishes between four different types: the release of hazardous substances, fire inside a containment, explosion inside a containment and exposure to hazardous substances in a containment.
Containment	A containment consists of one or more items of equipment, parts of which are in open connection with each other. These are intended to contain one or more substances and, in the event of a major accident (or imminent major accident), they can be quickly sealed. Here, the term 'containment' refers to items of equipment in process installations (such as reactors, process vessels and process pipelines), as well as storage units (such as tanks, drums and cylinders) and

	transport installations (such as transport pipelines, flexible hoses, loading arms), etc.
eMARS	A European Commission database (electronic Major Accident Reporting System). Member States are obliged to give immediate notification of any serious incidents and to supplement this with investigation data at a later time.
Immediate cause	This is the failure mechanism that, chronologically, directly precedes the incident. For example, the physical cause of a containment's failure or the immediate cause that led to a containment opening.
Incident	In incidents, one or more deviations from normal operation have occurred. Accordingly, 'incident' is a broad term that includes 'near misses', incidents with limited impact and accidents with larger impact.
Line of Defence (LoD)	A functionally coherent group of safety measures (barriers). These are grouped as such in the model.
Loss of control event	A loss of control event describes the safety condition following the failure or success of the preceding group of safety barriers (Line of Defence). Examples of loss of control events are the material condition of the equipment outside the operating window and pressure in the equipment outside the operating window. Together, the loss of control events in an accident path show the development of the incident.
Major accident	The EU Seveso III Directive defines a major accident as an occurrence, such as a major emission, fire or explosion, resulting from uncontrolled developments in the course of the operation of any establishment covered by this Directive and leading to serious danger for human health or the environment, immediate or delayed, inside or outside the establishment and involving one or more dangerous substances.
Major Hazard Control (MHC)	A unit of the SZW Inspectorate. The Major Hazard Control department focuses on safety at major hazard chemical companies. It bears some of the responsibility for monitoring compliance with legislation designed to prevent major accidents and to limit their consequences. The Major Hazard Control department carries out inspections and conducts incident investigations at companies that are subject to major accident legislation.
Management Delivery System	The management delivery system is the socio-technical system needed to control safety. Its purpose is to ensure that safety barriers function adequately. The Storybuilder model identifies eight different elements of the management delivery systems, also sometimes referred to as 'management factors'. These are: Plans and procedures, Availability of personnel, Competence, Communication and collaboration, Conflict resolution,

	Motivation and awareness, Ergonomics and man-machine-interaction, Equipment.
MHC incident analysis model	A specific Storybuilder model for the analysis of incidents involving hazardous substances was created for the Dutch Ministry of Social Affairs and Employment's former Major Hazard Control (MHC) Directorate in cooperation with the UK's Health and Safety Executive (HSE). This is the incident analysis model (Storybuilder MHC) that is used in this report.
NACE	NACE is the official statistical classification system of economic activities for the European Community. The classification uses four digits. The first two digits are identical to the ISIC classification of the United Nations.
Near miss	An incident in which one or more preventive barriers fail, while one or more others are successful in preventing the release of hazardous materials, fire, explosion or exposure within a containment. In Storybuilder terminology, a near miss starts with failures and deviations but doesn't arrive at the central event.
Occupational accident	A sudden, accidental event that affects an employee that is related to the carrying out of their work, which almost immediately results in damage to their health and leads to their absence from work due to injury, or which almost immediately results in death.
Safety management system (SMS)	To determine and implement the prevention policy, the individuals who run or manage an establishment that is subject to the EU Seveso III Directive are required to implement a safety management system. The goal of the Safety Management System is to reduce the risk of major hazard accidents to an acceptable level. The safety management system must address the seven elements listed in Annex III of the EU Seveso III Directive.
Seveso Directive	European Directive for the prevention and management of accidents involving hazardous substances at major chemical companies. Companies are subject to the Directive if the permitted quantities of hazardous substances exceed the threshold values indicated in the Directive. The companies concerned must take steps such as limiting the risk of accidents by means of a safety management system. Government agencies must be prepared for incidents. They must also determine which dangers and risks are tolerable for the surrounding area.
Seveso establishment	An establishment (company) holding hazardous substances of such a nature and amount that it breaches the limits that are stated in the EU Seveso III Directive (for one or more specified hazardous substances).
Storybuilder	Storybuilder is an investigative tool with a graphical user interface. It is used to record and analyse incidents. Details of the causal 'paths' are entered into the model. These paths indicate what occurred, how it occurred and

	why. See Appendix 2 for background information on Storybuilder.
SZW	Dutch Ministry of Social Affairs and Employment
Task	A task or barrier tasks are one component of the barrier control cycle. The Storybuilder model identifies four tasks: (i) provide, (ii) use, (iii) maintain and (iv) monitor (supervise). Together, the four tasks, when properly carried out, ensure that the barrier works: that its intended safety function is achieved.

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Appendix 1 Description of the Storybuilder model

Storybuilder was developed to record the results of a large number of incident analyses in a bow-tie model [3], [4], [5]. The name 'Storybuilder' refers both to the model that is used to perform the analyses and to the associated publicly available software. The software consists of a graphical user interface with which analyses can be performed and recorded as incident paths.

In the Netherlands, Storybuilder is used to analyse occupational accidents that have been investigated by the SZW Inspectorate. Specific models have been developed for various types of accidents and incidents[41]. Storybuilder's general characteristics are discussed in Subsection A1.1. Storybuilder MHC is the specific model used to analyse incidents involving hazardous substances at major-hazard companies [1], [2]. The specific characteristics of this MHC model are described in Subsection A1.2.

A1.1 General description of Storybuilder

In the Storybuilder model, incident scenarios are represented as an incident path. Besides general characteristics of the incident (administrative data), the model also contains a structure for analysing immediate and underlying causes. A 'bow-tie model' is used for these immediate and underlying causes. The central element of this bow-tie model (the central event or centre event) is the type of incident that is to be prevented. The left side of the central event has preventive barriers for preventing this event. The right side has repressive barriers for limiting its consequences. The relationship between the incident path, the central event and the barriers is shown diagrammatically in Figure A1.1.

The central event is the centre of the bow-tie model. It provides an answer to the question 'what happened?'. The central event is defined as the moment when the hazardous agent (harmful substance or energy) is released.

Barriers (referred to as 'safety measures' in the main report) are obstacles in the incident path that are intended to prevent incidents or to mitigate their consequences. Barriers, therefore, fulfil a specific safety function. The safety function can be implemented in various ways. Barriers must be managed by means of a management cycle to ensure that they are functioning adequately.

[41] 'Incident' is the term that is mainly used throughout the rest of the text. Here, the term 'incident' means an unforeseen, undesired event. The term 'accident' implies damage or injury. This is not always the case for incidents.

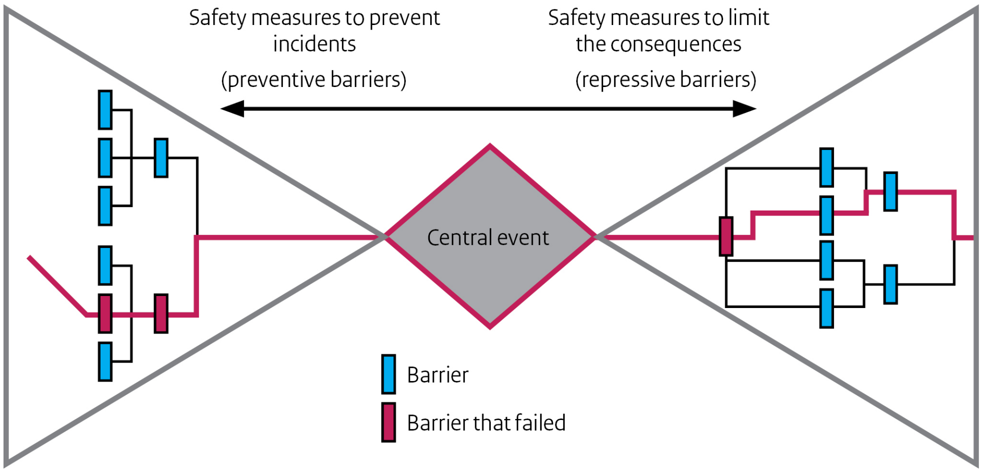

Figure A1.1. Storybuilder model with the incident path represented as a red line. This indicates the route of the incident scenario that occurred and the associated barrier failures.

On the left side of the bow-tie model are barriers for preventing incidents ('preventive barriers'). The central event occurs when the preventive barriers have failed. On the right side are the barriers used to limit the consequences of the incident ('repressive/mitigating barriers'). The severity of the consequences depends on the success or failure of the repressive/mitigating barriers.

Barriers are functionally grouped into 'lines of defence' (LoDs). Each specific Storybuilder model contains at least one preventive LoD and one repressive LoD. Barriers can fail or succeed, see Subsection A1.4. A barrier failure leads to a loss of control event (LCE). So each barrier group (LoD) is followed by one or more LCEs. These are shown on the right-hand side of the LoD in Figure A1.3.

The task failure (T) provides an answer to the question 'how could the barrier have failed?'. The model distinguishes between four distinct tasks (barrier tasks): Provide, Operate (use), Maintain and Monitor. Together, these tasks form a kind of management cycle for the barrier. If there is a possibility of a human error, the nature of that human error is also analysed.

The management delivery system (MDS) failure provides an answer to the question 'why did the barrier task fail?'. These factors can be organisational or behavioural. Failures in the proper functioning of these management delivery systems can lead to the failure of one of the tasks and – as a result – the failure of the barrier. The model distinguishes between eight separate management delivery systems.

Thus, the causes of incidents can be described as a causal chain of management delivery system failures, task failures and barrier failures. This is shown diagrammatically in Figure A1.2.

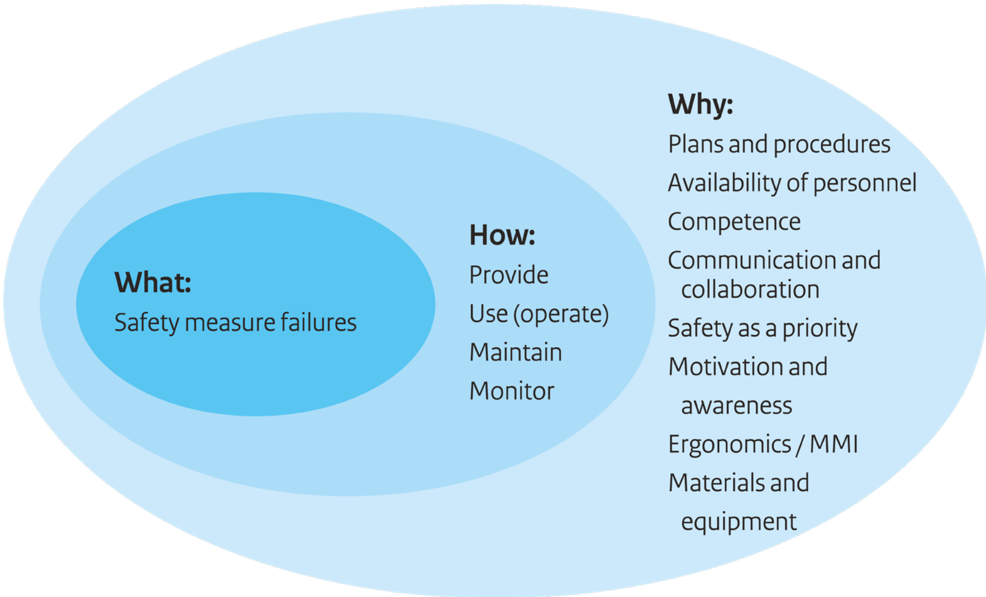

Figure A1.2. Structure for the underlying factors in the analysis model. The MDS management delivery system failures (why) precede the task failure (how), which precedes the barrier failure (what).

A1.2 General description of the MHC model

A specific Storybuilder analysis model has been developed for incidents involving the release of hazardous substances at major hazard companies. This was commissioned by the Ministry of Social Affairs and Employment. Elsewhere in this report, this model is referred to as the (Storybuilder) MHC model or Storybuilder MHC.

The original central event in the MHC model is the 'unintentional release of a hazardous substance'. Because some other incidents were also investigated by the SZW Inspectorate's Major Hazard Control (MHC) Directorate, the definition was later broadened to 'Major accident involving one or more hazardous substances'. In the current model, four different types of major accidents are distinguished:

1. the release of hazardous substances, also known as 'loss of containment' (LoC);
2. immediate fire: fire in a containment without a preceding 'loss of containment';
3. immediate explosion: explosion inside a containment without a prior 'loss of containment';
4. exposure to hazardous substances inside a containment.

To prevent a major incident involving hazardous substances and to limit any consequences, Lines of Defence (LoDs) of associated safety measures (barriers) must be in place and function adequately. The MHC model uses three preventive LoDs and three repressive LoDs, see Figure A1.3.

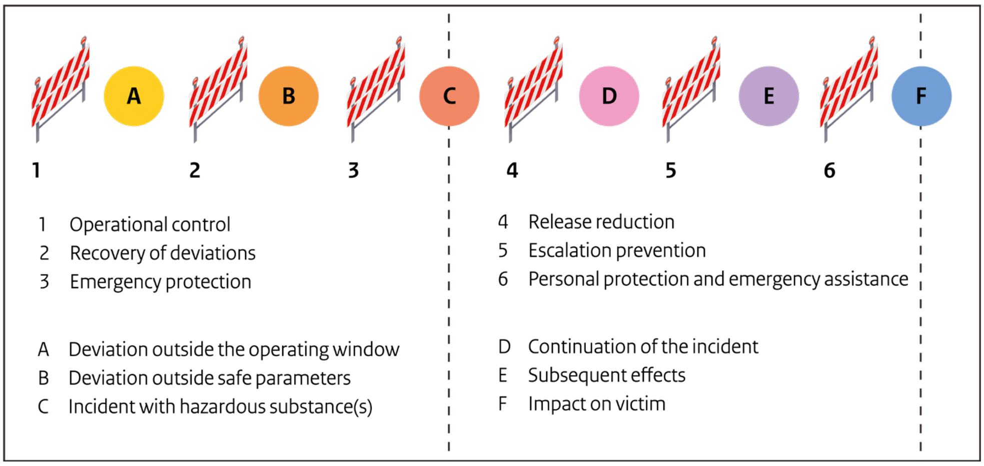

Figure A1.3. Summary of the Storybuilder MHC model. The lines of defence are represented by fences, the loss of control events by circles. The central event (C) is in the centre.

As described in Subsection A1.1, the bow-tie model in Storybuilder consists of barriers, barrier tasks and management delivery systems. The MHC model additionally includes the elements of the safety management system (SMS), as specified in the EU Seveso III Directive. The SMS elements are presented alongside the management delivery systems, with which they also overlap. For instance, the management delivery system Competence from Storybuilder relates to the SMS element 'Personnel and organisation' from the EU Seveso III Directive.

The MHC model has 41 barriers, subdivided into six lines of defence. Table A1.1 shows the individual barriers that make up the various lines of defence.

Table A1.1. Summary of barriers within the various LoDs.

LoD	**Code**	**Barriers within the LoD**
1. Operational control	G	*Control of start*
	01_B	Equipment selection
	02_B	Safeguarding prior to start
	G	*Control of equipment condition*
	03_B	Control of conditions w.r.t. material degradation
	04_B	Containment material
	05_B	Equipment (parts) design
	06_B	Equipment connections
	07_B	Installation of equipment
	G	*Control of process parameters*
	08_B	Control of movement/position of containment
	09_B	Temperature control
	10_B	Control of reaction
	11_B	Pressure control
	12_B	Flow control
	13_B	Separation of incompatible substances

LoD	Code	Barriers within the LoD
	G	*Control of surroundings and environment*
	14_B	Security and protection of the site/establishment
	15_B	Control of common mode failures
	16_B	Prevention of external impact
	17_B	Storage/transportation conditions
	18_B	Separation from heat sources
2. Recovery of deviations	20_B	Recovery of deviations
3. Emergency protection	51_B	Secondary containment
	52_B	Protection for opening of containment
	53_B	Protection for temperature outside safe parameters
	54_B	Protection for pressure outside safe parameters
	55_B	Protection for level outside safe parameters
	56_B	Protection for undesired flow to other containment
	57_B	Prevention of ignition (including self-ignition)
	58_B	Protection against impact and external load
	59_B	Use of PPE in a containment
	60_B	Protection for deviating substance(s)
4. Release reduction	28_B	Stopping the release
	29_B	Reduction of the driving force behind the release
5. Escalation prevention	31_B	Limiting evaporation or dispersion
	32_B	Emergency containment
	34_B	Ignition prevention
	35_B	Fire repression and explosion prevention
	36_B	Separation of installations
6. Personal protection and emergency assistance	38_B	Use of personal protective equipment
	39_B	Evacuation
	40_B	Safe shelter
	41_B	Keeping a safe distance from the danger zone
	42_B	Emergency aid

A1.3 Purpose and use of the Storybuilder MHC model

The analyses made with the Storybuilder MHC model are primarily intended to improve understanding of how incidents involving hazardous substances at major hazard chemical companies occurred. The bow-tie structure shows which barriers are important in terms of preventing incidents and limiting their consequences. The underlying barrier tasks and management delivery systems indicate how the proper functioning of these barriers should be assured.

For specific (individual) incidents, the model can be used to conduct a structured investigation to identify the important aspects of each incident. This concerns both the relevant barriers in the various lines of defence and the underlying factors (barrier tasks and management delivery systems). This knowledge can be used to improve the quality of incident investigations.

The characteristics of every incident that has been analysed are collected in a single database, making it possible to identify common patterns. If required, this information can be filtered, for example, by type of company, item of equipment, or substance. Inspection services can use this information for planning/prioritising topics for inspection. Companies can use this information to check that the attention given to recurring failures in the control of safety is sufficiently strong.

Two comments can be made with regard to the investigation of recurring patterns:

1. Only incidents that have been investigated either by the SZW Inspectorate or by the Dutch Safety Board have been analysed. The characteristics of unreported incidents or of those that the Inspectorate does not consider relevant for further incident investigation are therefore not included.
2. The analyses used the incident investigations available to the SZW Inspectorate and, where applicable, the Dutch Safety Board. Relevant aspects that were not investigated or could not be adequately shown are therefore not included. This particularly concerns management delivery systems such as ‘plans and procedures’, ‘competence’, ‘cooperation and communication’, and ‘control of conflict of interest’. Some management delivery system failures are more easily identified than others. Any management delivery system failures that are not evident in the incident investigation are not mentioned in the analyses. As a result, management delivery system failures that are difficult to prove continue to receive insufficient attention.

A1.4 Safety measure failures and successful measures

The barriers (safety measures) are the essence of the bow-tie model. Here, the spotlight is on safety measure failures. Records are also kept of any safety measures that were shown to be successful. In this regard, the following points should be considered:

- A measure is said to have failed if the incident investigation identified deficiencies. This could mean that the measure was entirely lacking or that it was not functioning properly. In some cases, a measure (or safety measure failure) is not mentioned in the incident investigation, while it is clear that the measure could have been used but was lacking. For these cases, the measure is said to have failed as well.
- A measure is considered successful if an incident was prevented by the intentional action of a person or system, or if the incident’s severity was limited. An additional condition is that the action must have gone smoothly. If the creation of a water curtain is delayed due to connection problems, this is not seen as a successful measure but rather as a safety measure failure. Furthermore, ‘success’ only refers to the specific safety function being assessed. If someone who is not wearing personal protective equipment closes a flange immediately, stopping the release is considered to be successful. However, the use of personal protective equipment and, possibly, also seeking safe shelter will be assessed negatively (safety measure failures).

- Some measures only apply to certain incidents. For instance, stopping the release is only relevant in the case of incidents in which substances are released and emergency aid only applies to incidents that involve victims.
- It is not always clear whether the lack of a measure was relevant to the incident. For example, if a release stopped after thirty seconds, did stopping the release fail? In such cases, the general agreement is to take the same line as the investigation report. If the absence of a measure is not included as a shortcoming, that measure has not failed.

Appendix 2 Additional data/statistics

A2.1 Number of incidents

A total of 326 incidents have been analysed. These mainly occurred between 2004 and 2018. A single incident dating from 2003 was analysed in error (see Footnote 2). By the end of 2018, incident investigations for 14 incidents had not yet been completed. These have not been included. See also Subsection 2.2.

A2.2 Nature of the accident

The model distinguishes between the immediate effect of the incident (also known as the 'central event') and the effects that follow this (the 'subsequent effects'). Table A2.1 shows the central events. An incident may involve multiple events, such as fire and explosion, or explosion and release of hazardous substances. The interrelationship is shown in Table A2.2.

A2.2.1 Central event (immediate effect)

Table A2.1. Central event.

Central event	Number of incidents	Number of victims
Release of hazardous substances	292	
from an open containment	292	190
from an opening normally open	13	17
through failing or loose connection	23	4
from an opening that is normally closed	67	33
from a newly created hole (integrity failure) including weld seams	93	83
catastrophic rupture	77	39
unknown	6	1
Immediate fire	32	18
fire in the containment	26	16
fire in the environment of the containment	5	2
Immediate explosion	31	18
physical explosion	3	6
explosive mixture in containment	21	8
dust explosion	6	1
runaway	7	4
solids explosion	31	18
Exposure within a containment	3	5

Table A2.2. Interrelationship of central events.

Initial event	**Number of incidents**	**Number of victims**
Release of hazardous substances	292	190
only hazardous substances released	273	181
also fire	6	0
also explosion	9	9
also fire and explosion	4	0
Immediate fire	32	18
fire only	13	11
hazardous substances also released	6	0
also explosion	9	7
hazardous substances also released and explosion	4	0
Immediate explosion	31	18
explosion only	9	2
hazardous substances also released	9	9
also fire	9	7
hazardous substances also released and fire	4	0
Exposure within a containment	3	5

A2.2.2 *Subsequent effects after the central event*

Table A2.3 shows the subsequent events; that is, the events that occurred or continued after the central event.

Table A2.3. Subsequent effects after the central event.

Subsequent effect after the central event	**Number of incidents**	**Number of victims**
Airborne dispersion	168	142
not controlled or limited	94	110
controlled or limited	69	28
Fire	66	35
pool fire	17	6
jet fire	19	9
flash fire	13	15
fireball	1	0
tank roof fire	1	0
fire within containment	13	3
fire outside containment	10	3
Explosion	7	7
BLEVE	0	0
explosive decompression	1	1
vapour cloud explosion (external)	2	1
delayed explosion vessel or pipe as a result of escalation or domino-effect	4	5
explosion in sewer or drainage system	0	0
explosion in external object	0	0
rapid phase transition outside containment	0	0
No relevant subsequent event	80	27
Unknown subsequent event	13	11

A2.3 Victims and injuries

A2.3.1 Nature and severity of injury

The 326 incidents analysed resulted in 215 victims. The analysis model records the nature of these victims' exposure, the related nature of their injuries and the severity of injury. These were reported in the main part of this report (respectively, Table 3.2, Table 2.3 and Figure 2.4).

Figure A2.1 shows how the type of injury relates to the severity of injury. Relatively speaking, burns often result in permanent injury, while poisonings (or exposure to substances with toxic effects) mainly involve recoverable injuries.

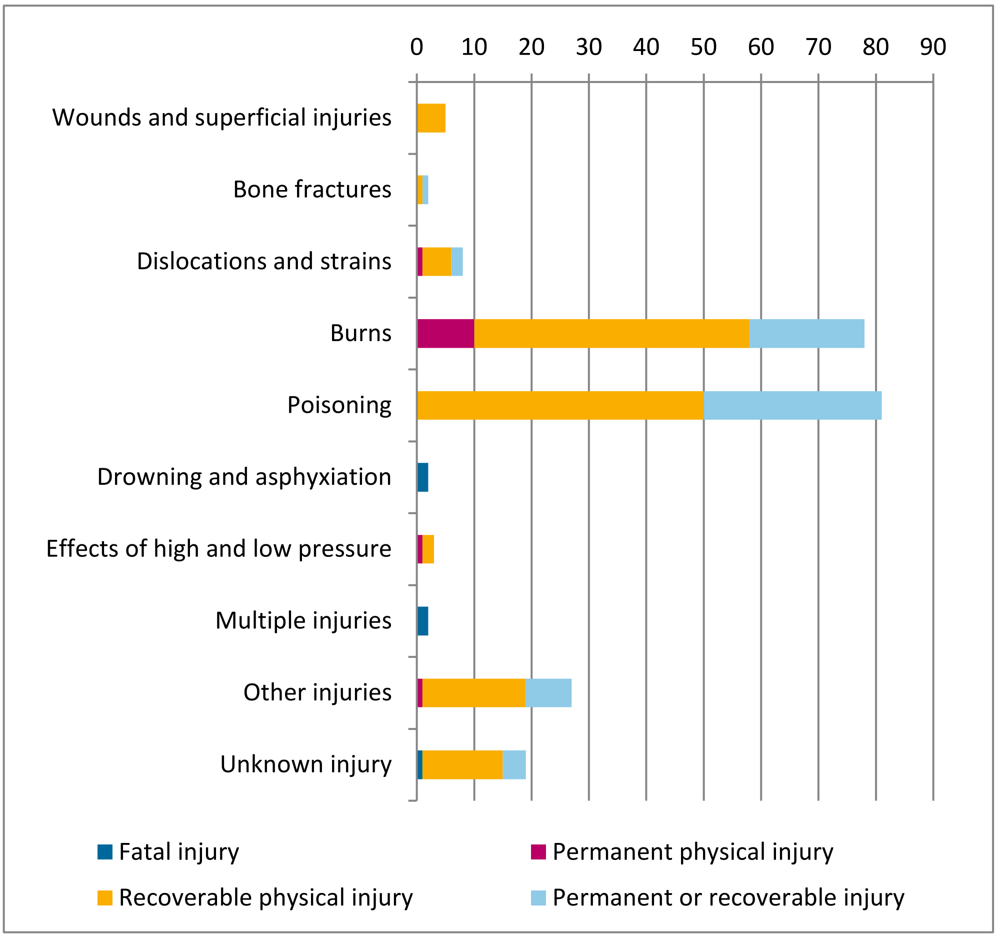

Figure A2.1. Nature and severity of injury (number of victims).

Burns occur both during fires and during the airborne dispersion of hazardous substances, see Figure A2.2. The first case involves thermal burns through contact with flames or heat. The second case concerns chemical burns through contact with acidic or corrosive substances. Even in the case of 'no relevant subsequent effects', victims still suffer burns. [42] This concerns incidents in which a victim is directly affected by the product. Poisonings are mainly linked to airborne dispersion and, to a lesser extent, to 'no relevant subsequent effects'. [42]

[42] If there are 'no relevant subsequent effects', the exposure to hazardous substances took place directly at the source. In the case of other subsequent effects, exposure may result from the immediate effect, the subsequent effect or a combination of both.

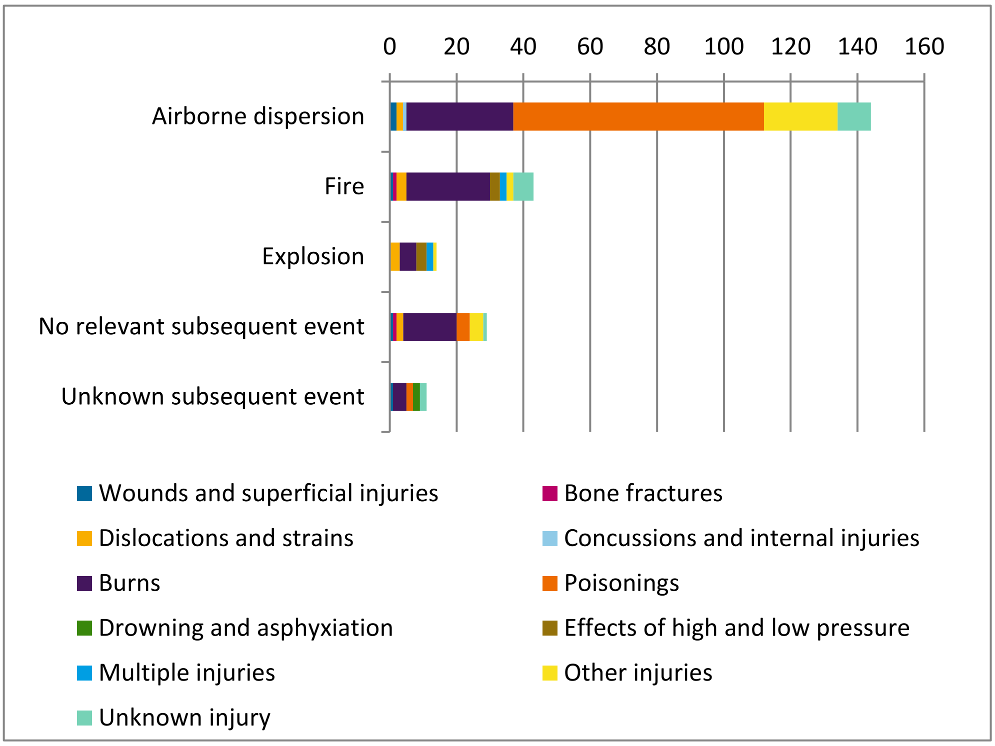

Figure A2.2. Type of injury in combination with type of subsequent effect (number of victims).

A2.3.3 *Other consequences*

Table 2.4 (see Subsection 2.4.3 of the report) shows how many victims were admitted to hospital for treatment. Table A2.4 below illustrates absence from work. For the majority of victims (73%) this is unknown.

Table A2.4. Absence from work.

Absence from work	Number of victims
Maximum of three working days	35
More than three working days	24
Unknown	156

A2.3.4 *Characteristics of the victims*

Figure A2.3, Figure A2.5 and Figure A2.4 show the victims' jobs, types of employment and ages, respectively. In addition, they are classified by their severity of injury.

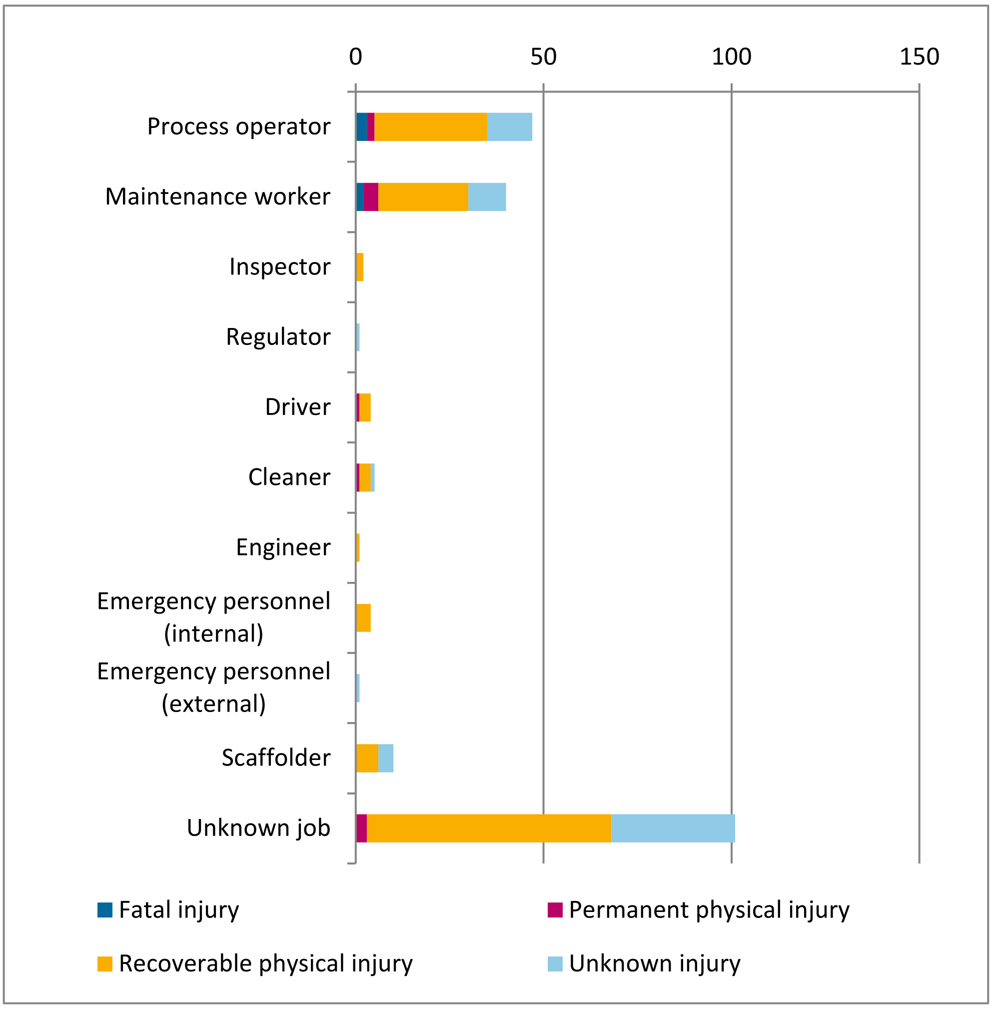

Figure A2.3. Job of the victim (classified by the severity of injury).

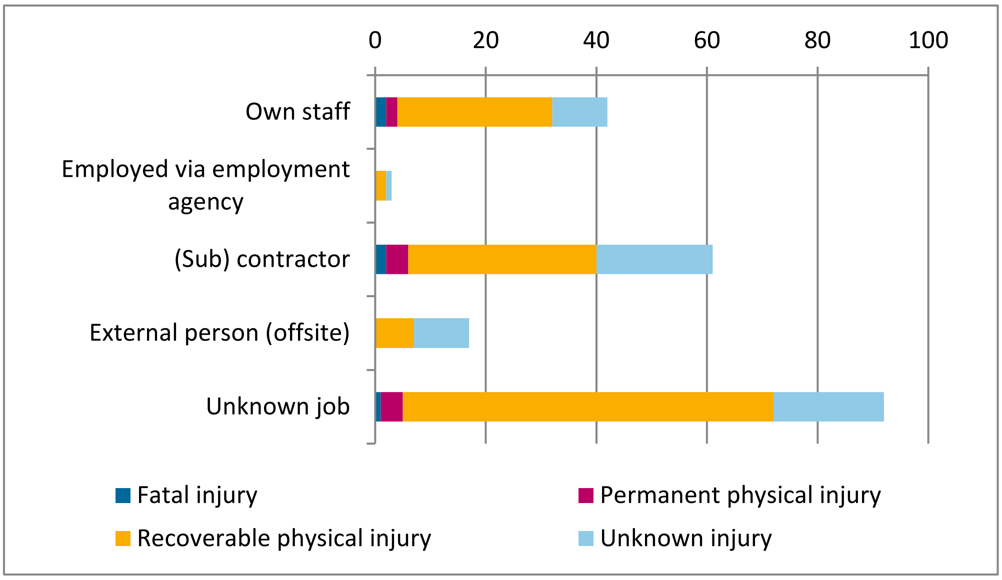

Figure A2.4. Type of employment of the victim (classified by the severity of injury).

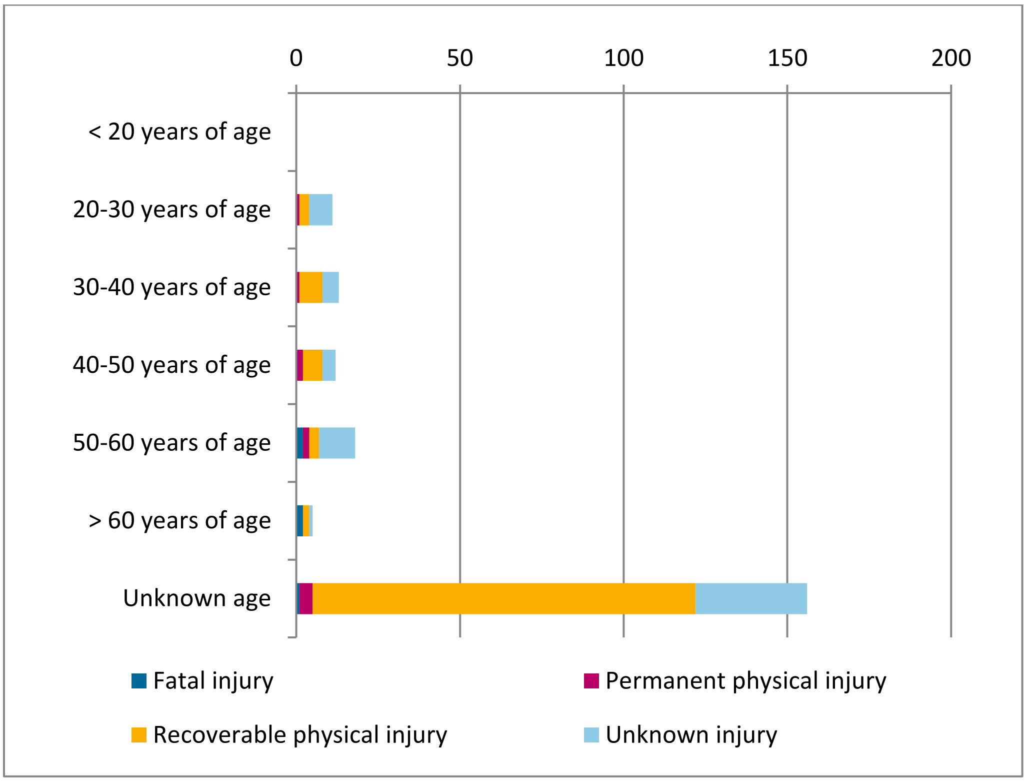

Figure A2.5. Age of victim (classified by the severity of injury).

A2.4 Substances and amounts involved

A2.4.1 Substances and products involved

Table A2.5 shows the substances and products involved. The database contains more than 150 substances and products. For reasons of conciseness, substances that were involved in identical numbers of incidents are grouped into a single cell. For example, benzene and ethylene oxide were both involved in 10 accidents (different accidents).

Table A2.5. Substances and products involved.

Substance name	Number of incidents
Hydrogen	21
Chlorine	14
Ammonia	13
Hydrogen chloride (hydrochloric acid)	11
Benzene, ethylene oxide	10
Hydrogen sulphide, caustic soda (solution)	9
Gasoline, caustic soda (solution)	7
Ethanol, gasoline (Diesel), methane, naphtha, propene (=propylene), steam/hot water, hydrochloric acid HCl	6
Acrylonitrile, ethene, phosphorus, carbon monoxide, nitrogen oxide gases (NOx) , crude oil	5
Butane, condensate, isobutane, methanol, nickel oxide, vinyl chloride, oxygen	4
Acetylene, aniline, biogas, boron trifluoride, coal gas, phenol, isopropyl alcohol, catalyst, kerosene, titanium tetrachloride, toluene, sulfuric acid	3

Substance name	Number of incidents
Acetone, acryl acid, butadiene, cyclohexane, ethylbenzene, ethylenediamine, formaldehyde, formalin, phosphorus oxychloride, phosgene, potassium tert-butoxide, carbon dioxide, methyl ethyl ketone, nickel, propane, propylene oxide, fuel gas, styrene, tert-butyl alcohol, TN120, vinyl acetate, hydrogen fluoride, sulphur dichloride, sulphur dioxide, sulphur trioxide	2
2-Butanol, acetaldehyde, acetyl chloride, alcohols (various), aldehydes (various), allyl methacrylate, amine solution, ammoniacal brine, ammonium nitrate, acetic acid (solution), bromine (dibromine), bromic acid (hydrobromate), butylene, cadmium oxide, captan 83%, cellulose, cellulose nitrate, cetepox, chloroacetaldehyde, chloroacetic acid, chlorine solution, chloropyrifos-methyl, cyclohexanone, cyclopentane, decaline, dichloropropane, dichloropropene, dichlorvos, dimethyl disulphide, divinylbenzene, EC5202A Fuel Antioxidant, epichlorohydrine, ethane, ethylene glycol, ethylidene norbornene, Exxsol D30, phenol-aqueous solution, finicon, furfural, resin, heavy vacuum gas oil, hexane, hydrazine, hydroxylamine sulphate, iron, isobutylene (2-methylpropylene), isopentane, isoprene, cobalt, cracked gas, light and medium cracked spirit, LPG (propane/butane), malto-dextrin, metal alkyls, methional allyl isothiocyanate, methylene diphenyl diisocyanate, methyl propyl ketone, methyl tert-butyl ether, mineral oil, sodium, sodium dichromate, sodium nitrite, nikane, oleum, para-amino-azobenzene, polyethylene, propyl bromide, pygas (pyrolysis gas), rubber, nitric acid (solution), silane, nitrogen, tar (vapours), turpentine, tert-butyl hydroperoxide, thionyl chloride, tri-ethylaluminium, trigonox 101, vinyl ester (resin), fly ash, hydrogen azide, hydrogen bromide, hydrogen cyanide, xylene, starch, zinc oxide, zinc sulphate, sulphur, carbon disulphide	1

In addition to the above substances/products, thirteen cases involved ‘hydrocarbons not further specified’, eight involved a ‘mixture or solution not further specified’, while two concerned ‘unknown’.

A2.4.2 CLP classification

Figure A2.6 shows the number of incidents for the various types of hazardous substance (CLP pictogram), classified by severity of injury.

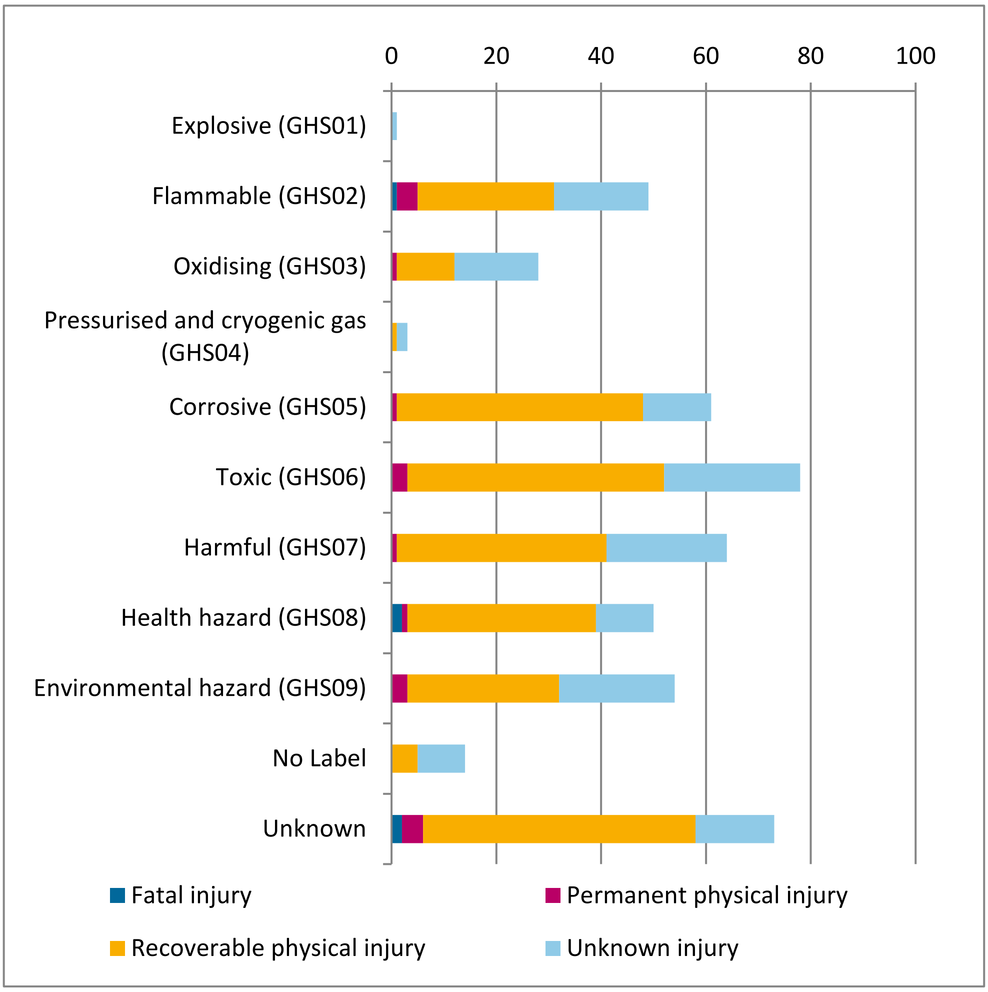

Figure A2.6. Number of incidents per type of hazardous substance, classified by severity of injury.

A2.4.3 Amounts involved

Figure A2.7 shows the amount of hazardous substances involved in relation to the severity of the victims' injuries. This amount is in many cases the released amount, but can also be the combusted amount in cases involving a fire or explosion.

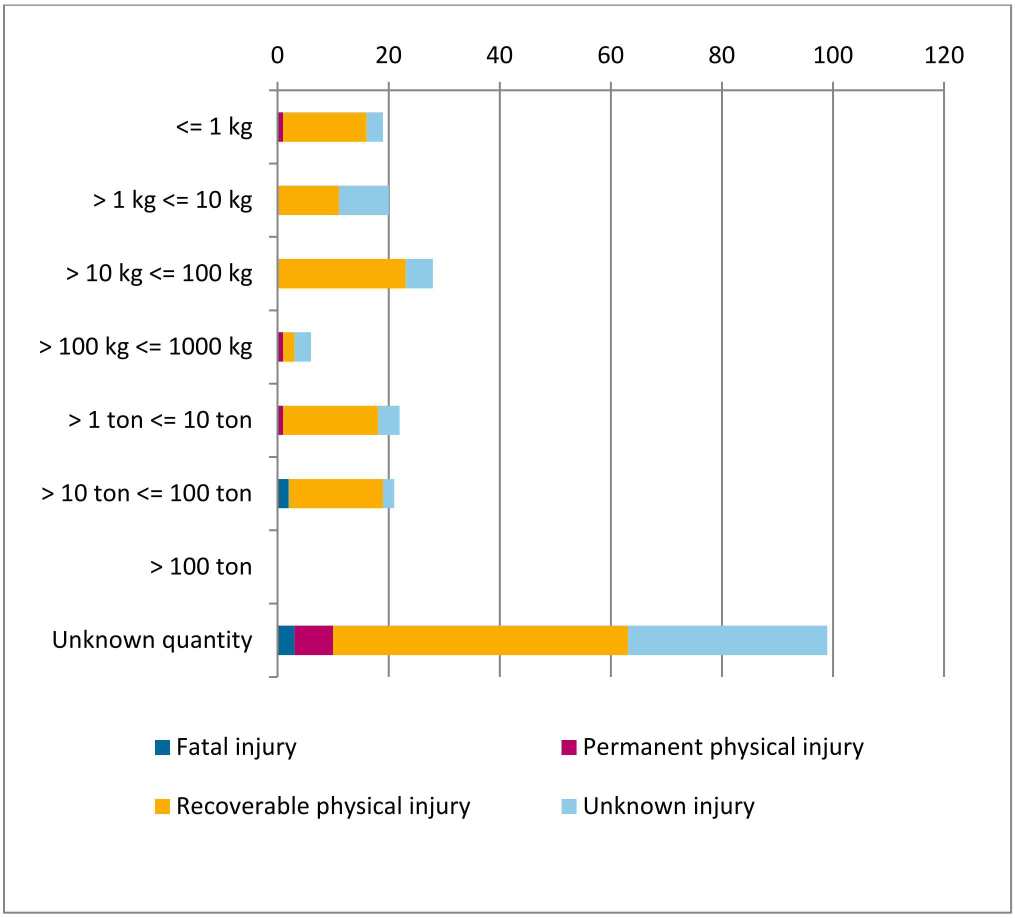

Figure A2.7. Amount involved in relation to the severity of injury (number of victims).

A2.5 Types of company and activities

A2.5.1 Type of company (NACE classification)

Table A2.6 shows the different types of company at which the incidents took place, using the European Classification of Economic Activities (NACE) [15]. The relevant two-digit NACE codes are always stated. For reasons of conciseness, 3- and 4- digit codes are only included in the table if there were three or more incidents.

Table A2.6. Type of company (NACE classification).

NACE code	Description	Number of incidents	Number of victims
06	Extraction of crude petroleum and natural gas	1	3
10	Manufacture of food products	15	25
10.4	Manufacture of vegetable and animal oils and fats	4	16
10.41	Manufacture of oils and fats	4	16
10.6	Manufacture of grain mill products	4	2
10.62	Manufacture of starches and starch products	4	2
10.8	Manufacture of other food products	4	7

NACE code	Description	Number of incidents	Number of victims
16	Manufacture of wood and products of wood and cork, except furniture	1	3
17	Manufacture of paper and paper products	2	0
19	Manufacture of coke and refined petroleum products	46	15
19.2	Manufacture of refined petroleum products	46	15
19.20	Manufacture of refined petroleum products	46	15
20	Manufacture of chemicals and chemical products	177	130
20.1	Manufacture of basic chemicals, fertilisers and nitrogen compounds, plastics and synthetic rubber in primary forms	139	110
20.12	Manufacture of dyes and pigments	21	16
20.13	Manufacture of other inorganic basic chemicals	25	20
20.14	Manufacture of other organic basic chemicals	50	30
20.15	Manufacture of fertilisers and nitrogen compounds	10	5
20.16	Manufacture of plastics in primary forms	26	35
20.5	Manufacture of other chemical products	23	10
20.53	Manufacture of essential oils	5	4
20.59	Manufacture of other chemical products (not elsewhere classified)	18	6
20.6	Manufacture of man-made fibres	8	6
20.60	Manufacture of man-made fibres	8	6
21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	1	0
22	Manufacture of rubber and plastic products	4	2
22.2	Manufacture of plastic products	4	2
22.21	Manufacture of plastic plates, sheets, tubes and profiles	3	2
24	Manufacture of basic metals	11	6
24.1	Manufacture of basic iron and steel and of ferro-alloys	6	3
24.10	Manufacture of basic iron and steel and of ferro-alloys	6	3
24.4	Manufacture of basic precious and other non-ferrous metals	4	2
25	Manufacture of fabricated metal products, except machinery and equipment	1	0
26	Manufacture of computer, electronic and optical products	1	1
33	Repair and installation of machinery and equipment	1	0

NACE code	Description	Number of incidents	Number of victims
35	Electricity, gas, steam and air conditioning supply	2	0
38	Waste collection, treatment and disposal activities; materials recovery	5	5
46	Wholesale trade, except of motor vehicles and motorcycles	19	4
46.1	Wholesale on a fee or contract basis	5	0
46.12	Agents involved in the sale of fuels, ores, metals and industrial chemicals	3	0
46.7	Other specialised wholesale	14	4
46.71	Wholesale of solid, liquid and gaseous fuels and related products	4	0
46.75	Wholesale of chemical products	10	4
49	Land transport and transport via pipelines	2	0
52	Warehousing and support activities for transportation	35	20
52.1	Warehousing and storage	30	19
52.10	Warehousing and storage	30	19
52.2	Support activities for transportation	4	1
52.24	Cargo handling	4	1
81	Services to buildings and landscape activities	2	1

A2.5.2 *Type of company (MARS classification)*

Table A2.7 shows the type of company, using to the MARS classification [20].

Table A2.7. Type of company (MARS classification).

Code	Description	Number of incidents	Number of victims
2000	Unknown	18	14
2001	General chemicals manufacture	111	83
2002	Petrochemical, refining and processing	81	36
2003	Plastics and rubber manufacture	12	1
2004	Pesticides, pharmaceutical	10	11
2005	Power supply and distribution	1	0
2007	Waste treatment and disposal	8	6
2008	Wholesale and retail storage and distribution	34	12
2009	Handling and transportation centres	12	21
2011	Metal refining and processing	15	7
2012	Electronics and electrical engineering	1	1
2014	General engineering, manufacturing and assembly	1	0
2019	Food and drink	10	6
2020	Timber and furniture	1	3
2999	Other	10	14

A2.5.3 *Activity prior to the incident*

Table A2.8 shows which activity took place prior to the incident. A few incidents involved more than one activity – for example, the active opening of a containment and simultaneously conducting activities on/near the containment.

Table A2.8. Activity prior to the incident.

Activity prior to the incident	Number of incidents	Number of victims
Adding/removing a substance	121	83
add/fill	91	22
remove/empty	21	58
unknown	9	3
Activity nearby	17	8
manoeuvring a vehicle	1	0
maintenance activity nearby	10	6
process disturbance/breakdown nearby	1	0
digging	1	0
lifting activity	1	0
moving or falling against	2	2
Activities on/near containment	52	54
closing/reclosing	4	0
maintenance, inspection and cleaning	20	25
hot work	8	6
applying or removing insulation	1	0
heating	7	9
cooling containment	5	1
deblocking	5	6
stopping a leak	4	8
Actively opening a containment	53	55
disconnecting (part of) containment(s)	19	15
manually opening the containment	27	34
opening for cleaning	2	0
entering containment	3	5
opening by signal	1	0
Other activities	4	0
Moving and transporting containers and packages	4	0
No relevant activity	88	26
spontaneous degradation of material or connection	54	9
spontaneous process deviation	16	10
exceptional weather conditions (e.g. freezing)	4	0
Unknown activity	1	3

Table A2.9 shows the 'method of task or process automation'. This concerns how tasks and processes are implemented and controlled. In the case of 'manual', the steps and actions relevant to the incident are performed manually. 'Automated' means that the relevant processes were controlled using a fully automatic control system. 'Semi-automated' signifies an interaction between an automatic control system and human actions.

Table A2.9. Method of task or process automation.

Method of task or process automation	Number of incidents	Number of victims
Manual	123	100
Semi-automated	87	40
Automated	88	53
Unknown	28	22

A2.6 Items of equipment, release locations and hole sizes

A2.6.1 Item of equipment in the installation related to the incident (immediate effect)

Two categories of items of equipment are used in the analysis model: 'items of equipment involved' and 'item of equipment related to the central event'. For the first category, all items of equipment in installations that were relevant to the occurrence of the incident are registered. The second category is more specific. This concerns the item of equipment in the installation from which the product was released (in the case of 'release of hazardous substances'), in which a fire or explosion occurred (for immediate fire or explosion), or which was entered by a person (or persons).

Table A2.10 shows the item of equipment in which the incident's central event took place. Most incidents occurred in – or from – items of equipment in process installations (160x). In more detailed terms, these involved process piping (58x), reactor vessels (35x), and various types of separators (31x). In addition, 36 of these incidents occurred in fixed storage tanks, 25 in piping at unloading sites, and 21 in long transport/unloading pipelines.

Table A2.10. Item of equipment related to the incident (immediate effect).

Item of equipment	Number of incidents	Number of victims
Fixed storage tank	36	31
Mobile tank or packaging	23	19
tank container	2	1
intermediate bulk container (IBC)	5	2
drum	5	10
gas cylinder	3	0
cylinder pack	1	1
spray can	1	1
bin/bucket	4	2
bag	2	2
Item of equipment in a process installation	160	115
buffer vessel	3	1
reactor vessel	35	17
separators	31	27
ab-/adsorber	3	1
centrifuge	1	2
cyclone	1	0
filter/sieve	11	4
scrubber (gas washer)	6	16
vapour-liquid (knock-out vessel)	3	0

Item of equipment	**Number of incidents**	**Number of victims**
stripper	1	1
liquid-liquid separator	2	0
unknown type of separator	3	2
evaporator (incl. reboiler)	4	0
condenser	1	1
mixer	1	1
process piping	58	47
pump (in process installation)	6	7
compressor (in process installation)	1	0
heat exchanger	10	10
distillation column	5	0
equipment for filling packages	3	8
other	3	1
unknown	4	5
Item of equipment related to loading	57	
pipeline (long pipeline)	21	3
piping (short pipes)	25	20
vapour return line	1	0
flexible hose or pipe	3	0
loading/unloading hose	1	3
loading/unloading arm	2	2
pump	3	1
compressor	1	0
Vehicles, trains and ships/barges	17	19
tank car	7	4
rail car	5	2
ship/barge	4	6
vacuum truck	1	7
Other	39	15
inert gas system	2	4
(cooling) water system	5	1
off-gas system	1	0
oven/furnace	8	5
incinerator	4	1
turbine	1	0
wastewater system (incl. sewerage)	4	3
(emergency) venting system	3	0
flare system	3	0
chimney	2	0
pig catcher/launcher	2	0
storage room/building	2	0
other	2	2
Unknown	6	2

A2.6.2 Location of release

Table A2.11 shows the items of equipment from which the release occurred. In 84 incidents, the release occurred from a hole in the wall of a tank or pipe. Releases also mainly involve failing or missing connections (39x), open valves (23x), pressure relief valves (22x), couplings (19x), taps for liquids (15x), open pipe ends (14x) and vents (11x).

Table A2.11. Location of release.

Location of release	Number of incidents	Number of victims
Open tank/vessel	13	17
Shell/body	112	77
wall	84	66
floating roof	3	0
ordinary weld	1	0
weak weld	4	0
rupture disc	3	6
explosion vent	3	3
manhole opening	4	5
lid/hatch	8	3
Provisions in/on equipment and connections	141	98
sampling point	2	1
opening for instrumentation	4	1
opening for mechanical part(s)	3	1
pressure relief valve/device (incl. water seal)	22	13
drain	15	15
closing or isolation valve	23	14
blind flange/plate	5	6
vacuum breaker valve	1	0
other type of valve	1	15
connection (incl. flange)	39	21
coupling	19	12
other	5	1
unknown	1	0
Openings and designated release points	44	15
ventilation hole	6	1
vent	11	0
flare	6	0
chimney	6	1
open pipe end	14	13
other	5	7
Unknown	8	4
Not applicable	15	12

A2.6.3 Hole size

Table A2.12 shows the absolute hole size, while Table A2.13 shows the relative hole size. In the overwhelming majority of incidents, the hole size was unknown. This means that, while the hole size was smaller than the full diameter of the pipe, valve or connection, its exact size was unknown.

Table A2.12. Absolute hole size.

Absolute hole size	Number of incidents	Number of Victims
0 <= 5 mm	11	12
5 mm <= 1 inch	13	6
1 <= 4 inch	5	5
4 <= 10 inches	2	1
> 10 inches	5	0

Absolute hole size	Number of incidents	Number of Victims
Catastrophic rupture vessel/containment	18	14
Unknown	256	165
Not applicable	16	12

Table A2.13. Relative hole size.

Relative hole size	Number of incidents	Number of victims
<= 1/3 of diameter	6	2
> 1/3 of diameter	6	1
Full diameter	68	61
Catastrophic rupture vessel/containment	18	14
Unknown	212	125
Not applicable	16	12

A2.7 Violations of the Dutch legislation and regulations, and enforcement

Exactly half of the incidents were found to involve violations of legislation and regulations. Table A2.14 shows the classification of the identified violations.

Table A2.14. Violations of Dutch legislation and regulations.

Violation of Dutch legislation and regulations	Number of incidents	Number of victims
Working Conditions Act	65	85
Art. 5	5	10
Art. 6	53	71
Art. 16	7	10
Working Conditions Decree	23	17
Art. 3.5	8	2
Art. 4.6	10	10
Major Accident Hazards Decree (Brzo)	98	94
Art. 5 (1)	94	92
Art. 5 (3)	69	48
Environmental Management Act	30	5
Art. 17.2	20	1
Unknown	27	21
No violation (found)	163	76

Most violations relate to the Dutch Major Accident Hazards Decree (Brzo), including the Major Accident Hazards Regulation (Rrzo) and the Dutch Working Conditions Act, including the Working Conditions Decree. The Major Accident Hazards Decree (Brzo) is the Dutch implementation of the EU Seveso III Directive.

The most frequent violations concerned the following articles:

- Article 5 (1) of the Major Accident Hazards Decree (Brzo) (94x).
- Article 5 (3) of the Major Accident Hazards Decree (Brzo) (69x).
- Article 6 of the Working Conditions Act (53x).

Under article 5 (1) of the 2015 Major Accident Hazards Decree (Brzo) (formerly 1999) and Article 6 of the Working Conditions Act, companies are required to take measures to prevent major accidents and to limit the consequences for employees (Working Conditions Act) and people and the environment (Brzo). Towards this end, under Article 5 (3) of the 2015 Major Accident Hazards Decree Brzo (formerly 1999), Brzo establishments (i.e. Seveso establishments) are required to implement a safety management system that complies with the requirements defined in an appendix of the Brzo.

Table A2.15 specifies the enforcement instruments that were used for the 326 incidents. In 132 incidents (40%), one or more of the following enforcement instruments were used. A legal requirement to comply was imposed for 40 incidents. A criminal investigation was initiated for 37 incidents.

Table A2.15. Enforcement.

Enforcement instrument	Number of incidents	Number of victims
criminal investigation/trial	37	36
legal requirement to shut	16	9
legal requirement to comply	40	26
legal warning	5	1
cease and desist	5	1
administrative fine	8	10
promotion letter	1	0
unknown legal sanction	20	11
no legal action or warning	158	82

A2.7.1 Violations identified during the Brzo inspection prior to the incident

The SZW Inspectorate carries out periodic inspections together with other Brzo regulators. These include inspections of the safety management system (SMS). In the Storybuilder analyses, a check was made to determine which violations were found in the last inspection carried out before the incident. An additional condition was that this inspection must have been carried out no more than two years prior to the incident. Figure A2.8 shows the results.[43]

[43] Two-thirds of the 'unknown' results of prior inspections relate to the period running from 2003 to 2007. Since 2007, the availability of information about prior inspections has improved and the term 'unknown' is rarely used.

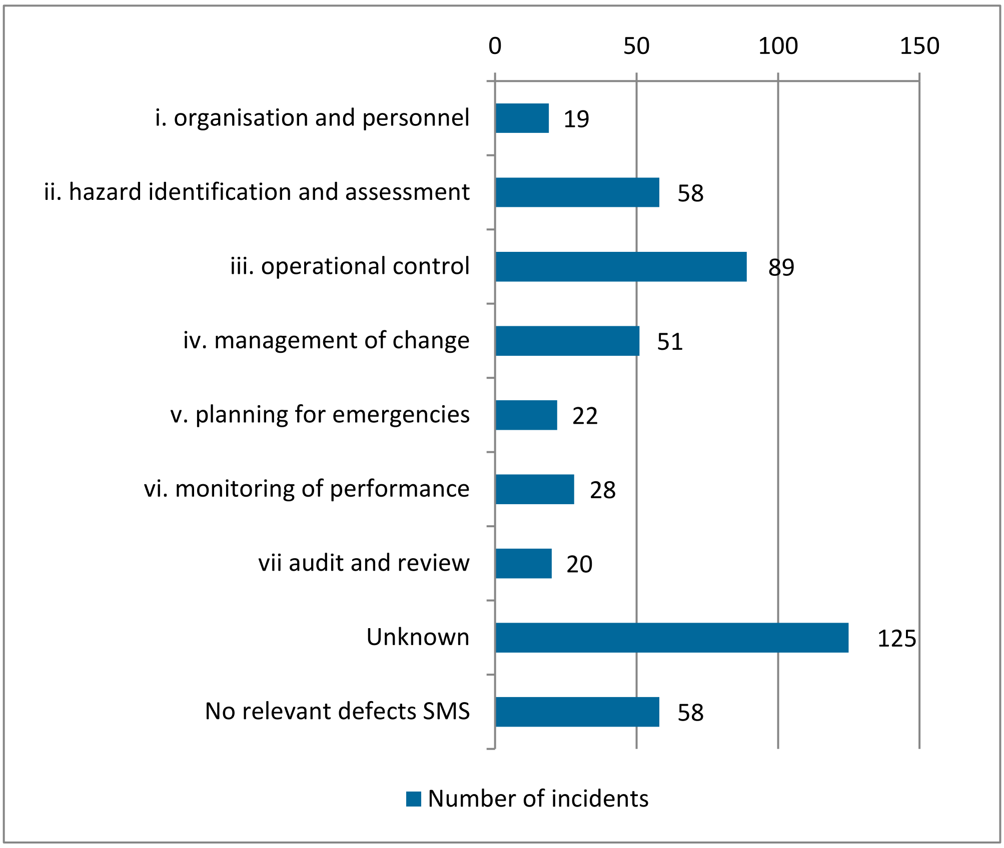

Figure A2.8. Safety Management System violations found during the last EU Seveso III Directive prior inspection.

Appendix 3 Direct and underlying causes

A3.1 Underlying factors: overall averages

Safety measure failures were examined to determine how and why they occurred and which elements of the SMS failed. Figure A3.1, Figure A3.2 and Figure A3.3 show the overall failure percentages of the underlying factors. These were calculated in two different ways:

- The upper bars (in blue) indicate the average percentage per safety measure failure. For instance, the database contains 1,223 safety measure failures for 326 incidents. Of these 1,223 safety measure failures, 33% failed because the measure had not been provided (see Figure A3.1). Similarly, deficiencies in plans and procedures accounted for 26% of safety measure failures (see Figure A3.2).
- The lower bars (in grey) indicate the average percentage per incident. In 69% of incidents, at least one safety measure failed because it had not been provided. Similarly, 57% of the incidents had at least one deficiency in the area of plans and procedures.

The second calculation method leads to higher contributions, as multiple safety measures (at least two) fail in any given incident. On average, 3.75 safety measures failed per incident. Which of these two calculation methods is more useful is a question of context.

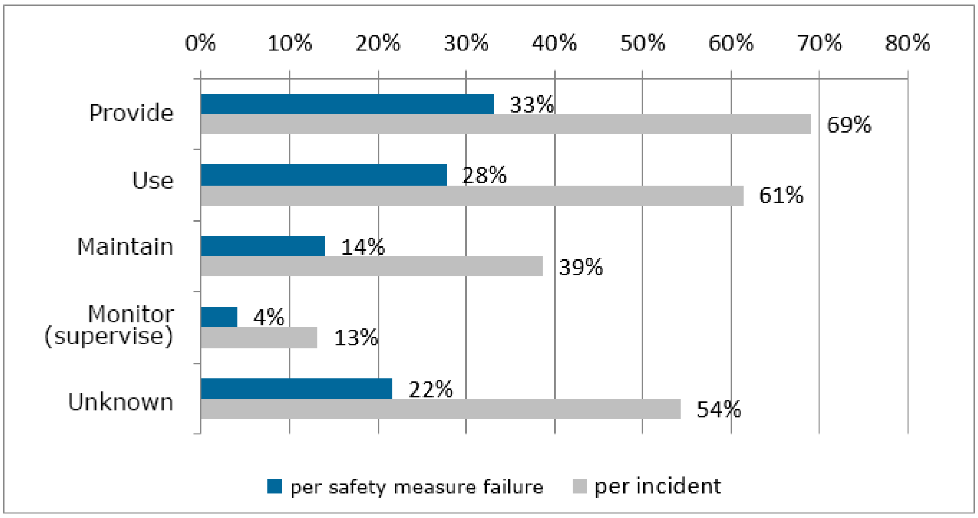

Figure A3.1. How did safety measures fail?

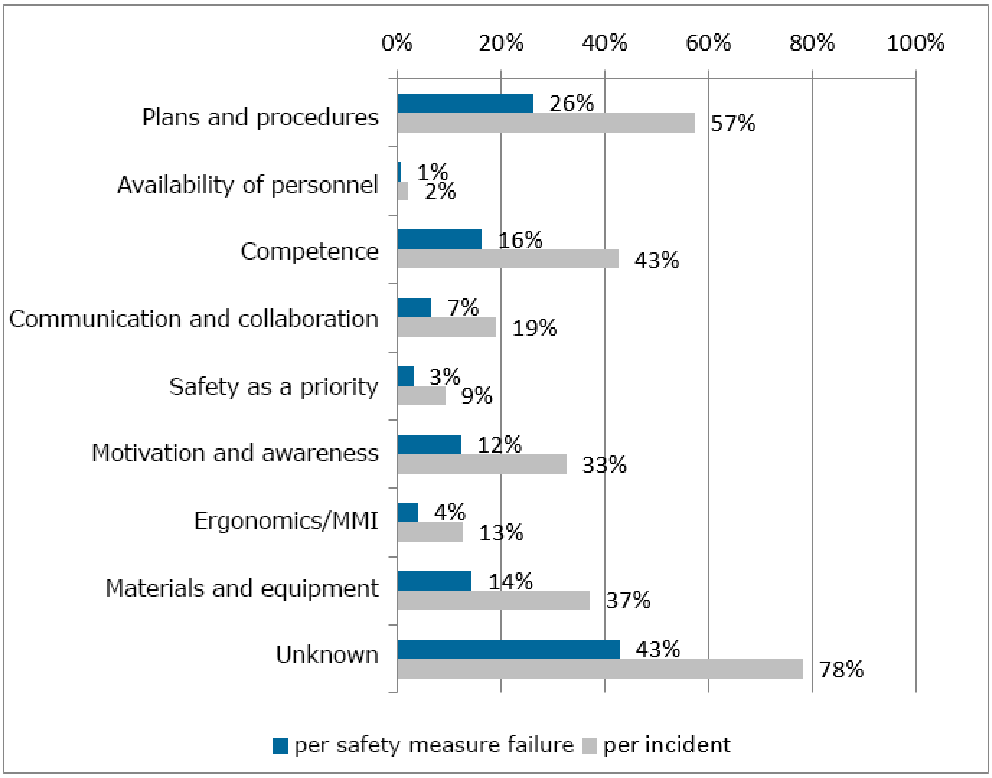

Figure A3.2. Why did safety measures fail?

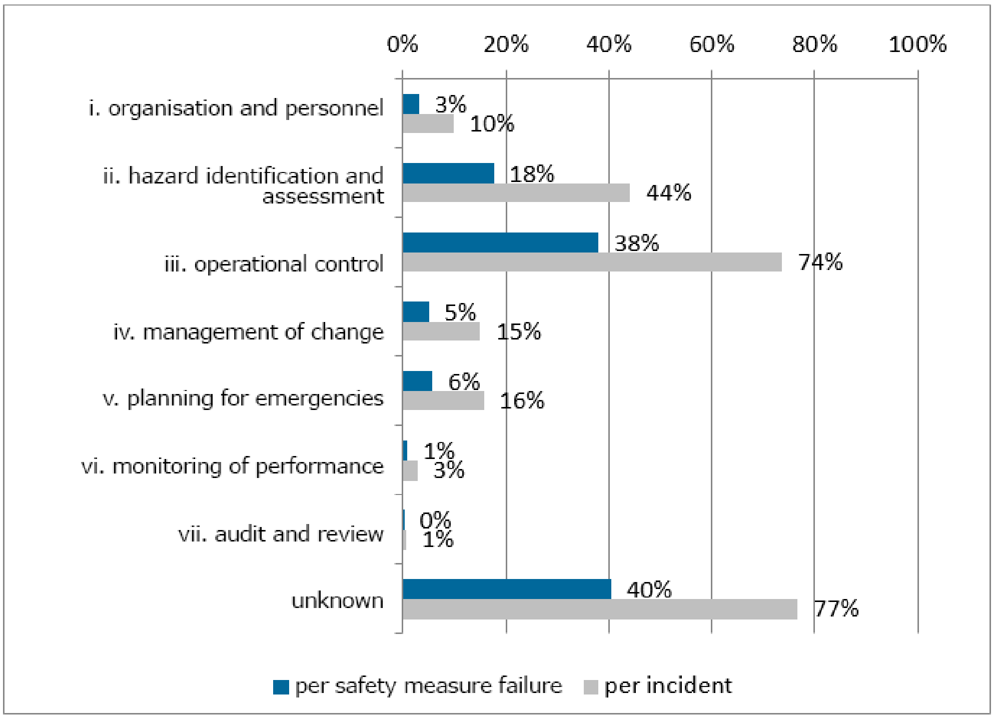

Figure A3.3. Which deficiencies in the SMS were relevant?

A3.2 1st LoD: operational control

Table A3.1 shows which safety measures the analysis model contains and how they are grouped together.

Table A3.1. Classification of safety measures in the 1st line of defence.

Measure group	Specific measures
Control of start	• Equipment selection • Pre-start-up safeguarding failure
Control of equipment condition	• Control of process conditions with regard to ageing • Equipment material • Equipment (parts) design • Equipment connection • Installation of equipment
Process parameters control	• Control of movement/position of containment • Process temperature control • Control of reaction • Pressure control • Flow control • Separation of incompatible substances
Control of surroundings/environment	• Control site environment • Control of common mode failures • Prevention of external impact • Storage/transportation conditions • Separation from heat sources
Unknown	• Unknown

A3.2.1 Safety measure failures

Figure A3.4 shows how often the various operational control safety measures failed. For details on how these measures are grouped together, see Table A3.1.

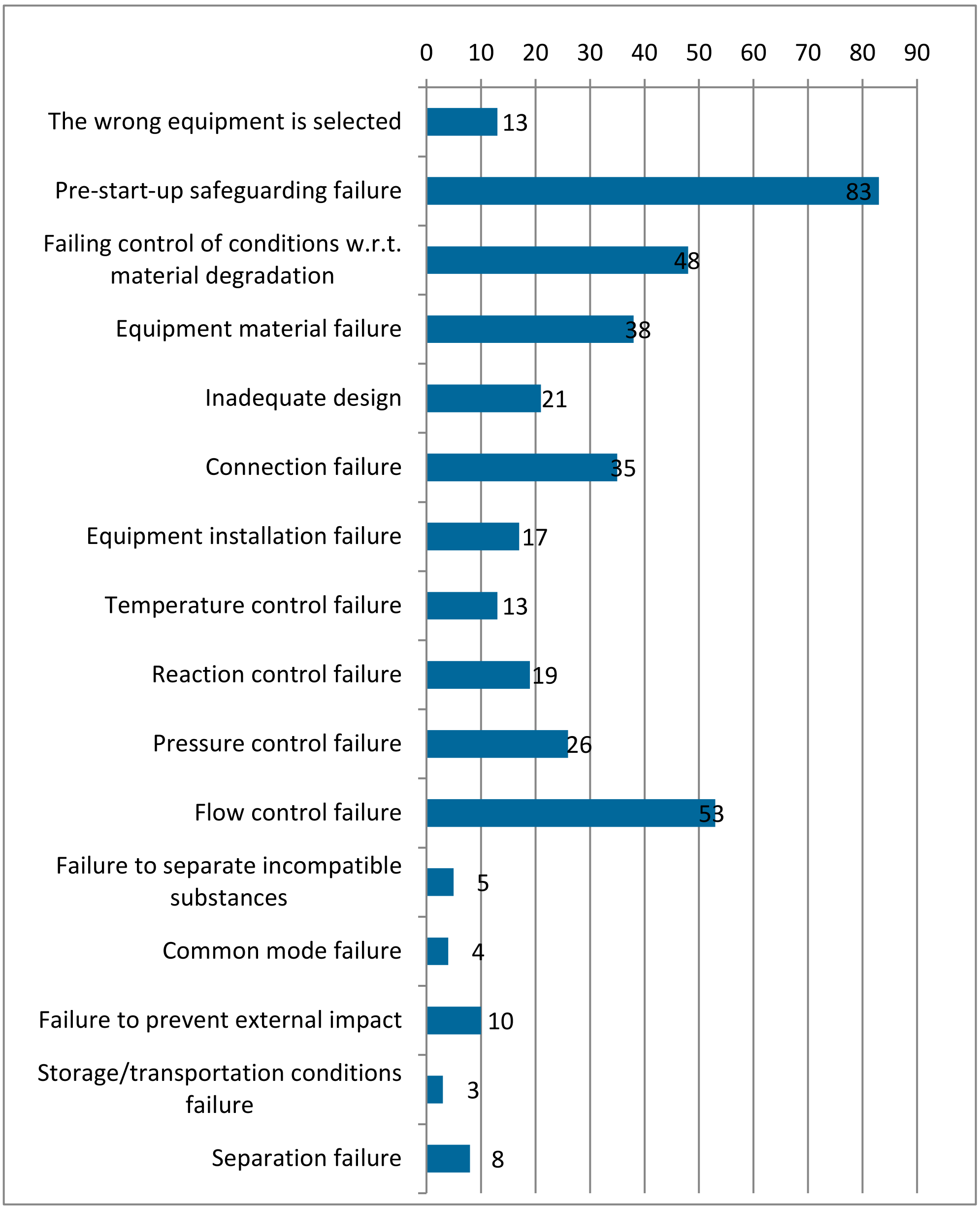

Figure A3.4. Safety measures in the 1st LoD – number of times the safety measure failed.

A3.2.2 *How did safety measures for safe operational control fail?*

Figure A3.5 shows how safety measures for safe operational control failed.

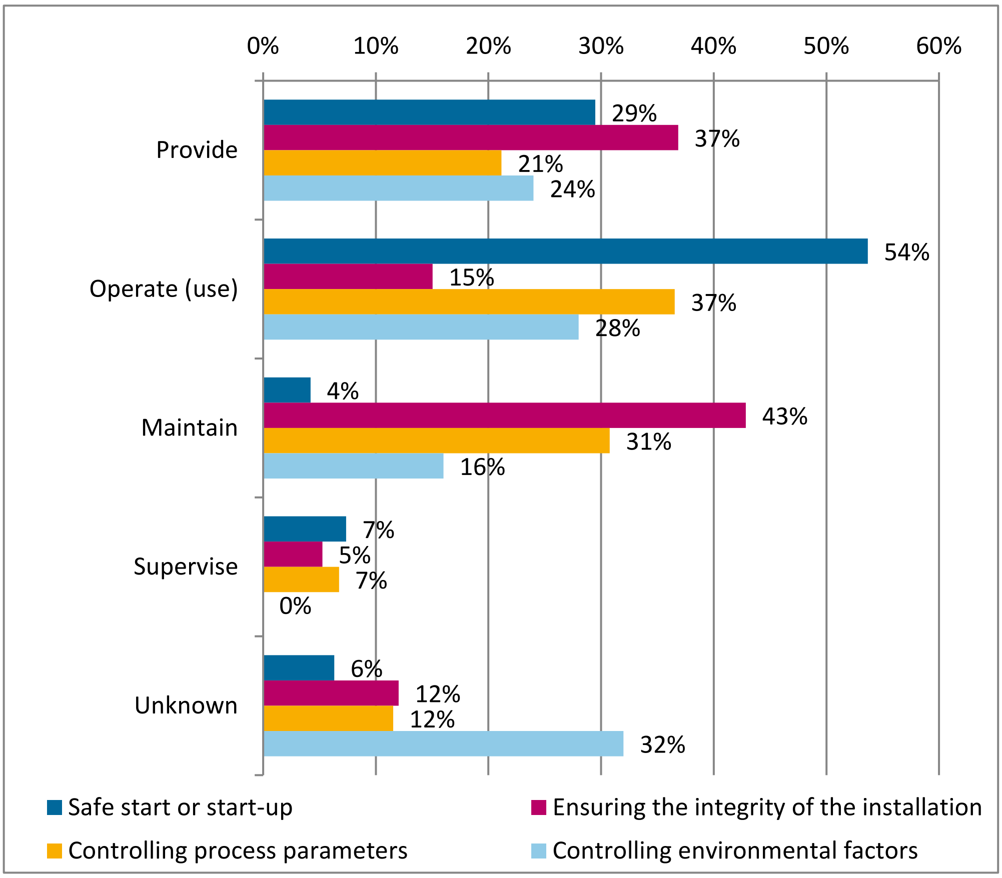

Figure A3.5. How did operational control fail – percentage of cases in which elements are relevant within the 1st LoD (operational control).

Safe start or start-up
In 29% of the incidents, the organisation had failed to implement the proper means (procedures and instruments) to enable a safe start-up. In 54% of the incidents, the resources provided were suitable, but they had been used/applied incorrectly or not at all.

Ensuring the integrity of the installation
In 37% of the incidents, the organisation had failed to implement adequate measures to ensure the integrity of the installation. This could mean that no measures had been provided at all or that they were inadequate (for example, an excessively low maintenance frequency). In 43% of the incidents, measures had been provided to ensure the integrity of the installation, but these measures had become ineffective over time. Accordingly, this concerned changes, for example, in the installation or the process, or changes in the maintenance itself.

Controlling process parameters
Control of the process parameters failed for a variety of reasons. In 21% of the incidents, no adequate safety measures had been implemented. This means that there were no suitable instruments or procedures to

keep the various process parameters within the operating windows. In 37% of the incidents, instruments or procedures had been provided, but had either been used incorrectly or not at all. In 31% of the incidents, measures for controlling process parameters were no longer effective, due to changes in the installation, process or instrumentation.

Controlling environmental factors
Control of environmental factors failed because adequate safety measures had not been provided (24%) or because these measures were not used correctly (28%). In one in every three instances, the reason why the safety measures failed to work properly was unknown.

A3.2.3 *Why did safety measures for safe operational control fail?*

Figure A3.6 shows why safety measures for safe operational control failed. For reference purposes, an indication is given of why safety measures in the other lines of defence failed.

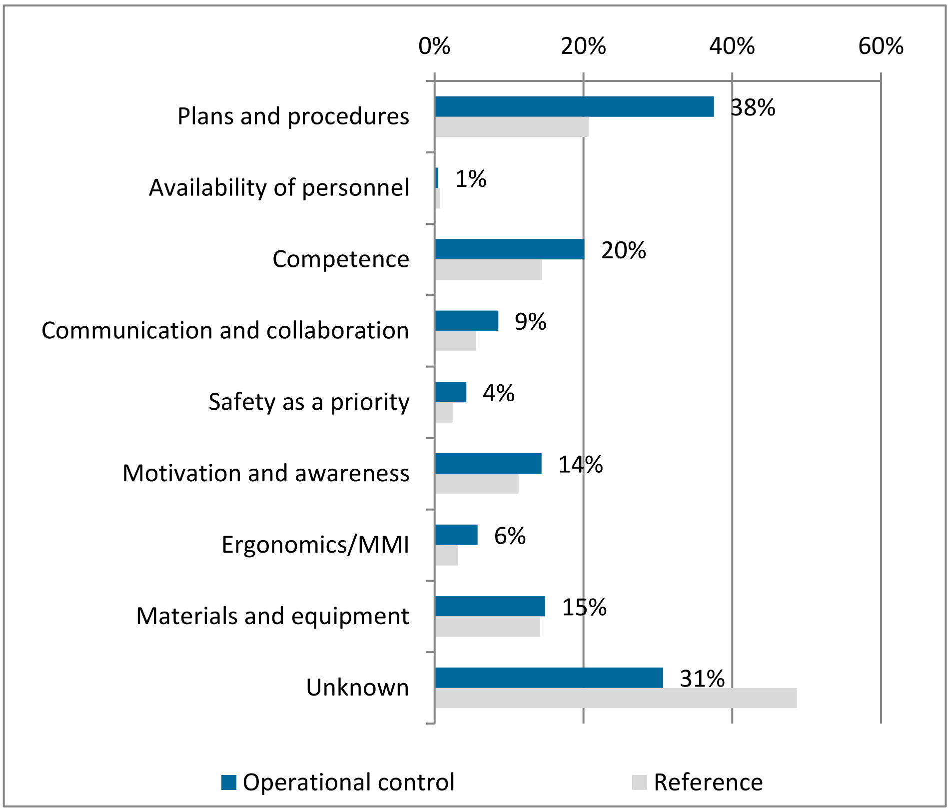

Figure A3.6. Why did operational control fail – percentage of cases in which elements are relevant within the 1st LoD (operational control).

The most frequent reason was the lack of suitable plans and procedures. This factor was involved in 38% of safety measure failures. It shows that the safety of establishments is highly dependent on the existence of suitable procedures, plus proper compliance. The relevance of suitable work plans and procedures is obvious in areas such as starting or starting-up processes, installing and assembling parts, maintaining installations and for processes that involve manual steps or checks.

Deficiencies with regard to staff experience and expertise (competence) were involved in 20% of safety measure failures. A lack of motivation and awareness accounted for 14% of safety measure failures. This means that people were working with insufficient care or concentration, or that safety awareness was lacking.

Figure A3.7 shows which SMS deficiencies were involved in the failure of operational control. For reference purposes, an indication is given of the deficiencies in the other lines of defence.

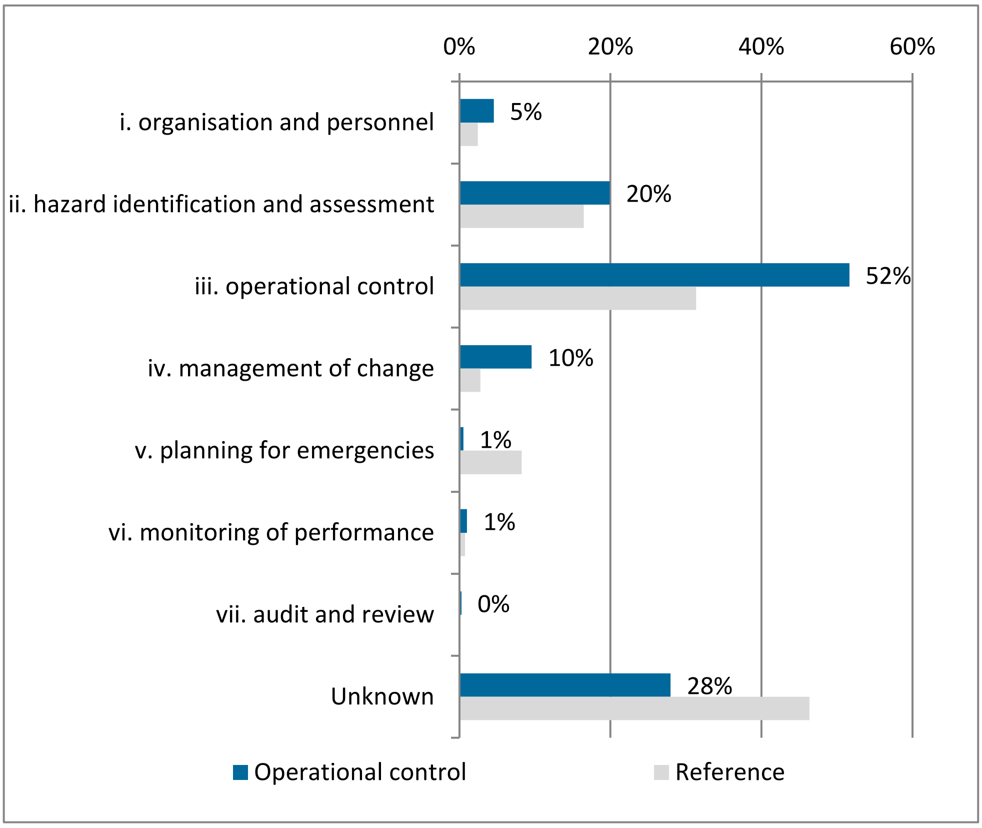

Figure A3.7. Which deficiencies in the SMS were relevant – percentages in which elements are relevant within the 1st LoD (operational control).

The figure shows that 20% of the safety measure failures involved deficiencies with regard to the identification and evaluation of hazards (element ii). Fifty-two percent of safety measure failures involved a failure of element iii – operational control. The risks and hazards involved in these incidents were clear, but the organisation had failed to adequately translate that knowledge into effective safety control measures. These deficiencies related both to normal operations (81x) and to the maintenance of installations (91x). Ten percent of safety measure failures involved defects in element iv of the SMS (management of change). In one-third of the incidents, it was not possible to reliably identify which element of the SMS had failed.

A3.2.4 Consequences

Table A3.2 specifies the consequences of the failure of operational control.

Table A3.2. Consequences of the failure of operational control.

Consequences of the failure of operational control	Number of incidents
unsafe starting or starting-up	95
containment not safeguarded/product free	45
undesired valve positions /openings	43
wrong containment selected	12
material deviation outside operational limits	125
corrosion	47
erosion	4
material fracturing/weakening/fatigue	35
loose connection (or not leakproof)	42
process deviation outside operational limits	110
temperature deviation	30
low temperature	3
high temperature	27
pressure deviation	39
high pressure	36
low pressure	2
flow deviation	41
other flow/substance	21
low flow	3
high flow	6
no flow	8
unintended flow	4
level deviation	11
low level	0
high level	10
saturation deviation	5
environmental deviation outside operational limits	16
object or person moving towards containment	8
equipment unstable	1
external load outside operational envelope	2
heat source near installation	5
unknown deviation outside operating window	12

A3.3 2nd LoD: recovery of deviations outside operating window

A3.3.1 Safety measure failures

In approximately half of all incidents (48%), the indication of the deviation failed, see Figure 3.5 in Section 3.3.1. In other words, there were no resources for calling attention to the deviations or the available resources were not sufficient. In the other incidents, detection of the deviation failed (16%), the correct diagnosis failed (11%), the correct remedial action failed (13%) or the cause of the failure was unknown (12%).

Figure A3.8 shows the relationship between the type of deviation that occurred and how the recovery failed. There are only minor differences between the five types of deviation in Figure A3.8. In the case of material deviations, indication fails slightly more often than remedial action, while the opposite is true of process deviations.

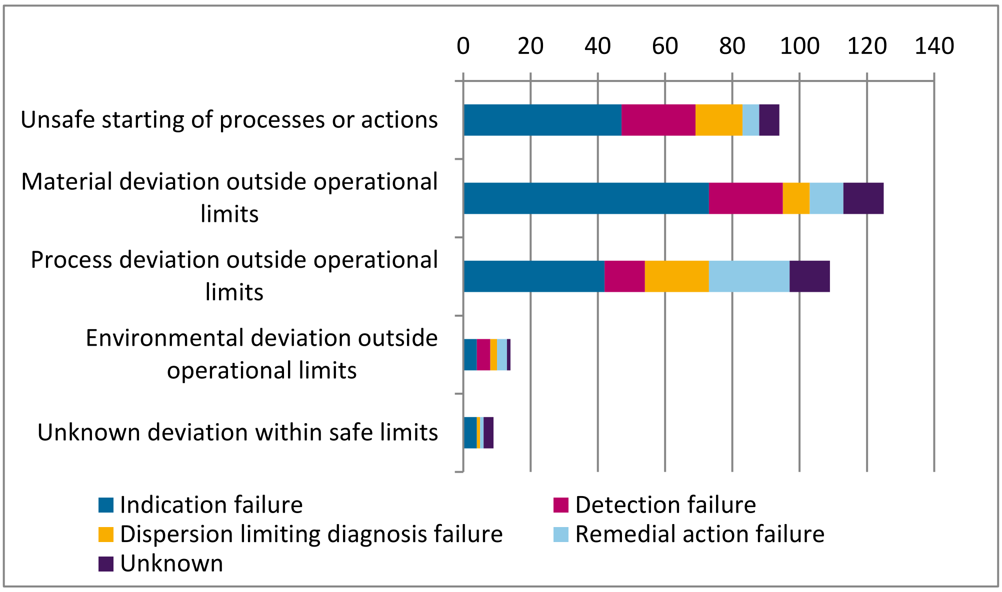

Figure A3.8. Ways in which recoveries failed.

A3.3.2 *How did safety measures for recovery fail?*

Figure A3.9 shows how safety measures for recovering deviations outside operating limits failed.

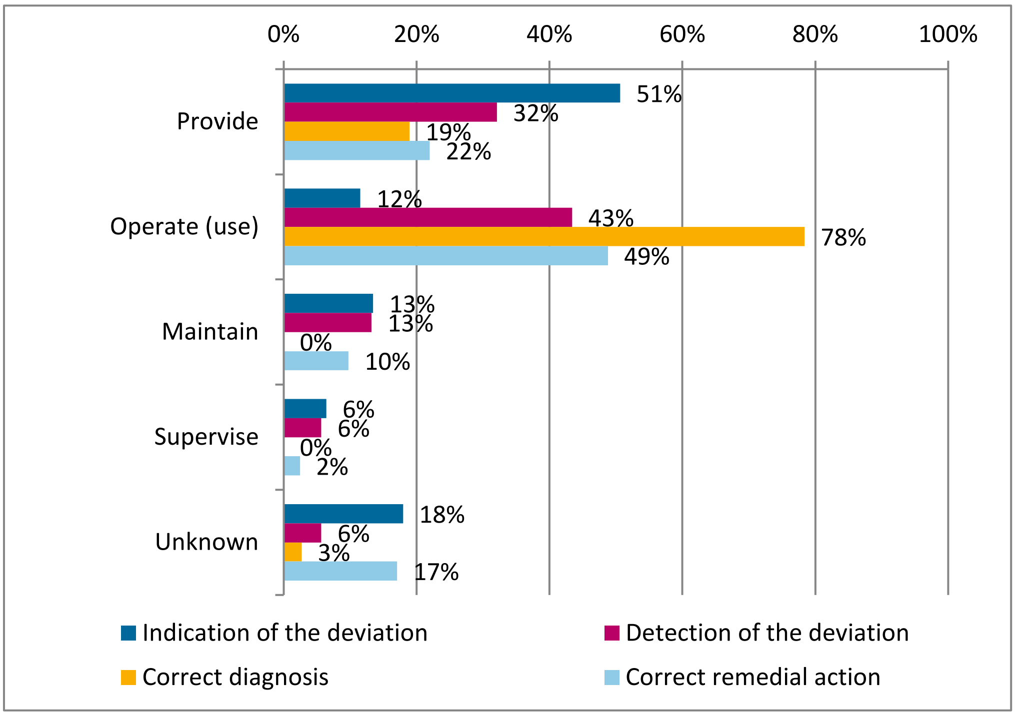

Figure A3.9. How did recovery fail – percentage of cases in which elements are relevant within the 2nd LoD.

Indication of the deviation
In 156 incidents, an indication of the deviation outside operating limits was lacking (see Figure 3.5 in Section 3.3.1). In approximately half of them (51%), this was because the organisation had not implemented suitable instruments and procedures for identifying deviations. This could mean that absolutely no measures had been taken to identify any deviations or that the measures taken were inadequate. In many cases, the organisation had apparently trusted the measures that were taken to ensure that the operational processes were safe, causing those involved to feel that no additional checks were needed.

- For instance, there was no inspection programme for indicating the integrity of the installation, the intervals between inspections were too long or the means of inspection (method/implementation) were unsuitable – in terms of properly identifying any deviations.
- With regard to process parameters, this means that they were insufficiently monitored – the relevant process or item of equipment in the installation lacked an alarm system for situations in which process parameters such as pressure, level or temperature exceeded the operating windows.
- With regard to safe starting or starting-up, this means that no built-in controls were available to verify – in advance of the action – whether this could indeed be started safely.

In the other incidents (49%), resources had been provided but were not used, not appropriately applied or no longer functioned properly due to changes in the process, installation or instrumentation.

Detection, diagnosis and remedial action
In the other 170 incidents, an indication of the deviation was provided; however, there was a failure to detect the deviation, to diagnose it or to take remedial action. In most cases, this was due to the incorrect application (operation/use) of available resources.

A3.3.3 Why did safety measures for recovery fail?
Figure A3.10 shows why the safety measures for recovery outside operating limits failed. For reference purposes, an indication is given of why safety measures in the other lines of defence failed.

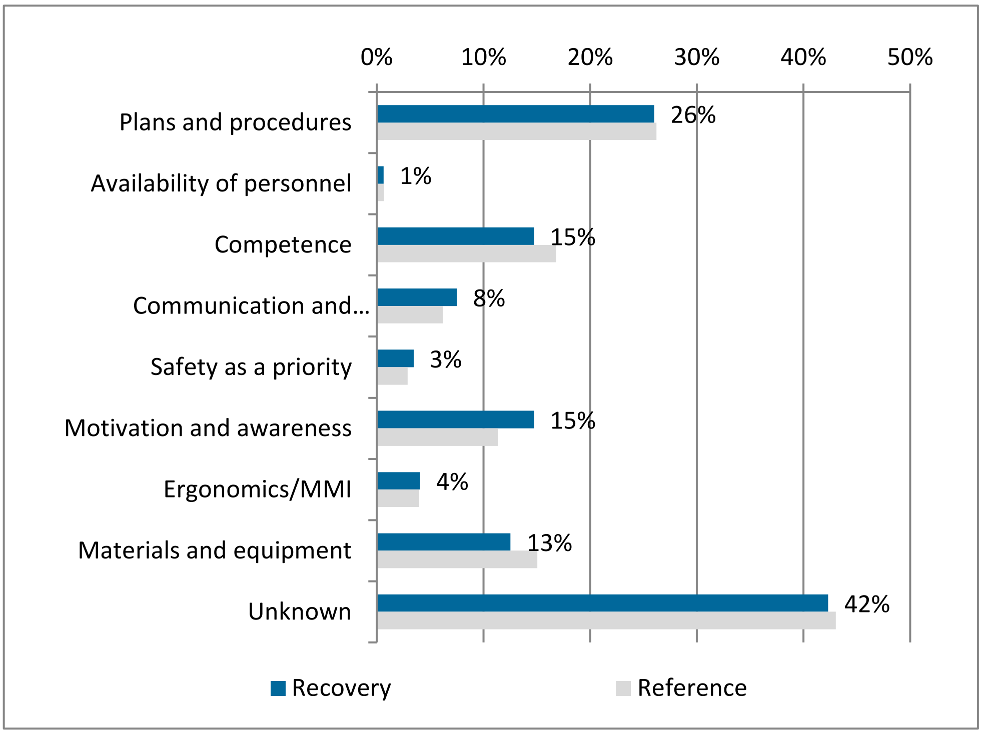

Figure A3.10. Why did recovery fail – percentage of cases in which elements are relevant within the 2nd LoD.

In 42% of the incidents, the underlying reasons that might show why recovery outside operating limits failed are unknown. One possible explanation for this is the fact that this element received relatively little attention in the accident investigations. In this 42% of incidents, the underlying factors for the occurrence of the deviations (the failure of operational control) had been investigated in detail, while the underlying reasons for the recovery failure were not. This represents an opportunity to improve future incident investigations in order to better understand why incidents occur.

In cases in which the underlying causes of recovery failure are known (58%), the overall picture is the same as that shown in Subsection A2.3.2. Deficiencies in plans and procedures were the most frequently reported causes (in 26% of all incidents), followed by competence (15%), motivation and awareness (15%), and materials and equipment (13%).

Figure A3.11 shows which SMS deficiencies were involved in the failure of recovery outside operating limits. For reference purposes, it provides an indication of the deficiencies in the other lines of defence.

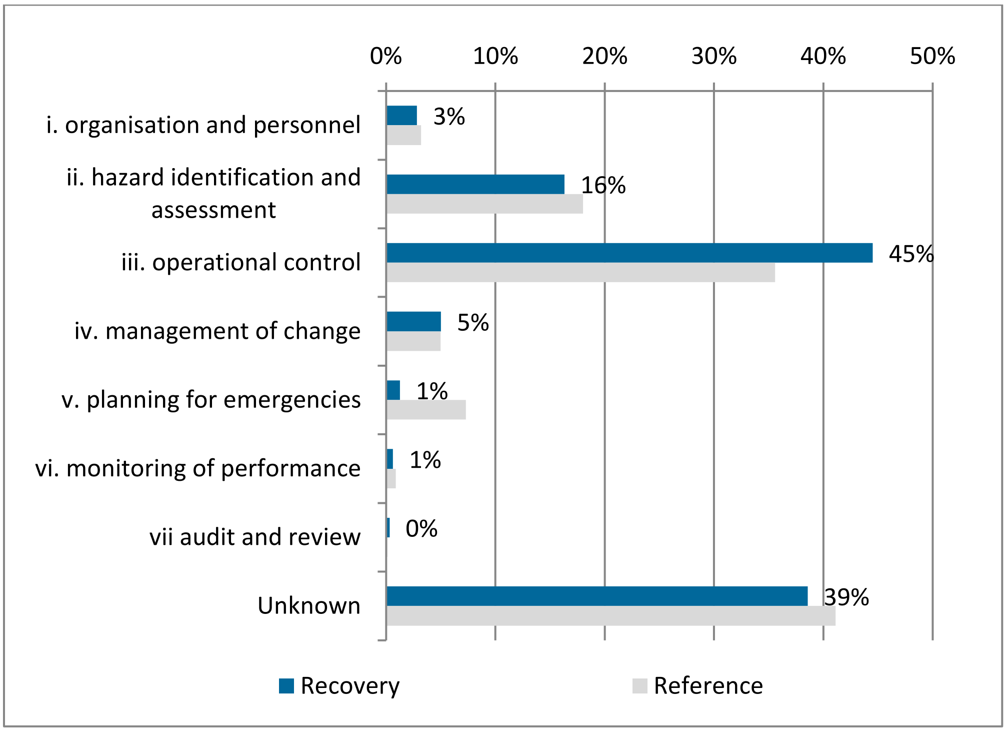

Figure A3.11. Which deficiencies in the SMS were relevant? – percentages in which elements are relevant within the 2nd LoD.

With regard to the elements of the SMS (Figure A3.11), the deficiencies in a substantial percentage of incidents (39%) cannot be reliably established, similar to the observations made for management delivery system failures (Figure A3.10). Those cases in which the deficiencies could be identified mainly involved deficiencies in terms of operational control (element iii). This means that, while the organisation had foreseen the potential hazards, they were not properly translated into adequate resources (instruments and procedures).

A3.3.4 *Consequences of the failure to recover deviations outside operating window*

Table A3.3 shows the consequences of the failure to recover deviations outside the operating window.

Table A3.3. Consequences of the failure to recover.

Consequences of the failure to recover	**Number of incidents**
Physical failure of primary containment (including loose connections)	117
as a result of material degradation	81
corrosion	46
erosion	3
fatigue	3
embrittlement	3
creep	1
vibrations	10
wear and tear/damage	7
other	4
as a result of incorrect assembly/installation	23
Opening of containment	84
opening a containment that contains product or is not properly isolated	65
adding substances to a system with an unintended opening	15
adding substances to a system with a regular opening	3
off-spec product	1
Temperature, pressure or level outside safe limits	66
product composition outside safe limits	5
as a result of a chemical reaction	3
high temperature outside safe limits	14
as a result of a chemical reaction	6
high pressure outside safe limits	45
as a result of explosive phase transition	2
as a result of a chemical reaction	13
high level outside safe limits	10
undesired flow to other containment	21
flammable conditions	40
flammable conditions in containment	33
flammable conditions in environment	7
undesired substance in containment	15
Environment deviation outside safe limits	9
moving object or persons enters danger zone	6
loss of stability	1
external load outside safe limits	2
Entering an insufficiently safeguarded containment	3
Unknown deviation outside safe limits	9

A3.4 3rd LoD: protection in the event of deviation outside safe limits

A3.4.1 Safety measure failures

The safety measures that failed in the 3rd LoD were shown in Figure 3.7 in Section 3.4.

A3.4.2 How did safety measures for emergency protection fail?

Figure A3.12 shows how safety measures for emergency protection failed. Only the four most frequent elements have been selected. Three of these are illustrated in greater detail.

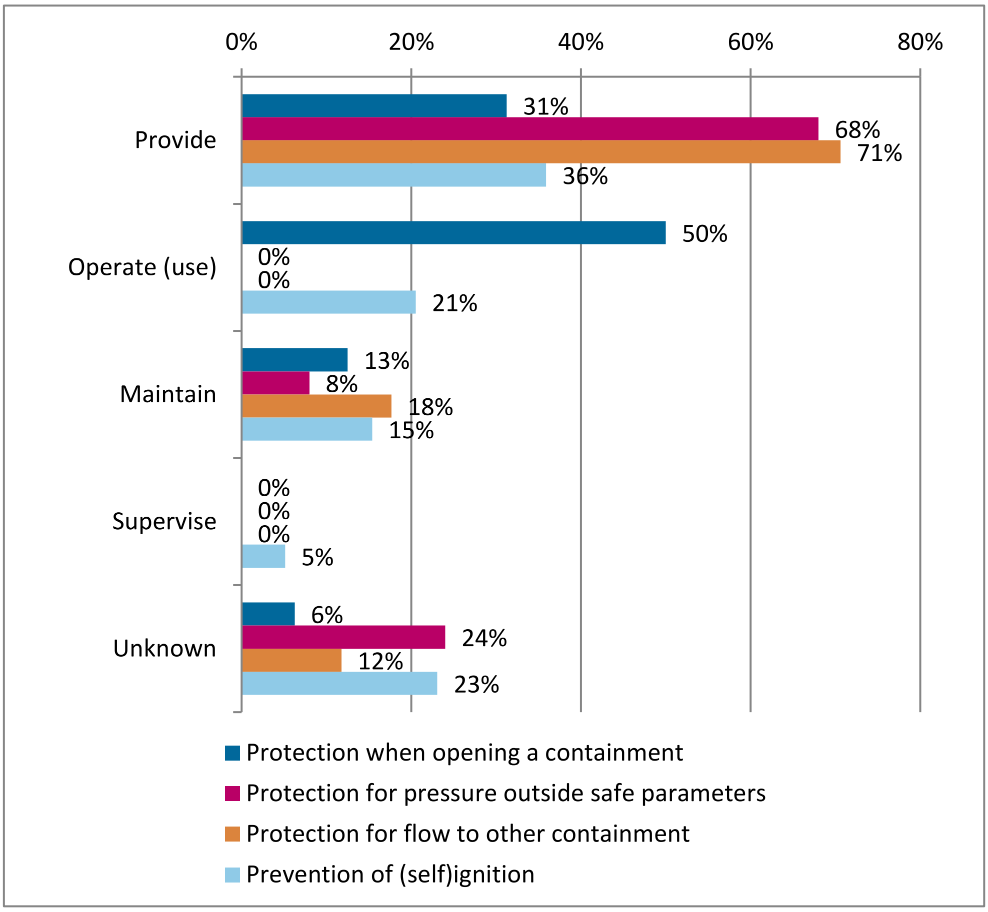

Figure A3.12. How did emergency protection measures fail? Selection of the four measures that fail the most in the 3rd LoD.

Protection when opening a containment
This mainly failed because the measures (instruments or procedures) that had been provided were not used or applied correctly (50%).

Protection for pressure outside safe limits
Emergency protection measures to prevent installations from failing as a result of excessive pressure failed mainly (69%) due to the absence of protection or because the capacity of the systems (especially pressure valves) was not sufficient. This, too, related mainly to deficiencies in identifying these risks (on 11 out of 17 occasions).

Prevention of ignition and self-ignition
The prevention of ignition and self-ignition can fail in a variety of ways. In 36% of the incidents, the measure was not implemented or was not correctly implemented. On 11 of the 14 occasions, the risks of fire were either not identified or not correctly identified by the organisation. In the other cases, measures to prevent ignition were not applied correctly (21%) or no longer functioned properly (15%).

A3.4.3 *Why did safety measures for emergency protection fail?*

Figure A3.13 shows why safety measures for emergency protection failed. For reference purposes, an indication is given of why safety measures in the other lines of defence failed.

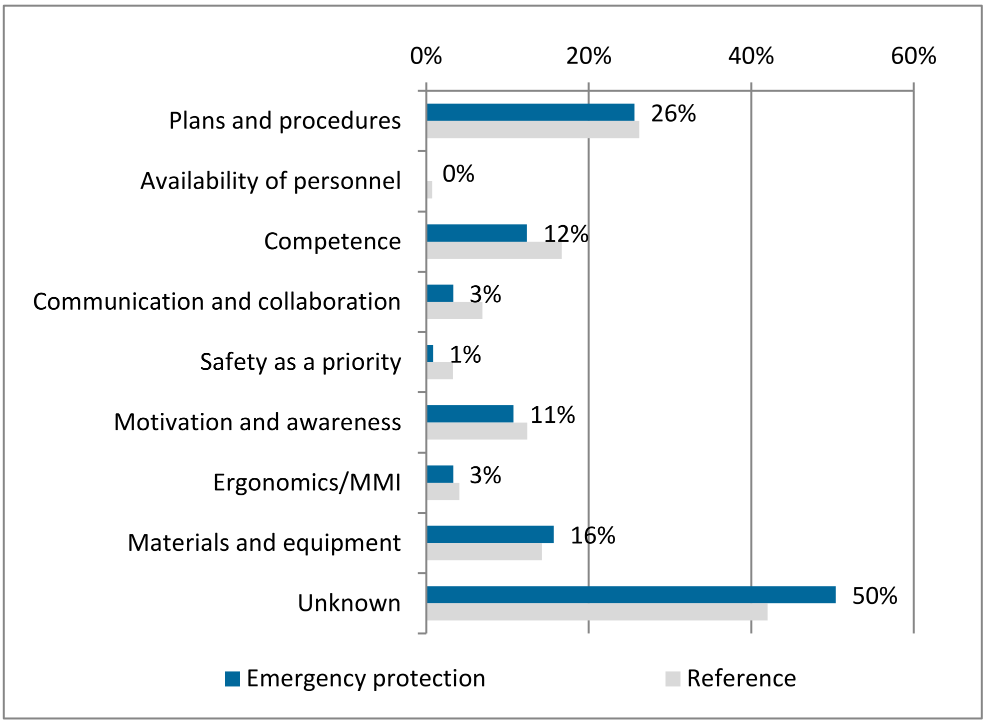

Figure A3.13. Why did the emergency protection fail – percentage of cases in which elements are relevant within the 3rd LoD.

As was the case with the failure of recovery (see Subsection A3.3.3), in half of the incidents (50%) it was unclear why the emergency protection failed. In the cases in which this is known, this mainly concerned deficiencies in plans and procedures (26%), materials and equipment (16%), competence (12%), and motivation and awareness (11%).

Figure A3.14 shows which SMS deficiencies were involved in the failure of emergency measures.

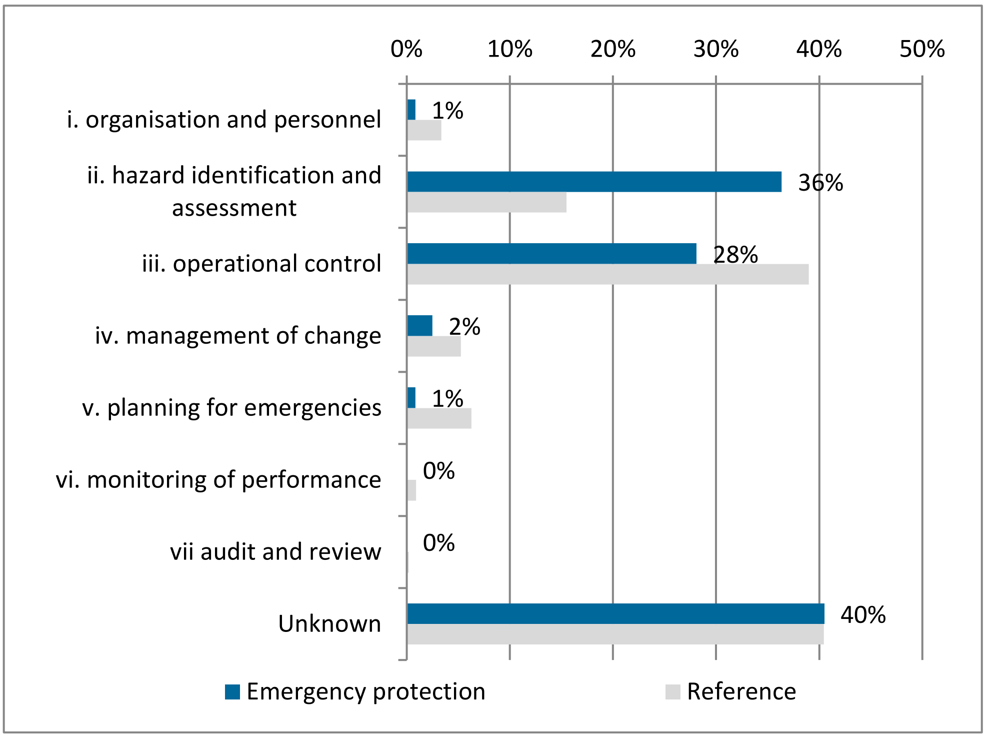

Figure A3.14. Which deficiencies in the SMS were relevant – percentages in which elements are relevant within the 3rd LoD.

With regard to the elements of the SMS (Figure A3.14), the deficiencies in a substantial percentage of incidents (40%) cannot be reliably established, similar to the observations made for management delivery system failures (Figure A3.13). Those cases in which it is possible to identify the deficiencies mainly involve deficiencies in terms of the identification of hazards and risk assessment (element ii, 36%). This means that the unsafe situations concerned were not sufficiently clear to the organisation.

A3.4.4 Consequences

If no safety measures are in place to protect against deviations outside safe limits or if such measures fail, an incident will occur. This event, which corresponds to a central event in the model, is described in Subsection A2.2.1. In some cases, emergency measures will succeed – for instance, if the failure of a tank due to overpressure is prevented by the activation of a pressure relief valve or the bursting of a rupture disc. Yet these measures result in the release of product, which is generally undesirable. As a result, those events are also seen as 'incidents'. The model makes it possible to distinguish between incidents that result from a successful emergency intervention and those that result from an emergency measure failure, including the absence of such a measure.

Table A3.4 shows the central event (the immediate effect of the incident). With regard to the release of hazardous substances, Table A3.5 gives further details about how the product was released. Table A3.6 indicates the phase of the released product.

Table A3.4. Central event (immediate effect of the incident).

Type of incident/accident (immediate effect)	Number of incidents
release of hazardous substances	292
immediate fire	32
fire within a containment	26
fire in the environment	5
immediate explosion	31
explosion inside a containment	31
physical explosion	3
explosive mixture in containment	21
dust explosion	6
runaway reaction	7
solids explosion	0
exposure within a containment	3
unknown type of incident	0

Table A3.5. Type of release.

Type of release	Number of incidents
from an open containment	13
from an opening that is typically open	23
through failing or loose connection	67
from an opening that is typically closed	93
from a newly created hole or breach (integrity failure), including weld seam failures	77
catastrophic rupture	20
unknown	6

Table A3.6. Product phase on release.

Phase of release	Number of incidents
release of vapour/gas at atmospheric pressure	45
release of pressurised vapour/gas	86
release of pressurised liquefied gas	17
release of pressurised liquid	82
release of cooled liquefied gas	5
release of unpressurised liquid[44]	51
release of solids (dust, granules, other)	11
unknown	4

[44] The term 'unpressurised liquid' is used if the containment is not actively pressurised by means of a pump or an inert gas. However, there is still hydrostatic pressure.

A3.5 Mitigating measures

Table A3.7 shows which mitigating safety measures are included in the analysis model. Towards this end, a distinction is made between three different lines of defence.

Table A3.7. Classification of safety measures in the 4^{th}, 5^{th} and 6^{th} LoD.

Line of defence	The safety measures involved
4: Limiting the release	• Stopping the release • Limiting the feed/flow or reducing the driving force
5: Escalation prevention	• Limiting evaporation and/or dispersion • Emergency containment of liquids • Control of ignition sources • Fire/explosion repression • Sufficient distance to other installations
6: Personal protection and assistance	• The use of personal protective equipment • Evacuation • Safe shelter • Keeping a safe distance from the danger zone • Emergency aid

A3.5.1 Safety measure successes and failures

The safety measures (successes and failures) are described in Subsection 3.5.1 of the report.

A3.5.2 How did the mitigating measures fail?

Figure A3.15 shows how the mitigating measures failed. The figure only shows the four most frequent elements. Three of these are illustrated in more detail.

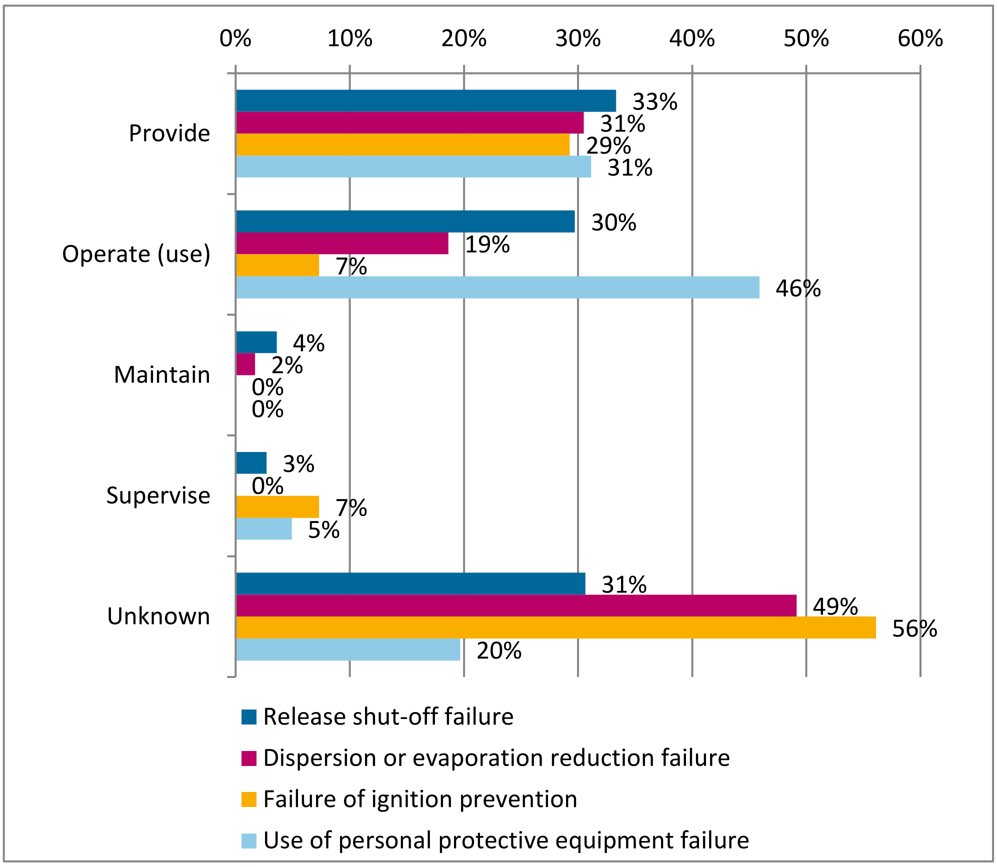

Figure A3.15. How did the mitigating measures fail? Selection of the four mitigating measures that fail most often.

Stopping the release (release shut-off)
In one-third of the incidents involved, the organisation did not have the right equipment and instruments to stop the release. In an equal proportion of incidents, those instruments and tools were available but were not used/applied correctly. In the remaining incidents, it is not known how this measure failed.

Limiting evaporation or dispersion (dispersion or evaporation reduction)
In 31% of the incidents involved, the organisation did not have the right equipment and instruments to limit evaporation and dispersion. In 19% of the incidents, the available resources were not used/not used properly. In the remaining incidents (49%), it is not known how this measure failed.

Use of personal protective equipment
In a relatively large number of cases (46%), no personal protective equipment was used. Mistakes (unintentional errors in applying rules and procedures) are more frequent than violations (deliberate deviations from rules and procedures). In 31% of the incidents, the organisation had not stipulated that the use of personal protective equipment was required for the activity concerned.

A3.5.3 Why did the mitigating measures fail?

Figure A3.16 shows why the mitigating measures failed. For reference purposes, it provides an indication of why safety measures in the other lines of defence failed.

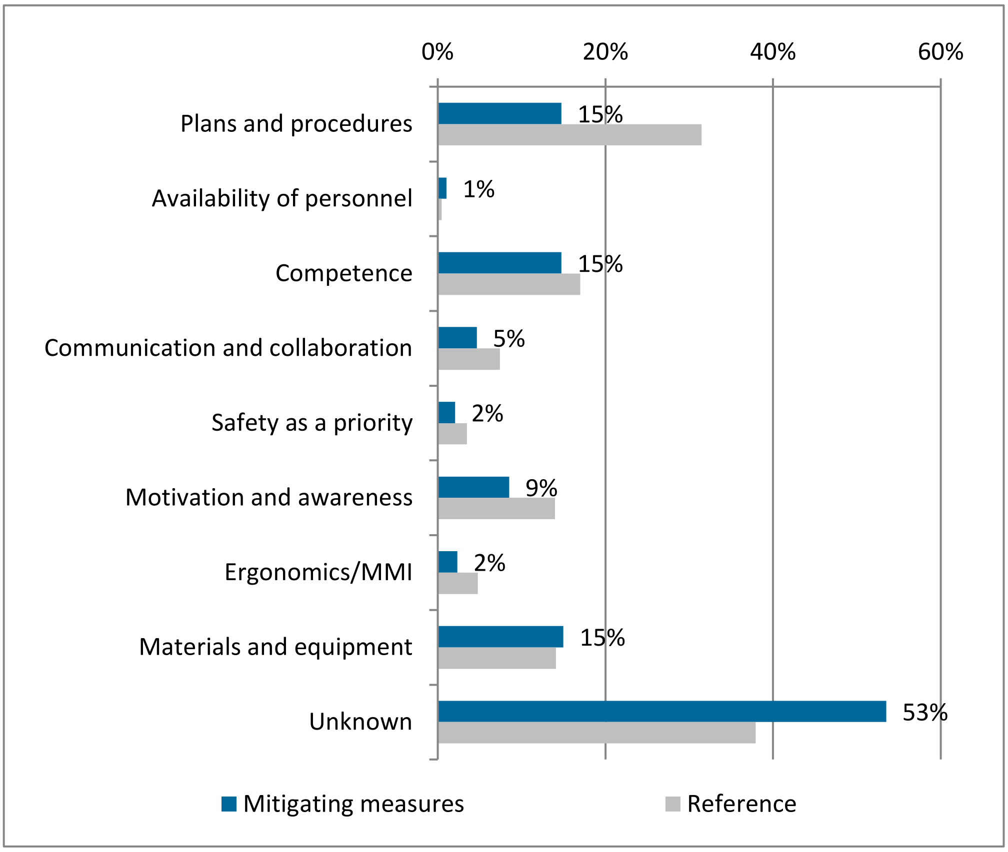

Figure A3.16. Why did the mitigating measures fail – percentage of cases in which elements are relevant to the mitigating safety measures.

In a relatively large proportion of cases (53%), the underlying causes of the failure of mitigating measures are unknown. In the cases where they are known, the most important elements are plans and procedures (15%), competence (15%) and material and equipment (15%).

Figure A3.17 shows which SMS deficiencies were involved in the failure of mitigating measures. For reference purposes, an indication is given of the deficiencies in the other lines of defence.

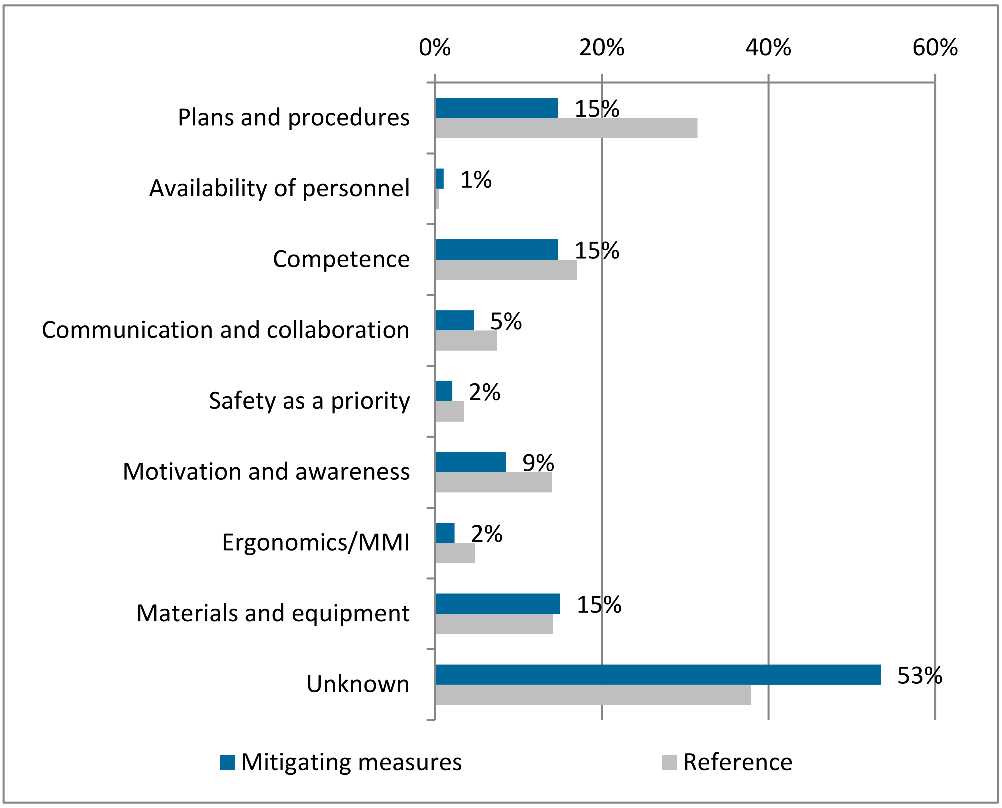

Figure A3.17. Which deficiencies in the SMS were relevant – percentages in which elements are relevant to the mitigating safety measures.

With regard to mitigating measure failures, there were many instances (55%) in which the underlying deficiencies in the SMS were unknown. In the cases in which they are known, the main factors were implementation (element iii, 21%) and planning for emergencies (element v, 16%).

A3.5.4 Consequences

The consequences of the success or failure of mitigating safety measures are described in Table A3.8 and Table A3.9.

Table A3.8. Extent of release reduction (4th LoD).

Extent of release reduction	Number of incidents
release was not limited	111
release was limited	128
unknown or not applicable	78

Table A3.9. Type of consequence resulting from the incident (5th LoD).

Type of consequence after the central event	Number of incidents
airborne dispersion of hazardous substances	168
not controlled or limited	94
controlled or limited	69
fire	66
pool fire	17
jet fire	19
flash fire	13
fireball	1
tank roof fire	1
fire within containment	13
fire outside containment	10
explosion	7
BLEVE	0
explosive decompression (external)	1
vapour cloud explosion (external)	2
delayed explosion of a vessel or a pipe as a result of escalation or domino-event	4
explosion in external object (e.g. sewer or drainage system)	0
rapid phase transition outside containment	0
no relevant subsequent event	80
unknown subsequent event	13

In the 326 incidents, 224 people were exposed to various types of hazard, such as contact with hazardous substances, heat radiation, flames, hot or cold products and overpressure. This is described in Table 3.2 of Subsection 3.5.2 of this report.

A3.6 Human error

When safety measures fail, an investigation is carried out to determine whether human error was involved and whether this was a violation, a mistake, or a slip or lapse. A violation involves a deliberate (intended) deviation from the rules and procedures. However, the intention does not have to be a bad one. A mistake involves an incorrect decision that was taken unintentionally. A slip or lapse involves incorrect actions at the subconscious level, for example due to lack of attention, a distraction or a memory lapse.

In total, 254 human errors were found that could be classified in one of these three categories. These are shown in Figure A3.18 (and in greater detail in Table A3.10). The majority of cases involved mistakes. This applies both to incorrect actions in the run-up to the incident (in the event of preventive measure failures) and to incorrect actions taken to combat the incident (errors in taking mitigating measures).

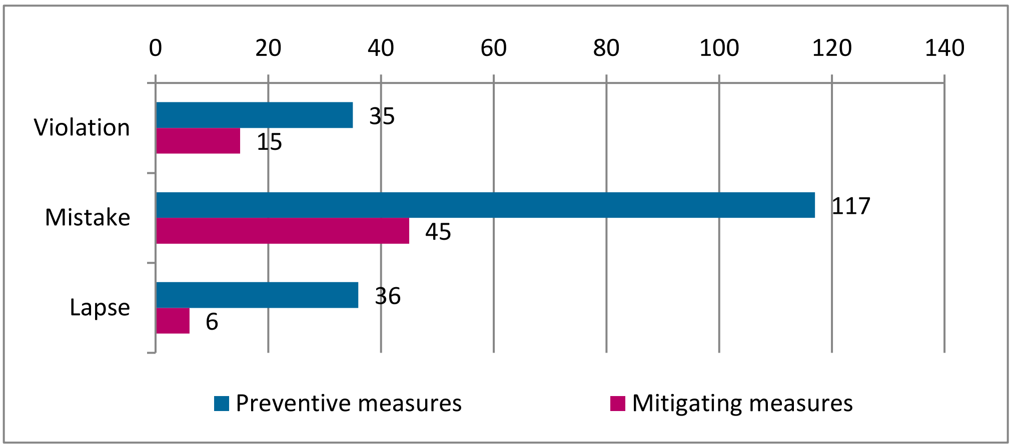

Figure A3.18. Number of human errors identified in preventive and mitigating measures.

Table A3.10. Human errors in preventive and mitigating measures.

Type of human error	**Number involved in preventive measures**	**Number involved in mitigating measures**
violation	35	15
situational violation	21	2
exceptional violation	2	5
routine violation	10	4
unknown	2	4
mistake	117	45
Knowledge-based mistake	54	32
Rule-based mistake	57	10
unknown	6	3
slip/lapse	36	6
attentional slip	18	4
memory lapse	16	0
unknown	2	2
total	188	66

Table A3.11. Definition of the different types of human errors in Storybuilder.

Type of human error	Description
Situational violation	A violation in which rules are breached due to pressure to complete the task or because the local circumstances make it difficult to comply with the rules.
Exceptional violation	Infrequent violation under special circumstances, such as emergencies.
Routine violation	A frequent violation, in other words, disregarding the rules and procedures is the normal working practice.
Knowledge-based mistake	An error caused by insufficient knowledge, as a result of which an incorrect action/measure is chosen. Errors in conscious behaviour at the knowledge level – this relates to new problems and, in many cases, to new actions that need to be carried out (which, as a result, tend to be the least automated).
Rule-based mistake	A mistake that occurs because existing protocols, daily routines and instructions (or the associated rules and procedures) are applied incorrectly or not at all.
Slip	Error due to an attentional slip.
Lapse	Essentially a temporary memory loss, often resulting from an interruption or due to ‘multitasking’.

Appendix 4 Filters used in frequently occurring scenarios

The following sections show how frequently occurring scenarios are structured, from a technical perspective.

Section 4.1.1: Physical failure of the containment as a result of material degradation
This cluster of similar incidents concerns incidents that pass through the following model elements:

- 1st LoD: Material failure (04_BFM) or failing control of conditions w.r.t. material degradation (03_BFM);
- 1st LCE: Equipment deviation (material) outside operational limits;
- 2nd LoD: Recovery action failure outside operational limits (20_BFM);
- 2nd LCE: Physical failure of the primary containment;
- 3rd LoD: Unknown or not applicable (BSU-L3);
- 3rd LCE: Release of hazardous substances.

Section 4.1.2: The failure to safeguard a containment before opening it
This cluster of similar incidents concerns incidents that pass through the following model elements:

- 1st LoD: Pre-start-up safeguarding failure (02-BFM);
- 1st LCE: Pre-start-up deviation outside operational limits;
- 2nd LoD: Remedial action failure outside operational limits (20_BFM);
- 2nd LCE: Opening of containment;
- 3rd LoD: Unknown or not applicable (BSUL3);
- 3rd LCE: Release of hazardous substances.

Section 4.1.3: High pressure in a containment
This cluster of similar incidents concerns incidents that pass through the following model elements:

- 1st LoD: Failure of process control (G_B_L1);
- 1st LCE: Process deviation outside operational limits;
- 2nd LoD: Recovery action failure outside operational limits (20_BFM);
- 2nd LCE: High pressure outside safe limits;
- 3rd LCE: Release of hazardous substances.

From an organisational and human perspective, the scenarios were developed as follows:

Section 4.2.1: Operational control
These are all the paths that pass through one of the barriers in the analysis model, through the 'SMS elements' element, and 'iii. operational control'.

Section 4.2.2: Identification of the hazards and assessment of the risks involved
These are all the paths that pass through one of the barriers in the analysis model, through the 'SMS elements' element, and through 'ii. hazard identification and risk assessment'.

Section 4.2.3: Management of Change
These are all the paths that pass through one of the barriers in the analysis model, through the 'SMS elements' element, and through 'iv. management of change'.

Section 4.3.1: Violations
These are all the paths that pass through one of the barriers in the analysis model, through the 'Human error' element, and through 'Violation'.

Section 4.3.2: Mistakes
These are all the paths that pass through one of the barriers in the analysis model, through the 'Human error' element, and through 'Mistake'.

Section 4.3.3: Lapses and slips
These are all the paths that pass through one of the barriers in the analysis model, through the 'Human error' element, and through 'Slip or lapse'.

Appendix 5 Comparison with the conclusions of the previous long-term report (2004-2013)

In 2014, an analysis of the incidents dating from 2004 to 2013 was carried out [10]. The conclusions of this report are repeated below, together with an indication of whether they are still up to date.

Conclusion 1: "Since 2009, there has been a decrease in the total number of incidents investigated by the SZW Inspectorate. It is not known whether this is due to an actual reduction in the number of incidents or whether it is simply that fewer incidents are being reported."
The conclusion is still valid. The decreasing trend that started in 2009 has continued. The precise cause or causes of this decreasing trend are still uncertain. See also Subsection 5.1.

Conclusion 2: "With regard to the causes of the incidents, no striking trends were identified. Each year, the same safety functions usually fail."
The conclusion is still valid. Over the years, the safety measure (previously: safety functions) failures have remained more or less the same, see Subsection 5.2.

Conclusion 3: "Process control, i.e. the level of control needed to keep processes within 'normal' safe limits, failed more often in the period running from 2008 to 2010."
According to current analyses, the peak in the period running from 2008 to 2010 is smaller than is indicated in [10]. With regard to the period running from 2003 to 2018, there were no structural changes in (failed) safety measures related to operational control. This also applies to process control, see Subsection 5.2.

Conclusion 4: "An average of 40% of the incidents appear to have involved poor equipment condition, so this is a significant cause of incidents. This can be either design-related or maintenance-related (ageing, choice of material)."
The conclusion is still valid. A failure to ensure the integrity of the installation (formerly: control of equipment condition) remains the leading cause of failure. This element of operational control failed in 41% of incidents, see Subsection 3.2.1.

Conclusion 5: "Over the years, the indication of the deviation failed in well over 40% of all incidents."
The conclusion is still valid. In 48% of the incidents, the absence of an indication of the deviation was the reason why there was no recovery of deviations outside the operational envelope, see Subsection 3.3.1

Conclusion 6: "In most incidents involving hazardous substances, it is not the strength of the containment that fails (it remains intact). The failure is due to the fact that the containment is bypassed. This includes

overfilling, the accidental opening of valves, pipe sections that were missing or that were not blinded off, etc."
The conclusion is still valid. In 32% of the incidents, installations fail (either partly or completely). Much more often, hazardous substances were released through closing valves and other valves that had accidentally been left open, see Subsection 3.4.2.

Conclusion 7: "The three underlying management delivery systems that fail most often are plans & procedures, equipment and competence."
The conclusion is still valid. The top three underlying factors (management delivery systems) are still plans and procedures (26%), competence (16%), and material/equipment (14%). The motivation and awareness element scores 12%, and communication and collaboration 7%. These percentages represent the averages for all barrier failures in the 326 incidents that have been analysed.

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RIVM-report 2020-0115

Published by

National Institute for Public Health
and the Environment, RIVM
P.O. Box 1 | 3720 BA Bilthoven
The Netherlands
www.rivm.nl/en

July 2020

012225

Committed to *health and sustainability*