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Ageing assets at major hazard chemical sites – The Dutch experience

Rikkert J. Hansler [a,*], Linda J. Bellamy [b], Henk A. Akkermans [c,d]

[a] National Institute for Public Health and the Environment (RIVM), Centre for Environmental Safety and Security, PO Box 1, 3720 BA Bilthoven, the Netherlands
[b] White Queen Safety Strategies, PO Box 712, 2130 AS Hoofddorp, the Netherlands
[c] Tilburg University, School of Economics and Management, PO Box 5000 LE, Tilburg, the Netherlands
[d] World Class Maintenance Foundation, Boschstraat 35, 4811 GB Breda, the Netherlands

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ABSTRACT

Operators of major hazard chemical sites increasingly face the problem that their assets are ageing. This paper highlights the major hazard aspects of ageing, particularly in the Netherlands where there are around 400 major hazard chemical sites, many coming to the end of or exceeding their design lifetime. Targeted inspections find failures in the safety management of ageing and every year there are ageing related accidents. Dutch investigated major accidents are analysed in a bow-tie structured database called Storybuilder, which contains 83 major accidents resulting from material degradation, this being 25% of all accidents in the database. The paper provides unique details on the accident causes and the difficulties operators have in foreseeing the outcomes. It explains the reasons for taking a holistic approach to modelling, which considers management, human and technical aspects. The analysis results provide information on the safety barrier, barrier task and barrier management failures. A detailed ageing accident scenario is also illustrated within the holistic model. Two prevention approaches are suggested. One uses scenarios as a basis for identifying the necessary prevention measures. The other results from a Dutch multi-disciplinary maintenance programme concerning smart maintenance, a shared initiative approach of companies looking for innovative solutions. The conclusion is that a scenario-based approach is needed for identifying currently unanticipated material degradation causal events and that, given the condition of ageing assets, a shift to condition-based maintenance, combined with technical, organisational and cultural changes, underpins the future approach to physical ageing.

1. Introduction

1.1. Aims

At major hazard chemical sites, accidents can happen that involve large quantities of hazardous substances. Accidents like these are undesirable not only for financial reasons but also because they pose a threat to people inside and outside an establishment and to the environment. This is a problem that is faced in the Netherlands and which is elaborated upon in Section 1.2. The paper examines chemical major accident scenarios in this country that are specifically linked to material degradation and failure in the management of ageing assets. This is done in the context of a holistic approach, combined with in-depth analysis of the ageing-related major accidents. The analysis highlights the dominant direct and underlying accident causes and acknowledges the difficulties in foreseeing what can go wrong. This unique data analysis fills a data gap in the understanding of the sociotechnical aspects of ageing in major hazard installations, as explained in Section 1.2. The objective is to highlight not only key areas for improvement but also to propose solutions consistent with the interest of chemical companies in innovative solutions in a time of renewal of ageing assets. The organisation of the paper is first to give a broad understanding of our approach to ageing in Section 1. This is followed by a description of a holistic model of ageing and a methodology for analysing accidents in Section 2. The results of the accident data analysis are given in Section 3, focussing on the material degradation aspect of ageing leading to loss of containment. Then, Section 4 gives both scenario-based and smart solutions for these issues. Section 5 draws conclusions from this examination of the problems and possible solutions. To assist the reader, an Appendix of terminology is given to explain how some key terms in the modelling are used in the paper.

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* Corresponding author.
E-mail address: rikkert.hansler@rivm.nl (R.J. Hansler).

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1.2. An integrated approach to ageing

In the Netherlands, 25% of the accidents investigated by the Major Hazard Control inspectorate of the Ministry of Social Affairs and Employment (SZW) over a 15 year period (2004–2018) showed material degradation, such as corrosion and fatigue, as the direct cause of loss of containment accidents (Kooi et al., 2020). There are around 400 major hazard chemical sites in the Netherlands which fall under the European Seveso Directive (EU Council 2012), also known as the Seveso-III Directive. This directive requires major hazard chemical sites to prevent and mitigate major chemical accidents by means of a prevention policy implemented through a safety management system (SMS). Companies must take “all necessary measures” (Article 5.1), both technical and organisational, and according to a new requirement in the latest revision (Seveso III) must specifically address the issue of material degradation of equipment in the management of safety. This reflects increasing concern about physical ageing as many installations are reaching the end of their design lifetime (OECD 2017, Marsh 2020). For the Netherlands it is estimated that this is around 41% of the asset base in the processing industry (More4Core, 2014). While there is extensive literature in research databases on ageing when looking at equipment degradation phenomena or maintenance or risk or asset management, there is very little that specifically addresses ageing in the major hazard chemical industry, particularly with respect to accidents. Exceptions include Gyenes & Wood (2016), Horrocks et al. (2010), INERIS (2010a, 2010b), Kieskamp et al. (2019); MAHB (2015), OECD (2017), Wood et al. (2013). Additionally, a team of researchers in Italy have been specifically looking at ageing and risk management aspects in the context of Seveso III (Ancione et al., 2020; Bragatto & Milazzo, 2016; Bragatto et al., 2020; Milazzo et al., 2018; Milazzo & Bragatto, 2019). Milazzo & Bragatto (2019) explain how ageing at a complex site represents the overall effect of multiple parameters on the deterioration processes. The innovative approach is to address the complexities by adopting a holistic approach, but data about the key aspects affecting ageing in the chemical process industry cannot easily be extracted from existing studies (Ancione et al., 2020). The current paper addresses some of these key aspects by presenting the underlying causes of ageing accidents in major hazard chemical plants using 83 investigated major hazard accidents from Dutch Seveso plants. It highlights the properties of safety barriers and their management which failed in prevention of loss of containment.

The paper presents a holistic model of different levels of major hazard control, which provides the framework for understanding the underlying interrelated factors in major hazard ageing accidents (see Section 2.1). The holistic view takes into account the human aspects from work floor through management, and the system of hazards and their controls. The concept of sociotechnical modelling (e.g. Rasmussen, 1997) can be applied to considering and even quantifying the relationship between technical failures and management (Papazoglou et al., 2003). Pasman et al. (2013) argue that a holistic approach is particularly required for dealing with process risks in the face of complexity and uncertainty. Safety is seen as an emergent property of a complex system and one has to develop an integral view on the design, operational and maintenance stages of a process.

A key aspect of emergent properties is that they are unexpected behaviours, stemming from interactions between components of complex systems and with their environment (Johnson, 2006). Since the behaviour of the whole cannot be predicted from the behaviour of the individual components, a concern is whether emergent properties can be predicted at all. Lindhout et al (2020) suggest that there is a gap between scenarios typically identified by company safety management systems and those actually occurring in accidents. They refer to the stagnating downward trend of major accidents in the Netherlands and Belgium and provide a scale of “unknown-ness” and suggest ways to think about these risks. Unknown dangers from exceeding the design lifetime of the plant are considered to be at level 3 on their scale, and that to reduce to level 2 requires, amongst other things, study and observation and gathering of information, which is one of the aims of the current paper.

Our integrated or holistic approach is consistent with a research and development history in the Netherlands. The Seveso Directive led to increasing integration in the working together of the separate Dutch ministries responsible for major hazard safety onsite, for external public safety, and for emergency response. A number of research and development projects reflecting an integrated internal-external and technical-organisational approach took place including the European integrated risk project I-Risk (Bellamy et al., 2000, Papazoglou et al., 2003), the AVRIM2 inspection and assessment method for the Dutch major hazard inspectors (Bellamy & Brouwer, 1999), and the Dutch Storybuilder accident analysis tool and database (Bellamy, 2015; Bellamy et al., 2007, 2008, 2013), which is used to analyse the investigated major hazard accidents (Kooi et al., 2020). The implementation of the Seveso regulation in the Netherlands (BRZO, 2015) and its elaboration (RRZO, 2016) has components which reflect integrated aspects. In particular, upper tier establishments (those with hazardous substances above a specified quantity) are required to consider specific causal scenarios when assessing the major accident risks (RRZO, article 10). These scenarios are corrosion, erosion, external load, impact, overpressure, underpressure, low temperature, high temperature, vibrations, and human error during use, modifications or maintenance. It is required that specific example scenarios from each of these generic types are described in such a way as to demonstrate the complete system of available technical and organisational facilities that adequately control the risks of major accidents. Therefore, ageing-related scenarios, which are due to mechanical, chemical and/or thermal loads over time, are implicitly included as a basis for addressing measures, but there is currently no specific advice on how these ageing-related scenarios might be elaborated. This paper gives the details of these scenarios.

1.3. Management issues

Traditional safety management principles are typically based on Deming-cycle management principles of Plan-Do-Check-Act, such as in the international environmental management standard ISO 14001:2015 (International Organization for Standardization, 2015). The cycle consists of agreeing an objective, defining a plan to achieve that objective, formulating the detailed work required to implement the plan, carrying out the work, checking the outcome against the plan, and planning and taking appropriate corrective action. As an illustration of some of the weaknesses in the safety management of ageing, these have been highlighted by Dutch inspectors in an extensive targeted inspection programme. In 2017 ageing was assessed in 333 Seveso establishments (BRZO+, 2018). Violations were identified in 15% of these companies. In 2019 ageing themes were addressed in 287 of the 405 Seveso establishments (BRZO+, 2020). Around a third had violations concerned with ageing. Amongst the negative findings of these inspections were:

- No established policy for adequately tackling the problems of ageing concerning degradation of installations and equipment. For example, too much trust that preventive maintenance will handle ageing despite inadequate knowledge about ageing mechanisms.
- Lack of a maintenance philosophy for ageing.
- Lack of knowledge assurance in the ageing of the organisation.
- Incomplete identification of degradation mechanisms and the dangers, particularly the dangers of corrosion.
- Incomplete inventorisation of ageing-sensitive equipment.
- Ageing is not sufficiently elaborated in the various parts of the safety management system. Companies are not ensuring the management and control of ageing such as through safety studies, failure analyses, routine preventive maintenance, inspection and unacceptability criteria.
- Failure to perform remaining life studies for installation parts.

- Inspection and maintenance issues for pipework, including corrosion under insulation.

It is reasonable to expect that ageing-related accidents in the Netherlands are associated with these types of management issues found by inspectors. There is a limited research literature to support the link between safety management and technical failures as any search combining safety management and major hazards reveals (little more than 150 articles in Scopus). A recent article by Schmitz et al. (2021) summarises the literature on different organisational aspects and their link to barrier systems. Pitblado et al. (2016) suggest that safety barrier management - activities that ensure that the safety barrier always functions (see Section 2.2) - has the most potential in the management of major accident risks in the operational phase. These papers support the approach taken here in presenting the unique data on barrier and management failures. To support companies it is desirable to provide practical information based on our existing knowledge of problems. But we do not want to stop there. For this reason in this paper in Section 4.1 we also broadly address scenario-based solutions associated with barrier failures and in 4.2 innovative solutions associated with the requirements of companies. What can companies do to reduce the likelihood of chemical accidents happening? There has long been a focus on either improvement in technology or in organisation and human behaviour. With regard to organisation and human behaviour, the emphasis has been on cultural change and behaviour modification (Anderson, 2005; ICSI Safety Culture Working Group, 2017; Le Coze, 2019). In the area of technology, the rise of digitization has led to significant opportunities for so-called smart solutions. Both approaches have their proponents, but in this paper we argue for a combination of the two. In Section 4.2 we call this smart maintenance (Akkermans et al., 2016; Bokrantz et al., 2019) or smart asset management, consistent with the integrated approach we have outlined.

1.4. Defining ageing and its occurrence in loss of containment accidents

In the current paper the focus is on physical ageing, in particular material degradation of the physical assets. Non-physical ageing, like obsolescence, knowledge, expertise and procedures issues also can be a contributory factor in material degradation and other major accident causes (Habrekke et al. 2011; IAEA, 2018; INERIS, 2009; MAHB, 2015, 2019), but a detailed analysis of non-physical ageing is beyond the scope of this paper. Physical ageing is a dynamic process of change over time, one of the results of which is that the failure rate is not constant. Ageing increases it. Over the lifetime of a plant the failure rate typically follows a bathtub curve (Wintle et al. 2006). The Marsh (2020) report shows that the number of losses in the hydrocarbon industry, when plotted against calendar age, also follow a bathtub curve. Besides the effect of time, the speed and location of material degradation can be accelerated - by changes in materials, products, process conditions, and the environment, or slowed down under the influence of decelerating factors like inspections, maintenance and protections (Milazzo & Bragatto, 2019). Material degradation accidents are typically classified by their direct causes related to ageing: corrosion, erosion, fatigue, and vibration (Geus & Kieskamp, 2018; Gyenes & Wood, 2016; Horrocks et al., 2010; INERIS, 2009, 2010a, 2010b; MAHB, 2015; Maroño et al., 2006; OECD, 2017). Of known causes of age-related accidents, studies mentioned here suggest that around half are caused by corrosion, so around 15% of all LOC accidents. The OECD (2017) report on 430 ageing-related accidents provided by member countries gives a breakdown showing 45% of ageing accidents were due to corrosion, 20% fatigue/wear/vibration, 13% unknown, 12% obsolescence and 10% erosion.

This paper goes deeper than has been done previously into the causes of material degradation in major hazard accidents using the Dutch accident investigation results, which have been analysed in the Storybuilder model mentioned earlier. The model is a construction of safety barriers in a bow-tie structure, as described in Section 2.2. The database provides sufficient detail to generate an integrated picture of the direct and underlying causes of failure including the technical, task and management aspects.

2. Models and methods of analysis of ageing-related loss of containment accidents

2.1. A holistic model for the complex system underlying ageing-related loss of containment

Only a small proportion of hazards on a chemical site are linked to loss of containment (LOC) and major hazards. The challenge for companies and regulators is to identify the relevant parts of the technical and management system and to assess whether all the necessary measures are in place for controlling major hazards. To assist in this process, a holistic model was developed (Oh & Bellamy, 2000) and subsequently elaborated in the current study on ageing. The holistic model is based on a lines of defence concept, also known as a defence-in-depth philosophy (INSAG, 1996; Rasmussen, 1994). Systems with major accident consequences such as nuclear facilities and chemical plants, have multiple protective layers, also known as safety barriers, such that the chance of simultaneous failure of all the lines is extremely small. Safety management requires the control and monitoring of these lines of defence to ensure they retain integrity. Failure of the defences, or barriers, resulting in an accident can be termed a *scenario*, which is the meaning of this term used in the current paper.

The essence of the model is that a slice can be taken from it in relation to a particular aspect or activity. This slice of the holistic “cake”, by being cut from the whole, contains the essence of the whole cake while still being specific for this aspect. The connectedness of the parts is still maintained whatever way it is sliced (the same is true for the Storybuilder model described in Section 2.2). For the purposes of focusing on ageing, the safety-related aspects of ageing in major hazard chemical installations are treated as a slice of this cake as shown in Fig. 1. Ageing, in particular material degradation leading to loss of containment, is considered to be an emergent property of the interactions that occur within and between the layers of a complex system. In this important respect we view ageing as holistic - a totality that is different from the parts themselves. So, while our ageing slice of the cake is an aspect of the major hazard complex system, it is the emergent properties, reflected in the accident scenarios, that tell the story of the interconnectedness between the parts. This is why we called the accident model *Story*builder.

In the model the ageing-management perspective can be understood as the need to link the safety management system (6) for the control of the risks associated with ageing equipment, to the hazards that need to be controlled and the technical measures taken (1–3). In the centre of this diagram are (1) the major hazards on a site, these being fire, explosion, and toxicity, which are the causes of harm to people and the environment, and where there are large quantities of the hazard agent, the hazardous chemical substances. The hazards are controlled by a system that is technical (engineered mechanical, electrical, software etc.) equipment (3), which is there to prevent the major hazard agents (the chemical agents) from (2) being released from controlled containment. Of specific interest here is the integrity of mechanical boundaries of vessels and pipework and their connections, and with associated equipment such as pumps, valves, process controls and instrumentation. In the slice, the physical ageing of a plant and the potential major hazard risks are in these parts (1–3) of the model. The control measures require human tasks (5) for their design, installing, commissioning, operating, monitoring, maintaining, testing etc. through the life cycle of design, construction, operation, maintenance and decommissioning. The relationship of the tasks to ageing can be understood in two ways: a) tasks associated with the identification and recovery from ageing in the technical physical part of the system and b) the negative effect of ageing of the organisational parts of the system on task performance. These

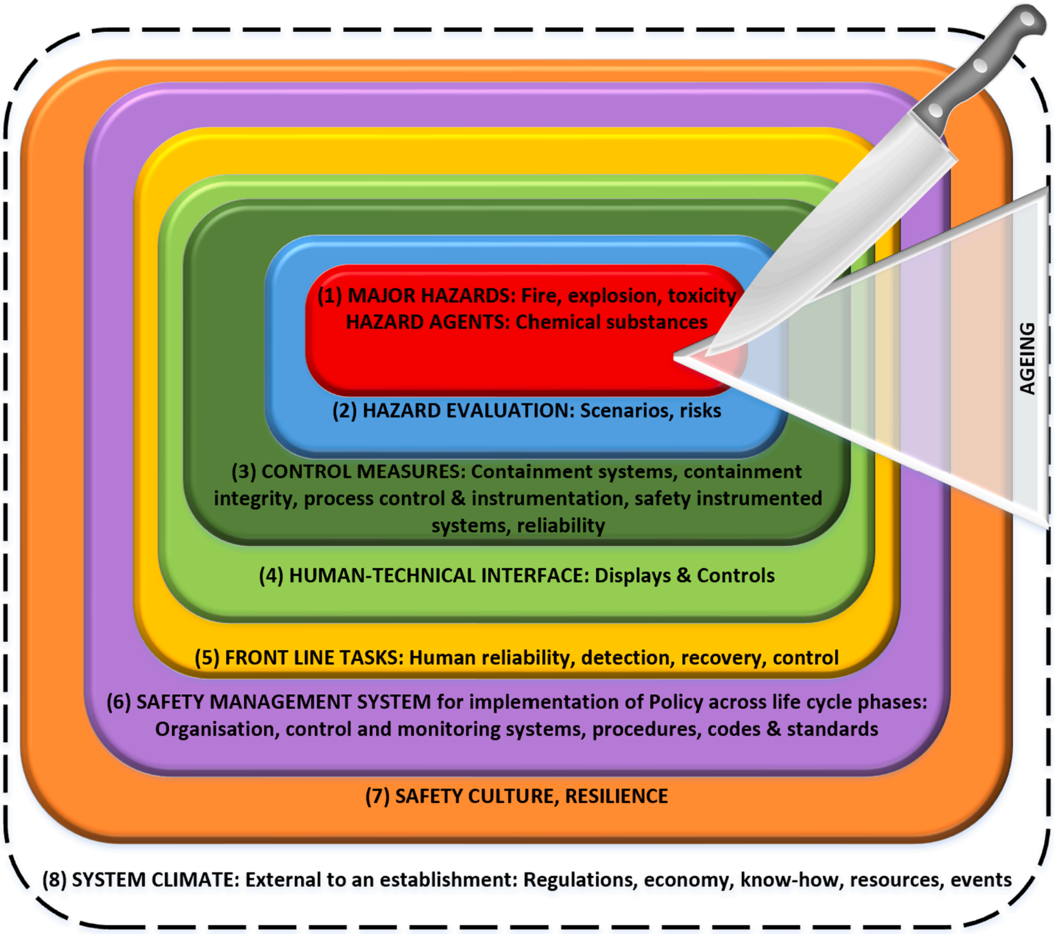

Fig. 1. A holistic model linking the technical, human and organisational aspects of safety, with ageing viewed as a slice of this “cake”.

front line tasks also require an interface (4) between the humans and the technical measures. This is often referred to in the human factors discipline as “displays and controls” but which effectively means anything that is part of enabling the interaction between the front line humans and the technical part of the plant. HFES (2021) provide a number of definitions. The interaction could be a computer screen displaying information about the process conditions, a control panel, a handle on a valve, or a tool used for maintenance. It may be that there is no interface, e.g. a person looks directly at a pipe to ascertain its state, or they directly see yellow smoke coming from a containment. In carrying out inspection and maintenance for example, that interface might consist of specialist tools to improve detection of corrosion, and labelling of equipment and spare parts.

The safety management system (6) is there to implement the major accident prevention policy of the company and so, ultimately, to manage these human tasks (5) to ensure that the integrity of the hazard control system is maintained throughout the life cycle of the plant. The safety management system is itself a control and monitoring system and delivers the required resources to the front line tasks, like the appropriate manning and competences, procedures and instructions, awareness of the risks, and the necessary tools and communications. When considering ageing, the management aspects of interest are, firstly, a policy for maintaining a safe condition of ageing major hazard plant and, secondly, implementation of this policy through the safety management system.

All this happens within the context of (7) the company’s safety culture (Guldenmund, 2000). This also determines how resilient the company is in managing uncertainties that give rise to unexpected events that were not planned for. Equipment and processes may also need to be resilient in order to handle uncertainties in conditions. Jain et al. (2017) discuss how the concept of resilience includes not only human and organisational aspects but also technical aspects of process and plant installation in design and operation. They define resilience as the capability to absorb and overcome unexpected, unforeseen, and unknown threatening disturbances that could otherwise result in a catastrophe. Early detection and error tolerant design are two examples they give of process resilience aspects.

Furthermore, a company or chemical plant is part of a wider external system (8), the system climate. This may affect an installation due to the regulations, the economic climate, the know-how and technology available, and events occurring which may impact operations, like extreme weather or cyber-attacks. Changes in system climate factors, such as outdated equipment leading to the unavailability of spare parts, have been identified as relating to the “obsolescence” aspects of ageing mentioned in Section 1.2.

All these aspects should be linked together in the right way. A holistic approach enables safety management to be tailor-made to the specific situation. In this paper the model provides the background for understanding the holistic quality of major hazard accidents. Thus, corrosion, for example, is no longer seen as the purely physical phenomenon that the word corrosion implies, but rather as an emergent property of the ageing slice from the cake.

2.2. *Method of accident analysis*

Major hazard accident analysis by RIVM uses the investigation reports of the Major Hazard Control (MHC) group of the inspectorate of the Ministry of Social Affairs and Employment (SZW) (Kooi et al., 2020). The investigated accidents are from chemical companies that fall under the Seveso Directive (European Council 2012) and in a few cases under a Dutch regulation ARIE (2004) which is for installations with large quantities of hazardous substances but below the threshold for Seveso. Currently the database contains 326 LOC accidents occurring between 2004 and 2018. These accidents have been analysed in the Storybuilder^{TM} software and major hazard chemical accident model (Bellamy et al., 2007; Hale et al., 2007). The model uses a large number of categories within which data are collected including equipment types, type of industry, activity at time of the accident, consequences for victims, environment and plant damage information, dates, regulatory aspects and organisational characteristics such as age, size and types, and amounts of hazardous substances released. Central to the model is a framework for analysing the direct and underlying causes of accidents using a graphical bow-tie structure with technical, human and safety management failures. This framework is described in Bellamy (2015) and Bellamy et al. (2013).

The Storybuilder method requires analysts to plot the path of events taken from each accident investigation report through a graphical bow-tie model, a model that was chosen at the beginning of the Storybuilder development because a major aim was to use it to feed data into risk assessment. The bow-tie is a logical model which integrates cause-consequence models, typically a fault tree structure on the left side of the bowtie whose top event forms the centre of the bow-tie and is the initiating event for the event tree on the right hand side (Bellamy et al., 2007). The model in Storybuilder is constructed from safety barriers with their safety barrier failure modes. Some key aspects of the Storybuilder framework are as follows. In Storybuilder modelling the safety barrier is a physical entity (object, state, or condition) that acts as an obstacle in an accident path, like the material of construction of a pipe or the process conditions being within a safe operating window. Operating these barriers requires human or automated tasks - the barriers have to be provided, used, maintained and monitored, as described in Table 1. These tasks have to be managed and in the model this is represented as resourcing by management delivery systems which have been reduced to 8 fundamental types as shown in Table 2. These types were derived from the I-Risk project (Bellamy et al., 2000) mentioned in Section 1.2.

Every barrier is attached to the 4 possible barrier tasks, and 8 possible management delivery systems per barrier, as well as the safety management categories specified in the Seveso Directive Annex III for each barrier (see Fig. 3). When the barrier fails the underlying failures are required to be identified. Analysis rules state that for any safety barrier failure only one barrier task failure and up to 3 management delivery system failures can be selected. The analyst cannot make assumptions or guesses about what the failures were and can only use information from the investigation. Barrier successes were included where reported but underlying tasks and delivery systems are not described for these.

Selecting an accident in the model selects all the failure (and success) events in a story sequence from left to right in the model and is effectively a slice of the holistic cake. The analyst translates an investigation report into a series of (failure) events in the model, based on definitions of the model components. The process and definitions are described in chapter 3 of Kooi et al. (2020). The analyst asks: What went wrong? (safety barriers), how did it go wrong? (barrier tasks) and why did it go wrong? (management delivery systems). Once a number of accidents have been plotted in the model, selecting any event node in the Storybuilder bow-tie picks out all the other accident paths that pass through it. In this way a set of accidents can be selected which contain specified events in common.

Table 1
Description of safety barrier tasks.

Barrier Task	Description
Provide	The safety barrier (function) must be present and implemented, and its design and realisation must be such that it can provide the intended protection.
Use (operate)	Front line personnel must use/operate the barrier and in a correct way.
Maintain	Once implemented, safety barriers must continue to work, which may involve testing, inspection and maintenance tasks. They must not be undermined by changes.
Monitor (supervise)	This task is to ensure compliance with requirements for the provision, use and maintaining of the safety barrier (function).

Table 2
Description of management delivery systems for safety barrier tasks (providing, operating, maintaining and monitoring/supervising the safety barriers).

Management Delivery System	Description
Plans and procedures	Company regulations, work instructions, manuals, checklists, maintenance schedules, plans etc. adequately cover requirements for the safety barrier tasks.
Availability of personnel	Sufficient staff are available to perform the different safety barrier tasks.
Competence:	Staff have sufficient knowledge, experience and skills to perform the safety barrier tasks correctly.
Communication and collaboration	Mutual coordination, communicating about how the safety barrier tasks should be performed, informing each other if something does not go as planned or if technical disruptions or deviations were observed.
Motivation and awareness	Being aware of potential risks and acting proactively to ensure safety, safety awareness when carrying out safety barrier tasks, concentration/attention to the safety aspects of the task, following the rules.
Conflict resolution	Safety as a priority in undertaking safety barrier tasks, an adequate focus on safety at the organisational level, not subordinating the interests of safety to production, economic or other interests.
Ergonomics/Man-machine interface	The resources for doing the safety barrier tasks, which are at the interface between people and the safety barriers, are convenient and workable according to human factors principles, and design does not lead to incorrect actions, assessments or decisions.
Equipment and materials	The equipment and materials used in the life cycle of the installations for the safety barrier tasks are of suitable type/quality, instruments can perform their function and the right tools for the job are available.

In the early development of the model and database, there were no actual safety barriers, only a logical concept and building rules for translating an accident investigation report into safety barriers. The analyst made a decision on what to call the safety barrier and this changed over time according to the nature of other accidents plotted in the model. Barriers might be merged or split, and furthermore their definitions were increasingly required to be detailed. The structures were regularly reviewed. There are currently 41 safety measures clustered in 6 lines of defence, the measures having been derived from the analysis of the accidents on the basis of a set of rules rather than a model that was pre-defined. In this respect, the model has grown over time. Fig. 2 shows the bow-tie part of the model with the safety measures. Fig. 3 shows how it looks in the software with the accident paths (connecting lines) running through the event nodes. It gives an impression of all the aspects of a single safety barrier that are analysed in the model. Every event node provides a count of the number of accident paths going through it.

A selection was made of accidents that pass through an event node called “material degradation” which is in a category of scenarios that are the immediate cause of the centre event, loss of containment. To these events were added some additional cases of vibration which were also identified as ageing related. In total there were 83 accidents identified as relating to material degradation. The focus of the analysis is therefore physical ageing and specifically degradation of materials leading ultimately to LOC, the centre event in the model. While events on the right hand side of the centre event (C in Fig. 2) are of interest, no events were selected of failures in the mitigation of the effects of a release where ageing may have played a role, such as in firewater systems for example.

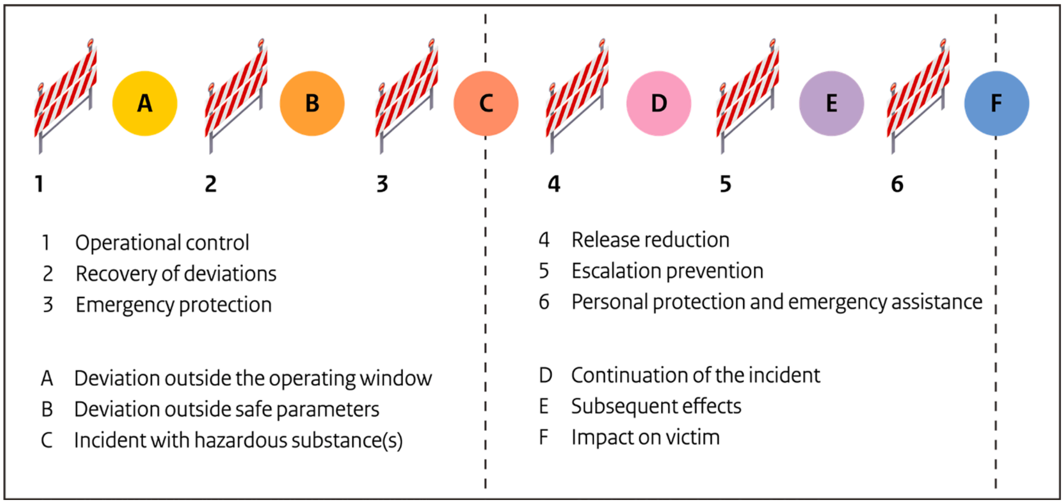

Fig. 2. Backbone of the Storybuilder bow-tie model showing lines of defence (represented by numbers) and the consequences of failures (represented by letters). From Kooi et al. (2020).

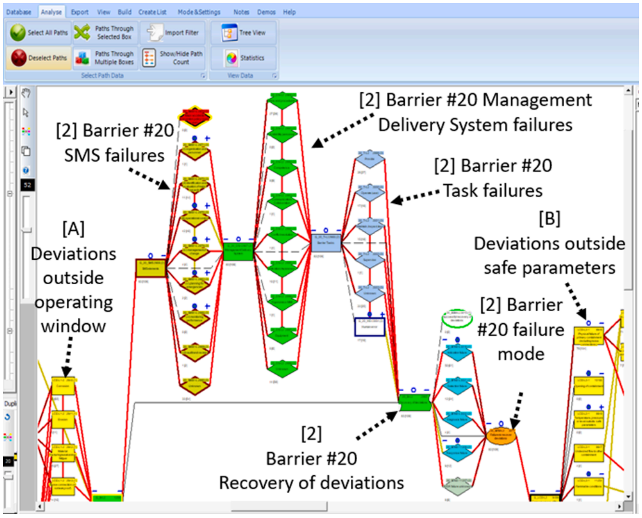

Fig. 3. Part of the model in Storybuilder showing a sample of events from the A – 2 - B segments indicated in the previous figure, elaborating on barrier #20 to show generic structure of barrier components in the model.

When considering the applicability and comprehensiveness of the model used here, it should be noted that it has been developed and revised over a number of years based on the 326 investigated major accidents in the Netherlands since 2004 (Kooi et al., 2020). Other separate analyses in Storybuilder which influenced the modelling included 64 major accidents in refineries across Europe from the MARS database (Bellamy et al., 2012), 975 loss of containment accidents investigated by the Health and Safety Executive in the UK (Lisbona et al., 2012) and an unpublished report of 86 overfilling accidents (Baksteen et al., 2007). In this respect there is confidence that the model would be able to accommodate any major accident scenario.

3. Results and discussion of the analysis of the material degradation accidents

3.1. *Analysis of the data set in Storybuilder*

The 83 material degradation accidents identified in Section 2.2 were from 2004 to 2016 inclusive (over 13 years, ranging from 2 to 13 accidents in any one year) and were 25.5% of all the LOC accidents in the total database (2004–2018). Ten of the accidents were MARS (major accident reporting system) reportable by virtue of the quantities released. MARS is the official reporting repository for submitting accident reports to the European Commission according to the criteria established in the Seveso III Directive. There were 45 victims (no deaths) resulting from 19 (23%) of the accidents of which 43 were on-site, including 4 permanent injuries. There were 2 off-site victims. 44 accidents (53%) resulted in damage to the installation and 8 (10%) caused environmental damage, mostly soil contamination, and one case of contaminated surface water.

The majority of the accidents were on upper tier Seveso sites, as shown in Table 3. Further investigations into the possible reasons for this identified such factors as: the criteria for investigation; the number and size of the installations in the different categories – upper tier sites have higher quantities of hazardous substances, are bigger, and there are more of them; and, ideas from the major hazard control inspectors - for example, upper tier sites are more complex technically and organisationally. In 2020 there were 407 Seveso sites, the number of upper and lower tier being 265 and 142 respectively (Ministry of Infrastructure and Water Management, 2021).

In this section, all 83 accidents were analysed together as the failure data patterns appeared similar between upper and lower tier.

Table 4 shows that for 25% of the accidents the age of the installation could be identified. 16% were older than 25 years. In the rest of the data set, so excluding these material degradation accidents, there were 243 accidents. 20% had known ages of which only 4% were older than 25 years.

Table 5 shows the hazards. Around half of the substances released were flammable (53%). Besides the potential for fire there were other health hazards, including 42% being toxic if inhaled, and 23% were potentially toxic to aquatic life. 13% of the accidents were hydrogen releases, 7% were ammonia, 6% hydrogen sulphide and 5% chlorine.

Most of the accidents occurred during normal operations (83%)

Table 3
Installation types with material degradation accidents.

Legal regime	Accidents	% Accidents
Seveso II	79	95%
Upper tier	70	84%
Lower tier	9	11%
ARIE[1]	4	5%

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[1] Dutch regulation requiring additional risk inventorisation and evaluation when over a certain threshold of dangerous substances. One accident is both ARIE and Seveso lower tier.

Table 4
Ages of the installations with material degradation accidents.

Age of installation	Accidents	% Accidents
New <=5 years	1	1%
Medium 5–25 years	7	8%
Old > 25 years	13	16%
Unknown	62	75%

Table 5
Hazard classification according to the European CLP Directive (EC, 2008) of the substances involved in the material degradation accidents.

Hazard category	Accidents	% Accidents
H220-231 Flammable	44	53%
H270: May cause or intensify fire; oxidizer	5	6%
H280: Contains gas under pressure; may explode if heated	1	1%
H300-399 Health hazards	55	66%
(e.g. H330-332 Toxic if inhaled)	(35)	(42%)
H400 & 411 Toxic to aquatic life	19	23%
Unknown	27	32%

compared to during commissioning/start-up after maintenance (10%) or during maintenance or shutdown (6%). Corrosion was the immediate cause in 53% of cases followed by 31% fatigue/embrittlement/creep, as shown in Table 6.

Fig. 4 shows that the main failing safety measures were in controlling the conditions that gave rise to degradation (48%), followed by the containment material (36%). Inadequate equipment connections (14%), such as poor bolt tightness or a damaged gasket, and failure in design (13%), such as inadequate supports, were also important. Sometimes more than one barrier failed so the percentages are not mutually exclusive. A breakdown of the failures for the top two causes is given in Fig. 5 and Fig. 6. Taken together, failure in controlling corrosive conditions (30%) and materials specification failure (20%) account for half of the ageing accidents. Material protection failure accounts for 11% and corrosion under insulation 6%.

As a result of failures in the first line of defence, the main deviation from the operating window was corrosion as shown in Fig. 7.

At this stage the deviations had been recoverable before LOC. However as Fig. 8 shows they were not recovered in 60% of accidents due to missing indications. This means there was no perceptible signal of the deviation, such as due to missing inspections or difficulties in conducting inspections such as when corrosion cannot be seen such as under insulation or is internal or buried, or equipment is difficult to access due to its location. In 14% of cases there was a signal but it was not detected and in 11% of cases the deviations were detected but not responded to. In 5% of accidents the deviation was detected but misdiagnosed.

The patterns of underlying causes for the top two barriers in the first line of defence and recovery of all deviations in the second line of defence are given in Table 7, Table 8, and Table 9. Most failures are occurring in (iii) operational control but failures in (ii) identification and evaluation of hazards, and (iv) management of change also play a role (Table 7).

With respect to management delivery systems (Table 8), failures in plans and procedures dominate, particularly in the recovery failures where 32% of all the accidents have procedure system failures.

Table 6
Immediate causes of loss of containment in the material degradation accidents (in 2 cases of vibrations there is overlap with other categories).

Immediate cause	Accidents	% Accidents
Corrosion	46	55%
Fatigue, embrittlement, creep, etc.	26	31%
Vibrations	5	6%
Erosion	2	2%
Material degradation, unknown type	6	7%

The delivery systems have failed to support the barrier tasks in a number of ways, not just through planning and provision of procedures, but also in delivering safety motivation and awareness of the risks, appropriate competences and the right equipment. Barrier tasks provide, operate, maintain and supervise the barriers themselves (Table 9). The more important task failures are in *providing* deviation recovery barriers (34%) and in *maintaining, inspecting and testing* the control of conditions that could lead to material degradation (25%). Failures in providing adequate containment material, or in maintaining it, together contribute to 34% of the accidents.

The third line of defence, emergency protection, was either inapplicable or unknown in 92% of accidents. For example, no emergency protection measures are in place between the failure of the corrosion inspection and the occurrence of the corrosion leak. There were a few cases (8%) of failure in protection, these being to prevent unwanted flows to other parts of the installation, to prevent auto-ignition or to protect against the negative impact of a deviating substance inside a containment.

Finally, Table 10 gives details of the mode of failure and the equipment that failed. Integrity failures or catastrophic ruptures occur in 64% of the accidents, but degraded connections occur in 26%. Pipework and pipelines are commonly affected.

3.2. *Applying the holistic model*

Every accident in Storybuilder has a narrative that can be considered from a holistic viewpoint. Fig. 9 gives an example of corrosion in a transfer pipe.

This example accident covers many concerns about the issues in managing ageing. It is an elaboration of a generic scenario, in this case *failure to maintain conditions with respect to preventing material degradation*. The deviation was not recovered before leaks occurred and there were no indications prior to the accident, such as through inspection, to enable these corrosive conditions to be identified. Analysis of accidents associated with ageing helps to elaborate on those scenarios.

Results shows that major chemical accidents caused by material degradation are typically a result of failure of several different interrelated "management factors". For example, damage of a pipe may be caused by corrosion. Corrosion may not have been noticed because no proper inspection is carried out, or perhaps this part of the installation is not identified as being susceptible to corrosion, or it may be noticed but is not properly repaired. Personnel may not have the right training, tools, or procedures for inspection and maintenance. Procedures may be incomplete, outdated or absent. In this respect, it is possible from the accident data to come up with some priority accident scenarios for considering the measures associated with preventing ageing accidents from material degradation leading to loss of containment:

- 48% of ageing scenarios are *failures in barrier functions for controlling operating conditions* (Fig. 4) particularly corrosive conditions (Fig. 5), and particularly due to procedural failures (16%) and in maintaining the adequacy of these conditions (25%) or in making sure the right conditions are being provided in the first place (Table 8 & Table 9).
- 36% of ageing scenarios are *inadequate containment material barriers* (Fig. 4), particularly in the material specifications (Fig. 6) and particularly due to failures in ensuring management deliver the right equipment (10%), and procedures (13%) in providing barrier (17%) and procedures for maintaining the correct specifications of the barrier (17%) (See Table 8 & Table 9).).
- 15% of ageing scenarios are *inadequate equipment connections* (Fig. 4), almost entirely associated with maintenance (11%).
- 60% of ageing scenarios are *recovery failures due to invisibility* (Fig. 8): no indication/unexpected degradation, 30% being related to indicators of corrosion.

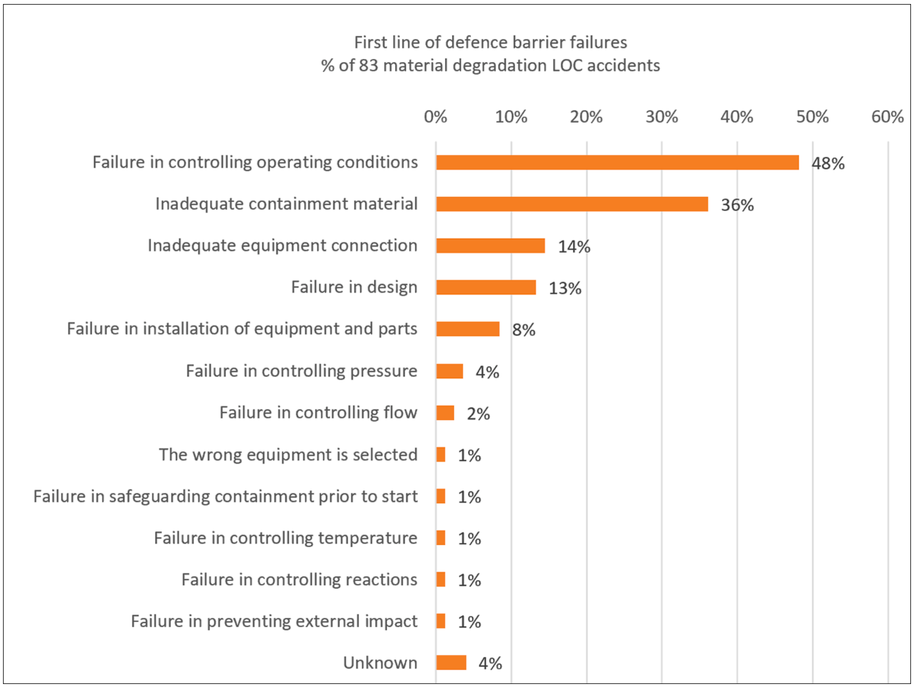

Fig. 4. First line of defence – Operational control failures in preventing material degradation.

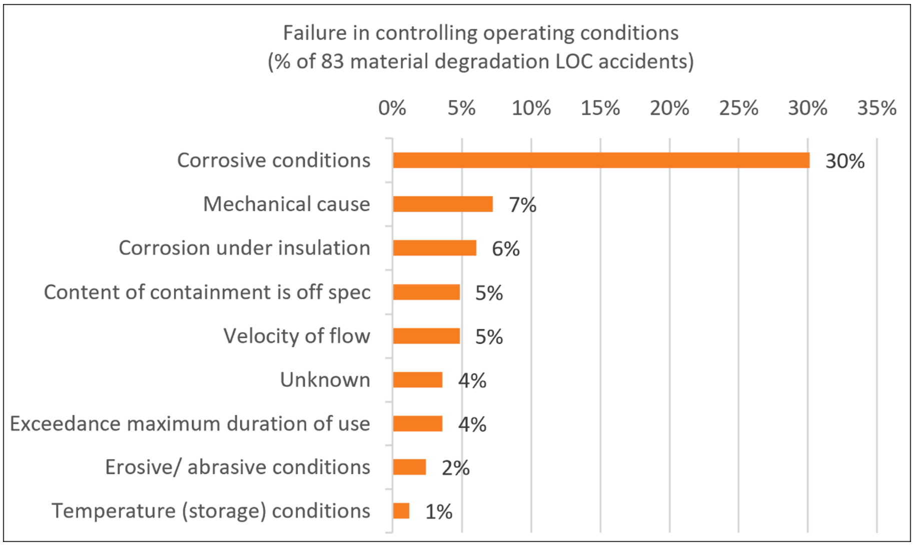

Fig. 5. Breakdown of failures in controlling operating conditions.

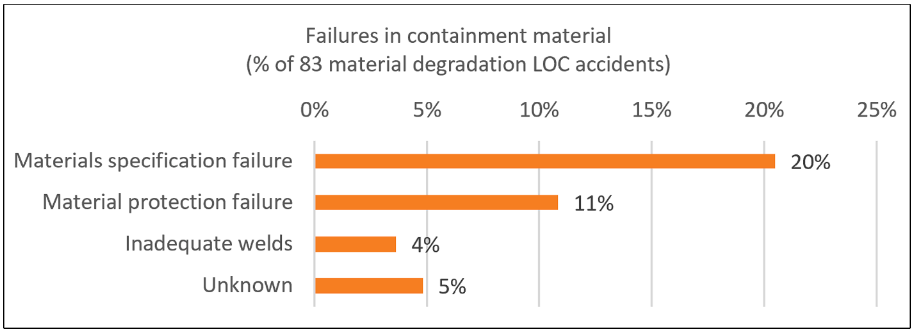

Fig. 6. Breakdown of failures in containment material.

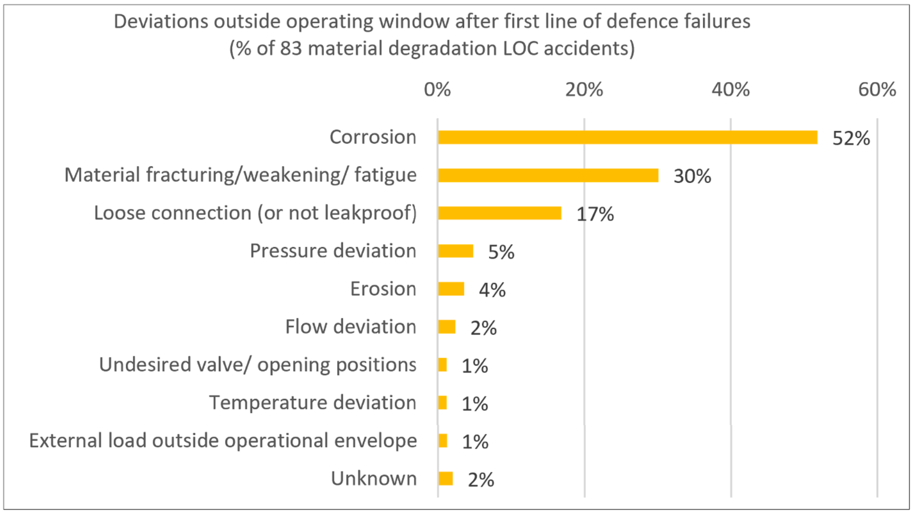

Fig. 7. Deviations arising from loss of operational control in the first line of defence.

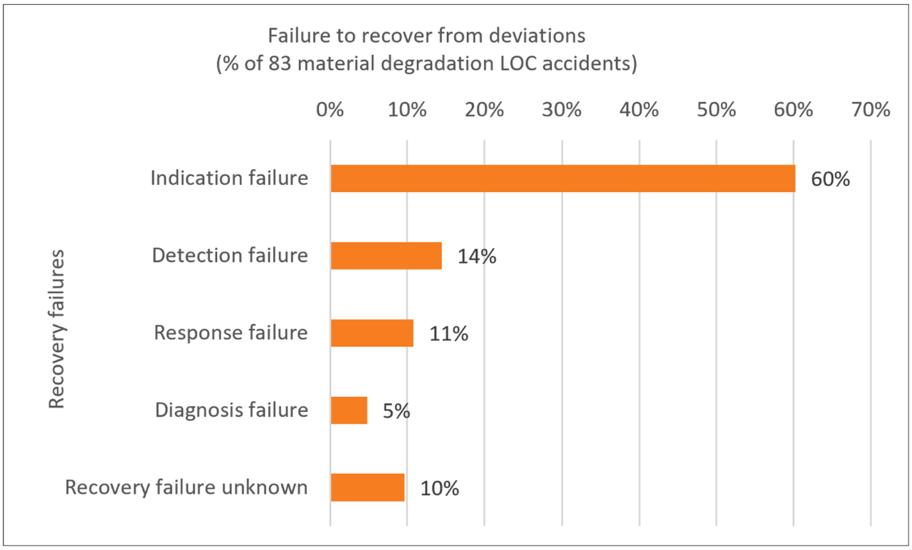

Fig. 8. Second line of defence failures: Deviation recovery failures.

Invisibility as mentioned here can arise because:

- The inspection procedure does not provide for an indication of a particular scenario, e.g.:
  - o Inspection carried out but the point of corrosion is very localised and is missed.
  - o No signal provided of unexpected damage to the protective lining or coating (such as due to poor design, increased production rate, damage during installation or maintenance).
  - o (Part of) a pipe is buried.
  - o Hidden by insulation.
  - o Unrecovered error/damage during maintenance (e.g. wrong bolt tension, damage to gasket, wrong equipment, which can be due to inadequacies in procedures, available equipment, or training).
- Inspections are not carried out or not carried out in time to recover from the material degradation.

3.3. *Comparison with results of regulatory inspections*

In Section 1.3, a summary was given of some of the main findings of the program of regulatory inspections. The accident data in Section 3 support the findings that maintenance is not working to prevent material degradation. Further analysis indicates that the percentage of accidents showing barrier task failures to *provide* barriers against ageing scenarios in the first line of defence (operational control), eliminating any double counting where multiple barrier failures were involved, was 37% of all ageing accidents, suggesting that ageing is not being accounted for in preventive barriers. The percentage of accidents showing *maintain* barrier failures across all the barriers in the first line of defence, eliminating any double counting where multiple barrier failures were involved, was 53%. At the level of the safety management system, as identified by the categories in the Seveso Directive (see example in Table 7), for the first line of defence: 24% of ageing accidents have failures in the (ii) identification and evaluation of the hazards; 45% in (iii) operational control; and 18% in (iv) management of change. For the second line of defence (deviation recovery), it is 13% for (ii) identification and evaluation of the hazards, 51% for (iii) operational control and 5% for (iv) management of change. This shows agreement with the inspection results that ageing is not being sufficiently elaborated in the various parts of the safety management system. Providing barriers against ageing and operations and maintenance management are particularly important here and indeed, as found by the inspections, a big problem for pipework.

Table 7

Safety Management System: Failures in managing the top two barrier failures in the 1st LOD and in managing recovery of all deviations in the 2nd LOD shown as % of the 83 accidents.

SMS Category (Seveso Directive Annex III)	Control of conditions failures	Control of containment material failures	Recovery failures
	1st LOD	1st LOD	2nd LOD
(i) organisation and personnel	1%	2%	1%
(ii) identification and evaluation of major hazards	11%	6%	13%
(iii) operational control	20%	12%	51%
(iv) management of change	5%	6%	5%
(v) planning for emergencies	0%	0%	2%
(vi) monitoring performance	0%	0%	0%
(vii) audit and review	0%	0%	1%
Unknown	16%	12%	40%

Table 8

Management delivery system failures: Failures in delivering adequate resources to the top two barrier failures in the 1st LOD and to recovery of all deviations arising from failures in the 2nd LOD shown as % of the 83 accidents.

Management delivery systems	Control of conditions failures	Control of containment material failures	Recovery failures
	1st LOD	1st LOD	2nd LOD
Plans and procedures	16%	13%	32%
Motivation/ Awareness	5%	4%	12%
Competence	5%	4%	10%
Equipment	5%	10%	7%
Communication/ Collaboration	1%	1%	1%
Conflict resolution	2%	0%	1%
Ergonomics/ Man-machine interface	1%	0%	1%
Availability of personnel	0%	0%	0%
Unknown	20%	11%	53%

Table 9

Barrier task failures: Failures in the barrier tasks for the top two barrier failures in the 1st LOD and for recovery of all deviations arising from failures in the 2nd LOD shown as % of the 83 accidents.

Barrier tasks	Control of conditions failures	Control of containment material failures	Recovery failures
	1st LOD	1st LOD	2nd LOD
Provide barrier	13%	17%	34%
Operate (use) barrier	2%	2%	20%
Maintain, inspect, test barrier	25%	17%	18%
Supervise barrier	1%	0%	1%
Unknown	6%	0%	26%

Table 10

Type of loss of containment and the equipment involved.

Nature of the loss of integrity	Number of accidents	Equipment involved (not mutually exclusive)
From a new hole (integrity failure) including failing welds.	49 (59%)	18 process pipework 13 provisions in/on equipment (of which 11 were valves) 9 long transfer pipelines (3 of which were underground) 7 short transfer pipelines 7 vessels in process installations 6 fixed storage tanks 5 connections or couplings 4 heat exchangers 3 gaskets or seals 3 pumps 3 (cooling) water system 2 distillation columns 1 flexible hose 1 gas cylinder 1 furnace 1 tank car 1 ship/barge
Through a failing or loose connection with another installation component	22 (26%)	15 gaskets and seals 12 connections and couplings 7 provisions in/on equipment (such as valves and instrumentation) 10 with vessels in process installations 9 other equipment in process installations 4 mobile tanks and packaging 4 transfer piping and pumps 2 fixed storage tanks 1 vehicle/train/ship 1 flare system
From an opening that is normally closed	5 (6%)	3 provisions in/on equipment 2 transfer pipes/pump 2 blowoff/blowdown systems 2 chimneys 1 connection 1 process pipework 1 incinerator
Catastrophic rupture	4 (5%)	3 fixed process pipework 1 separator
From a normally opened opening	4 (5%)	2 cool water systems 1 other equipment in process installations 1 fixed storage tanks 1 vessels in process installations 1 seal

4. Solutions

4.1. *Focus on measures for preventing unanticipated ageing scenarios*

How can the problems identified in inspection and accident data be addressed? There is not only a need to identify the safety critical assets associated with ageing but also to understand how the barriers against ageing-related failure of the containment integrity can be properly managed for these assets. In Section 1.2 we introduced the concept of scenarios which can be used for demonstrating that all the necessary measures are in place. Taking a lead from the accident data, the scenarios which need to be considered in terms of the technical and organisational measures, and which could be elaborated in the context of the model in Section 2.1 are underlying causes of: corrosion, loading conditions which result in fatigue, loosened or leaking connections, vibration and erosion. These comprise the following:

(1) MAJOR HAZARDS
Natural gas condensate containing benzene, an extremely flammable and toxic hazard and also environmentally hazardous.

(2) HAZARD EVALUATION (SCENARIOS, RISKS)
An unidentified LOC scenario occurred in a transfer pipe due to localised corrosion resulting from settling of water mixed with salt AND an unexpected pressure increase below the triggering pressure of the relief valve.

(3) CONTROL OF SCENARIO
The pipe wasn't maintained so it went on corroding. Due to an accidentally closed valve, pressure increased and caused leakages at points of corrosion. The relief valve was designed for a higher pressure so wasn't triggered.

(4) HUMAN-TECHNICAL INTERFACE
There was no information on what was happening in the pipe or to indicate that the valve to the tank was closed when it shouldn't be.

(5) FRONT LINE TASKS
No inspection or maintenance was carried out on a pipe carrying condensate to the tank. Valve for the tank was accidentally closed during maintenance work on an electrical cabinet, which was either not recovered in any checks or checks had not taken place.

(6) SAFETY MANAGEMENT SYSTEM
The pipe that corroded was not documented as being part of an inspection regime. The change was not included in any management of change regime.There was no hazard evaluation of the change so the corrosion scenario and its implications were not identified. There is no mention of any assessment of the risks associated with the associated electrical work or control over the maintenance work with respect to interactions with other parts of the system.

(7) SAFETY CULTURE, RESILIENCE
Different aspects of the organisational system had become disconnected so there was no awareness that the pipe was not resilient with respect to the gradual changes in the technical conditions

(8) SYSTEM CLIMATE
A supplier pumps natural gas condensate via a pipe to the company after a transition from crude and from a higher to a lower flow rate.
The company was classified as an upper tier Seveso site.

Fig. 9. Example of a Dutch material degradation accident from 2010, portrayed as a slice of the holistic model.

- *Operating conditions with respect to material degradation:* This is about management of human and technical measures for preventing deviations in conditions which could result in any of these generic ageing scenarios or accelerate their occurrence. These scenarios need to consider identification of the risks of deviations and prevention of deviations such as the occurrence of corrosive conditions, failure to protect against corrosion, as well as prevention of mechanical loadings such as incorrect mountings, or vibrations. Temperature, pressure and flow conditions may also have an effect. Failures in procedures for inspection and maintenance are important, but awareness, competence and provision of equipment are also considerations. Failure to provide for the protection against deviating conditions, such as in the case of increased flow due to increased production pressures can be another source of underlying failure. Change scenarios, including gradual changes, need to be considered in terms of deviations in operating conditions that could accelerate ageing or accumulate over time.

- *Material of the containment*: Management of the provision and maintenance of the appropriate containment materials, given the conditions inside and outside the containment, is paramount for preventing corrosion and material weakening. The supply of appropriate equipment and the procedures for inspections and maintenance are important. Scenarios with failures in the process of assurance of correct materials for equipment carrying hazardous substance need to be considered. Leaks can also be a sign of incorrect materials. How are these scenarios dealt with?

- *Inadequate equipment connections* can particularly be a problem associated with task failures in maintaining the barrier, and these can be associated with inadequate procedures and equipment resources. For example incorrect bolt tightness or incorrect mounting of equipment. The result can be such as loose connections or material fracturing over time.

- *Indications and detections* of ageing related deviations with respect to the direct causes of integrity failure. This is a second line of defence and refers to detecting deviations from normal conditions, like corrosion or small leaks. It appears that many of these events are effectively invisible when they occur (like corrosion under insulation) suggesting an early warning system with respect to deviations from normal in terms of better monitoring of conditions, containment and other equipment materials, and connections between different pieces of equipment, as well as supervision of maintenance activities associated with critical assets.

Schmitz et al. (2020) have also come up with the idea of early warning systems, in particular linked to unforeseen mechanical failure scenarios, particularly for preventive barriers for which early warnings can be derived. They use actual examples from an ammonia plant and determined that there was missing information and additional scenarios to be considered. They further suggest that alarms could also be generated at a higher level of aggregation – such as at the level of management delivery systems.

4.2. Smart solutions

The solutions suggested in Section 4.1 address a preventive approach, particularly with respect to the provision, operation and maintenance of barriers against loss of containment of hazardous materials. In the last decade, there has been a significant increase in the level of attention for maintenance innovation, in industry in general and in the process industry in particular. One reason for this greater focus on maintenance innovation may be the availability of new technology, but another reason is certainly a greater need for maintenance. Throughout the Western world, industrial assets are ageing, which leads to higher maintenance requirements. Most companies will continue using their existing sites by means of lifetime extension programmes, modernisation projects, and dedicated replacements. As they are doing so, the need for a broader perspective on these activities becomes clearer. In response, companies are shifting from maintenance to asset management (Mainnovation, 2018). Where preventive and corrective maintenance are primarily aimed at maintaining the asset for its lifespan, asset management is all about extending, renewing, and terminating the life of assets. This shift also entails a broader, holistic view on assets and how they are managed. A holistic perspective firstly means that the entire life cycle of the asset is taken into account, whereas traditionally a more traditional maintenance function would typically have a horizon of zero to three years.

Secondly, such a holistic perspective also implies broadening the scope of maintenance and asset management. As our holistic model in Fig. 1 suggests, there are many non-technical aspects that are relevant for maintenance. A Delphi study among 50 Dutch experts in maintenance yielded a top-14 of maintenance innovations, both technical and non-technical, which were all seen as interrelated, as shown in the causal model in Fig. 10 (Akkermans et al., 2016). At the core of Fig. 10 is condition and risk-based maintenance (Olde Keijzer et al., 2017; Tiddens et al., 2018, 2022). This means maintenance conducted based on the known condition of the asset. This is still quite uncommon in industry, and limited to perhaps a tenth of all maintenance activities (Grubic, Redding, Baines, & Julien, 2011; PWC & Mainnovation, 2018). The bulk of maintenance is still corrective or planned. With corrective maintenance, obviously the condition of the asset is known: it has failed. However, in most cases such run-to-failure is not an intended policy, but simply maintenance done too late: assets that fail unexpectedly lead to unforeseen behaviour of installations, to safety risks, pollution, loss of production and expensive corrective activities under time pressure. If corrective maintenance is maintenance done too late, then planned maintenance is often maintenance done too early. Taking safety margins based on the average asset, not the specific asset under consideration, maintenance work is usually done some time before the asset's condition would really require it. This leads to more frequent work on installations, which increases safety risks and of course again costs. So, condition-based maintenance is clearly a superior maintenance policy (Feng & Shanthikumar, 2018; Jardine et al., 2006) but it requires that the condition of the asset is indeed known, and that from this known condition assessments can be made on what to do and when. Being able to do so requires extensive innovations of both a technical and organisational nature, as Fig. 10 shows.

On the technical side, innovations are needed to collect more condition-related data and to analyse that better to make better decisions regarding maintenance actions, as well as more technological support to execute these actions. On the organisational side, innovations are needed to create the economic, social and cognitive conditions that make this new way of working an attractive one for organisations and the humans in them. Regarding the technical aspects, smart maintenance is best visualised as a cyclical process, as Akkermans and van Kempen (2016) suggest in Fig. 11.

If we follow this cycle clockwise and starting at A, we immediately notice the crucial importance of Internet of Things (IoT)-enabled sensors, which collect condition-related data in the first place. As Mainnovation (2018) points out, such measurements have become quite common in the chemical process industry in recent years. The use of drones and robots for inspections also fits in this step. These data need to be combined in steps B and C with other data sources, such as the SCADA and DCS data that are generated anyway for operational process control. Big-data analytics, using AI and statistics, are used in steps D and E to arrive in step F at a sound assessment of the current condition of the asset and its maintenance needs now and in the future (Uit het Broek et al., 2020, 2021). The right-hand side of this cycle focuses more on maintenance execution. A digital maintenance workflow in L is an obvious, but still often lacking, process innovation, just as using Augmented and Virtual Reality (A/VR) techniques in maintenance problem solving and execution is in step M. Robots and drones will increasingly replace humans here, leading to greater safety and productivity increases.

At the same time, smart asset management is perhaps even more

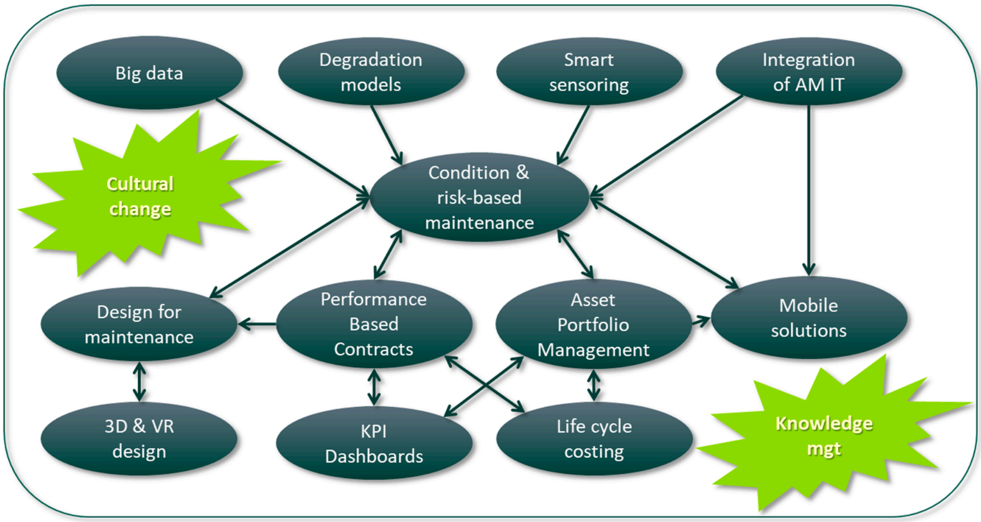

Fig. 10. Causal links between maintenance innovation priorities, from Akkermans et al. (2016).

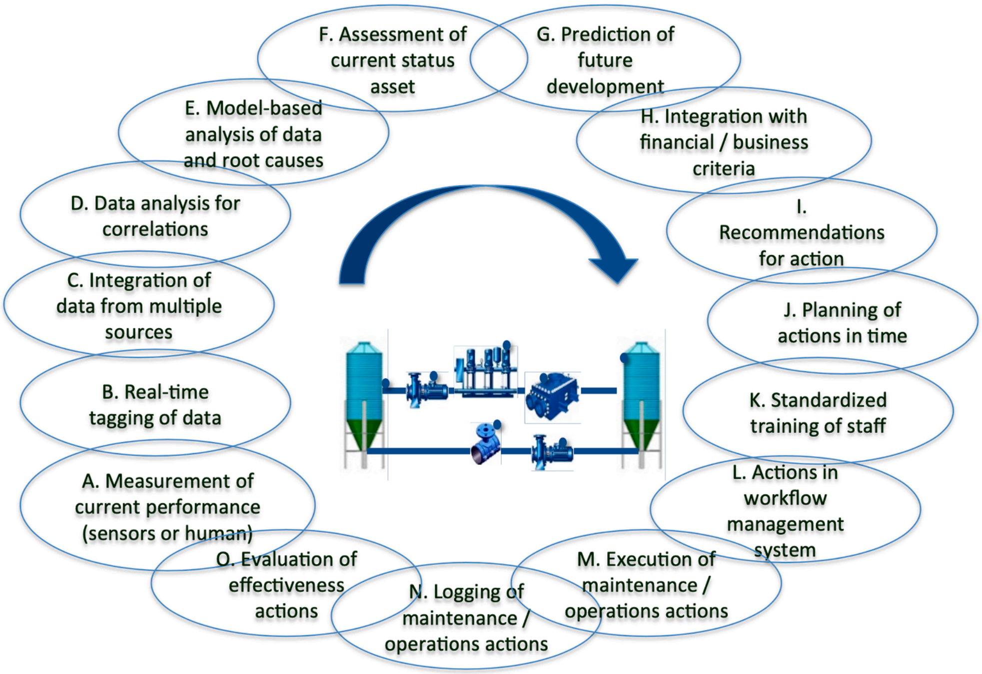

Fig. 11. The smart maintenance cycle, from Akkermans and van Kempen (2016).

about social than about technical innovations. Bokrantz et al. (2019) define Smart Maintenance as ‘an organizational design for managing maintenance of manufacturing plants in environments with pervasive digital technologies.’ For them, data-driven decision-making is only one of the four key elements of smart maintenance, while human capital resources - people capable of working in these digitized, fact-based environments - are just as important. This is also suggested by step K, the standardised training of staff, in Fig. 11. Indeed, Akkermans et al. (2016) also see knowledge management as one of the key maintenance innovation areas. Internal and external integration of the maintenance function are the two other essential elements of smart maintenance, according to Bokrantz et al. (2019).

Integration, internal just as well as external, asks for innovation in economics and business areas as well. Steps H, I and J of the smart maintenance cycle in Fig. 11 concern economic decisions that take technical, safety and organisational factors into account. From the 2016 Delphi study, innovation areas such as asset portfolio management, life cycle costing, performance-based contracts and performance dashboards are all needed here to assure that a holistic perspective is applied to maintenance decisions. Taken together, these will incentivise humans to make data-driven decisions, leading to better performance and higher safety at the same time.

The organisational change implications of all this are significant. Organisations that move from a reactive, short-term and locally oriented view on maintenance work need to move to a proactive, long-term and holistic view on asset management. That is no less than a major culture change, at the operational and managerial level, especially in the context of major hazards. The literature on ‘unsafe acts’ has taught us that when major disasters occur, it is usually a very unfortunate combination of several fairly unlikely events or situations that turn out to happen at the same time (e.g. Reason 1990, 2008). In the terminology of Taleb (2007), these are black swan events, which are so unlikely that they cannot be foreseen. However, most accidents at chemical sites are better classified as grey swans: they are still very unlikely events that happen through a fluke combination of intrinsically fairly unlikely occurrences, but similar events have happened at some time in the past, in the same organisation or in a similar one. Explicitly monitoring and controlling several hundreds or even thousands of variables is a wise step towards foreseeing and tackling such grey swans more effectively (Akkermans and van Wassenhove, 2013). This may help to achieve the situational awareness that is required in these complex dynamic systems (Endsley, 1995). However, only technically signalling that a situation may be degrading is not enough. Management also needs to have the awareness that action needs to be taken sooner rather than later. As Akkermans and van Wassenhove (2018) suggest, such managerial preparedness tends to be present shortly after a major calamity has occurred, but it is also inclined to wane over the years, when things have been going well for such a long time, as disasters happen rarely. Organisational forgetting (de Holan and Phillips, 2004) is another form of ageing that we do not consider directly here, but that certainly has an impact on accidents, even in digitized environments. How to accomplish a cultural change towards structural managerial preparedness, to be on the lookout for grey swan events, remains a major innovation challenge, next to all the others.

5. Conclusions

As ageing assets demand increasing attention because of an increasing proportion reaching the end of their working lifetimes, solutions are required in dealing with (i) prevention of safety barrier failures that lead to (accelerated) material degradation, and (ii) the maintenance regime and its management. Of particular concern in this paper are major hazard installations where a loss of containment caused by physical ageing can cause serious harm to people and to the environment, a problem that is addressed by the European Seveso Directive.

The greater need for maintenance, coupled with new technology, creates an interest in smart maintenance, with maintenance shifting from reactive fixing of failed components to asset management which takes a proactive and holistic approach to maintenance and which includes technological advances. A holistic approach, as described in the paper, encompasses the technical, human and organisational aspects of a system as well as the conditions within which it operates. Ageing phenomena in major hazard chemical installations, and more specifically material degradation as dealt with in this paper, are complex. Interacting underlying factors in different layers of complexity give rise to unexpected deviations that are not recovered, primarily because they are unanticipated and invisible, and so ultimately lead to loss of containment. These deviations fall into dominant categories of barrier failures, management failures, and front-line human task failures. From analysing 83 material ageing loss of containment accidents that occurred on Dutch Seveso sites, it can be concluded that the dominant direct causes were corrosion (55%) and fatigue, creep or embrittlement (31%). Deviation recovery failures were predominantly the result of the invisibility of signals that something was wrong (60% of accidents). There are multiple interacting factors which need to be managed, not just the physical nature of the assets but also the human, organisational and economic aspects. For example, requirements include knowledge about the ageing phenomena and the new technology, cultural changes in shifting from reactive maintenance to condition monitoring, and related investment decisions for the ageing asset.

There are different types of ageing phenomena, which are defined in the paper. Ageing-specific failure scenarios where material degradation occurs, which is the main theme here, connect to the related parts of the holistic system from which they emerge. In this respect corrosion is not just a physical phenomenon occurring with materials but an emergent property of a sociotechnical system. Failing to control deviating process conditions (48% of accidents), or not providing the right materials, or the correct installation of equipment, and then failing to recover these deviations, are significant in the emergence of corrosion. The same is true of other material degradation phenomena. At the front-line level, problems can primarily be identified as: planning and procedural failures, failures in the provision of the barrier itself, in particular in the recovery phase, and failures in maintenance and inspection. The problems are being identified in regulatory inspections, with attempts to preempt them escalating into a loss of containment by giving feedback on missing management components. These include the need for identification of safety critical ageing-sensitive equipment or having an appropriate maintenance policy for ageing equipment, for example. The use of some more detailed and focused scenarios associated with the unanticipated failures caused by negative changes over time (material degradation) have been outlined.

Finally it is concluded that the future of asset management ultimately requires a shift in maintenance philosophy from reactive maintenance to smart solutions. These solutions include innovations such as the Internet of Things (IoT), the use of drones and robots in inspection, big data analytics and Augmented and Virtual Reality (A/VR). However, organisational and economic aspects also play a crucial role here in incentivising data-driven decisions. Organisational and cultural change therefore underpin the future approach to handling the material changes associated with ageing.

Future work will address the issues associated with the practical implementation of the overall approach.

CRediT authorship contribution statement

Rikkert J. Hansler: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Linda J. Bellamy:** Writing – review & editing, Conceptualization, Investigation, Methodology, Writing – original draft. **Henk A. Akkermans:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Terminology

Some key terms as used in this paper are defined here.

Barrier	See ‘safety barrier’.
Barrier task	A barrier task is one component of the safety barrier control cycle. The Storybuilder model identifies four tasks: (i) provide, (ii) use, (iii) maintain and (iv) monitor (supervise) the barrier. Together, the four tasks, when properly carried out, ensure that the barrier’s intended safety function is achieved.
Bow-tie	A logical model which integrates cause-consequence models, typically a fault tree structure on the left side of the bowtie whose top event forms the centre of the bow-tie and is the initiating event for the event tree on the right hand side. In the Storybuilder bow-tie the centre event is a loss of control event which releases the agent bearing the hazard. In the model described in the paper the centre event is a loss of containment of a chemical substance with toxic, fire or explosive properties and which could lead to a major accident.
Holistic safety model	A holistic approach to safety considers safety from the multiple aspects of a system involved in the control of the risks (technological, human, organisational, regulatory, economic, social etc.) and the interrelatedness of these aspects. It considers that these work together as a whole such that one aspect can have links to other aspects. Interrelationships may be linear causal ones between one part and another e.g. breakdown due to a failed component. However, there can also be complex interactions of a number of parts which generate collective properties, also called emergent properties, with potentially unexpected results e.g. corrosion emerging unexpectedly from a push for increased production combined with a knowledge drain over the years. In an approach to safety which strives for zero accidents, an holistic approach would be desirable in order to address all the parts and their interactions. In this paper a holistic model is presented as a series of concentric layers of control and influence on safety, with the idea that there are interactions between the layers. The central parts define the subject matter, in this case loss of containment of major hazard substances, and the outer layer defines the boundary of the factors that are considered, in this case the system climate within which a major hazard company operates.
Line of defence	A functionally coherent group of safety barriers. Multiple lines of defence could be deployed such that if one line of defence fails another comes into play, as modelled in the Storybuilder major hazard model. Lines of defence can be named to reflect their objective or means of obtaining their objective, such as ‘operational control’ or ‘release reduction’.
Major accident	An uncontrolled release (loss of containment) of a chemical agent in the course of the operation of an establishment covered by the Seveso Directive (EU Council, 2012). Included in the Storybuilder database are a few cases of accidents from establishments which fall below the threshold definition for Seveso establishments but which have sufficient quantities of dangerous substances to potentially cause serious harm to human health. These come under the Dutch regulation ARIE (2004). For the purpose of simplicity, all the accidents in the major hazard Storybuilder database are referred to as major accidents.
Major hazard	A property of an agent which if released in an uncontrolled way could result in a major accident, In this paper the major hazard properties are toxicity, fire and explosion.
Management delivery system	In the Storybuilder model, eight management delivery systems are identified which each deliver a group of resources, controls and criteria to barrier tasks for each safety barrier such that the barrier tasks can be adequately performed to keep the safety barriers functioning. These eight systems, which were identified in an earlier study (Bellamy et al., 2000), are: plans and procedures; availability of personnel; competence, communication and

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	collaboration; motivation and awareness; conflict resolution; ergonomics/man–machine interface; equipment and materials. Accident investigation reports tend to only describe failures in the outputs of the management system, e,g, the inadequacy of procedures, rather than identifying the underlying failures in the management system itself which resulted in the procedures being inadequate. This is why this approach of only identifying failed system outputs was adopted. In principle all eight systems should be delivering to each barrier task and in an accident some of these fail. To assist the analyst, the number of possible management delivery system failures identified per accident per safety barrier was restricted to a maximum of three key failures. Unknown delivery system failures were not infrequent.
MARS	The official reporting repository for submitting accident reports to the European Commission.
Safety barrier	Barriers are obstacles in the accident path that are intended to prevent accidents 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 major hazard model comprises six groups of barriers (see 'line of defence'), three of which are situated to the left of the 'bow-tie' centre event (preventive barriers) and three to the right (mitigating barriers).
Scenario	A temporal sequence of failure events resulting in an accident with specific consequences, which can be connected by a line through the Storybuilder bow-tie. When a group of scenarios all pass through a common event, they can be given the name of that event e.g. inadequate containment material scenarios, corrosion scenarios, procedure delivery failure scenarios. In this paper the scenario begins with the management, task and barrier failures in the first line of defence, continues through all the lines of defence, and ends with the final consequences such as injuries, equipment and environmental damage and costs. Each event, or the whole scenario, may also be associated with further details of description such as whether there was also a breach of the law, what the ongoing activity was when the loss of containment occurred, or how old the installation was in which the scenario occurred.
Sociotechnical	Referring to both the social and technical aspects of an organisation and the relationship between them. This relationship is about humans and technology interacting within complex social structures and which cannot be considered at just one level (e.g. just at the front line) in the structure. The idea is that the sociotechnical system should be considered as a whole and in this respect the term is closely related to 'holistic' (see 'holistic model').
Storybuilder	A model and software tool developed for the analysis of accidents. The major hazard loss of containment model described in this paper is one of a number of models developed for different types of accidents. Each model has a 'bow-tie' structure based around a central loss of control event.

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