A study of maintenance-related major accident cases in the 21st century

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Abstract

This paper is based on a review of 183 detailed, major accident investigation and analysis reports related to the handling, processing and storage of hydrocarbons and hazardous chemicals over a decade from 2000 to 2011. The reports cover technical, human and organizational factors. In this paper, the Work and Accident Process (WAP) classification scheme is applied to the accident reports with the intention of investigating to what extent maintenance has been a cause of major accidents and what maintenance-related causes have been the most frequent.

The main objectives are: (1) To present more current overall statistics of maintenance-related major accidents, (2) To investigate the trend of maintenance-related major accidents over time, and (3) To investigate which maintenance-related major accident causes are the most frequent, requiring the most attention in the drive for improvement.

The paper presents statistical analysis and interpretation of maintenance-related major accidents' moving averages as well as data related to the types of facility, hazardous substances, major accidents and causes. This is based on a thorough review of accident investigation reports.

It is found that out of 183 major accidents in the US and Europe, maintenance was linked to 80 (44%) and that the accident trend is decreasing. The results also show that "Lack of barrier maintenance" (50%), "Deficient design, organization and resource management" (85%) and "Deficient planning/scheduling/fault diagnosis" (69%) are the most frequent causes in terms of the active accident process, the latent accident process and the work process respectively.

Keywords: Maintenance, Major accident, Statistics, Hydrocarbon, Chemical, Process

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1. Introduction

The handling, processing and storage of hydrocarbons and hazardous chemicals by industries whether small or large scale, inherently implies a potential for major accidents. Maintenance can keep the integrity of safety barriers and thus contribute to the prevention of major accidents. On the contrary, it can also be a cause of the major accidents themselves through insufficiency, incorrectness, new hazard inducement or being an initiating event for an accident scenario (Okoh and Haugen, 2013a,b).

Several investigations reveal that 30-40% of all accidents and precursor events in the chemical process industry are maintenance related. The UK's Health and Safety Executive linked maintenance to 30% of all accidents (a mixture of major accidents, occupational accidents and serious incidents) in the chemical process industry between 1982 and 1985 (HSE, 1987; Smith and Harris, 1992). As reported by Hale et al. (1998), out of 30 to 40% of serious accidents in the chemical process industry, 17% occurred during preparation for maintenance, 76% during maintenance itself and 7% during or soon after handback to production, whereas at least 8% of the chemical process accidents occurred in other phases (start-up,shutdown or normal operations) due to technical failures influenced by inadequate maintenance. In the same reference by Hale et al. (1998), Koehorst's report of 1989 based on the analysis of accidents in FACTS database (formerly of TNO, The Netherlands) indicates that 38.5% of accidents involving chemical releases were linked to maintenance. Furthermore, as cited by Hale et al. (1998), the 1991 report of Hurst et al. links 38.7% of 900 accidents associated with piping failures in the chemical industry to maintenance. In the hydrocarbon industry reports, there are also some statistics showing maintenance contribution. A report from Australia indicates that 33% of hydrocarbon topside gas releases between 1985 and 1988 in Australia were linked to maintenance (NOPSA, 2008). A similar study of gas releases in the Norwegian offshore industry shows that over 65% of major hydrocarbon leaks on the Norwegian sector of the North Sea were linked to maintenance (Vinnem et al., 2007). Furthermore, a study of 242 accidents in relation to storage tanks in both industries between 1960 and 2003 reveals that about 30% of such accidents were caused by human errors including poor operation and maintenance (Chang and Lin, 2006).

Most of the aforementioned statistics are about 25 years old. In addition, the most recent statistics do not cover all equipment, being limited to storage tanks only. The data in this paper are recent and cover all types of equipment. The objectives of this paper are: (1) To present more current overall statistics of maintenance-related major accidents, (2) To

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investigate what the accident trend has been over the period 2000-2011, and (3) to determine which causes are the most frequent, requiring the most preventive efforts. To this end, the Work and Accident Process (WAP) classification scheme (Okoh and Haugen, 2013a) will be applied to 183 major accident cases consisting of 63 from the U.S. Chemical Safety Board (CSB) reports (U.S. Chemical Safety Board, 2013) and 120 from the BARPI's ARIA database (Bureau for Analysis of Industrial Risks and Pollution, 2013). The accident reports cover technical, human and organizational factors associated with the handling, processing and storage of hydrocarbons and hazardous chemicals in the process industries. Many of the accident reports also point to other causes than just maintenance. However, our intention in this paper is to focus on only the maintenance-related causes.

The rest of the paper is structured as follows. The paper will discuss the concept of major accident and present statistical analysis and interpretation of maintenance-related major accidents trend as well as data and interpretations related to the types of incident facility, hazardous substances, major accidents, causes and combination of causes. This will be followed by discussion and recommendations, and finally, concluding remarks will be presented.

The study is carried out by both authors independently and with iterative scrutiny. The Work and Accident Process (WAP) scheme is applied after having sorted the major accidents from the occupational accidents and identified the maintenance-related major accidents among the overall major accidents. The WAP scheme has defined accident causation categories. Each accident report has been revised and relevant causation categories were identified. Based on this, we could identify which causes and combination of causes occurred most. The study is also applied in relation to the chosen definition of a major accident. The usability and suitability of WAP had been verified in the previous paper (Okoh and Haugen, 2013a), being comprehensive, complete and finely categorized to address the peculiar challenges of industries (Okoh and Haugen, 2013a). Besides, the accident investigation reports which are the source of this study, are detailed and comprehensive.

Several significant contributions from researches related to major accidents have been recorded in the chemical process industry. These include the works of Kidam and Hurme (Kidam and Hurme, 2013), Cheng et al. (Cheng et al., 2013) and Fabiano and Curr*ò* (Fabiano and Currò, 2012).

2. Various views on major accident in relation to the process industry

There is no conventionally accepted definition of the term "major accident" across authorities linked to the process industry. The Norwegian Petroleum Safety Authority (PSA) (PSA, 2010), the European Commission (in relation to Seveso II directive) (EC, 2005) and the UK government (in relation to the Control of Major Accident Hazards regulations) (UK, 1999) have quite similar definitions for a major accident, which can be summarized as follows: An acute/adverse event such as emission/discharge/release, fire or explosion resulting in a serious loss with regards to human life/health, the environment and material assets.

The International Association of Oil and Gas Producers - OGP (OGP, 2008) and the Commonwealth of Australia (Commonwealth of Australia, 2009) also have similar definitions for a major accident, which can be summarized as follows: Events connected with an installation having the potential to cause multiple fatality/serious damage inside or away from the facility.

The definitions of a major accident by the UK's Health and Safety Executive (HSE) (HSE, 1992) and the US Occupational Safety and Health Administration (OSHA)/US Environmental Protection Agency (USEPA) (USEPA-OSHA, 1996) also have expressions that imply the potential for serious loss and that the effects may be felt inside or outside the facility. Similarly, the US Department of Energy (DOE) (DOE, 2004) defines an incident as "an unplanned event that may or may not result in injuries and/or loss" and an accident/accident event sequence as "an unplanned event or sequence of events that has an undesirable consequence."

We have chosen to include also events with the potential to cause large consequences in our definition. The benefit is that the database is extended significantly. This introduces some uncertainty since there may be differences in causes of events involving losses and events that could have involved losses, but this is considered to be a limited problem. The consequences are usually defined by more or less arbitrary factors not connected to the causes at all, such as whether an ignition source is present at the time of a combustible gas release. Hence, a major accident as applied in this paper is "an unexpected event that causes or has the potential to cause serious consequences such as several serious casualties, extensive environmental or asset damage, with immediate or delayed effects experienced, within or outside the incident facility" (Okoh and Haugen, 2013a).

The term "process accident" is also often used with more or less the same meaning as the term "major accident" in the process industries. Accidents related to modification and maintenance are some of the types of process accidents that occur. Modification-related accidents are connected with the changing of the required function of an item to a new required function, whereas maintenance-related accidents are connected with an item being retained in or restored to a state in which it can perform it's original required function (EN 13306, 2010).

3. Overall statistics

According to the U.S. Chemical Safety Board (2013), from the year 2000 to 2011 the US experienced 74 major accidents in the process industry, 64 of which investigations were completed at the time of preparing this paper. Out of the 64 major accidents, 34 (i.e. 53%)are maintenance-related (see Table 1).

Based on information from the Bureau for Analysis of Industrial Risks and Pollution (2013), from the year 2000 to 2011, 120 major accidents occurred in Europe which were completely investigated. Out of the 120 major accidents, 46 (i.e. 38%) are maintenance related (see Table 1).

Table 1: Geographical locations of maintenance-related major accidents

Year	USA	Moving Average	Europe	Moving Average	USA & Europe	Moving Average
2000	0		7		7	
2001	3		3		6	
2002	4	2.3	5	5.0	9	7.3
2003	6	4.3	6	4.7	12	9.0
2004	4	4.7	5	5.3	9	10.0
2005	2	4.0	6	5.7	8	9.7
2006	2	2.7	2	4.3	4	7.0
2007	2	2.0	2	3.3	4	5.3
2008	4	2.7	4	2.7	8	5.3
2009	1	2.3	3	3.0	4	5.3
2010	3	2.7	2	3.0	5	5.7
2011	3	2.3	1	2.0	4	4.3
Total	**34**		**46**		**80**	

As regards trends, Some useful conclusions can be drawn from the charts in Figure 1 and Figure 2. Since investigations are still pending on 10 major accidents that occurred in the US in 2008 (2 accidents), 2009 (3 accidents) and 2010 (5 accidents), it will be incorrect to draw a conclusion on the trends over the period 2002 - 2011. However, we can conclude that Figure 1 shows that there has been a reduction of maintenance-related major accidents over the period 2002 - 2007. Figure 2 shows that of the overall total, the US contributes about 40% and Europe about 60% to the major accidents.

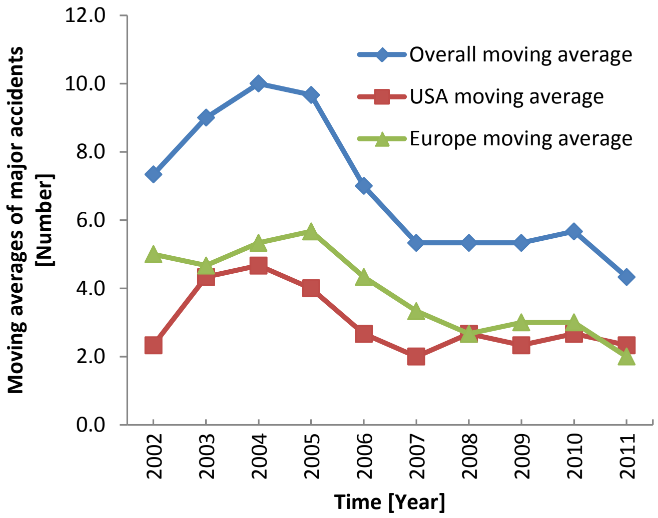

Figure 1: Trends of moving averages of maintenance-related major accidents over time

The aforementioned moving averages were calculated using the Microsoft's Excel function, AVERAGE. We used the moving average of 3 years (i.e. 2000 to 2002, 2001 to 2003, 2002 to 2004, etc.). The series of averages helps us to understand how the trend is by smoothing out short-term fluctuations. Shorter length moving averages (e.g. order 3) are more sensitive and identify new trends earlier than longer ones. Besides, the smaller the interval, the closer the moving averages are to the actual data points and this limits the loss of information unlike in higher order moving averages. However, using no moving averages or order 2 would obviously give less smooth curves (for trending). The alternative to using moving averages is trend lines or the raw data. We have included the raw data and it is possible to plot them directly. But we have chosen to use moving averages for the reasons given.

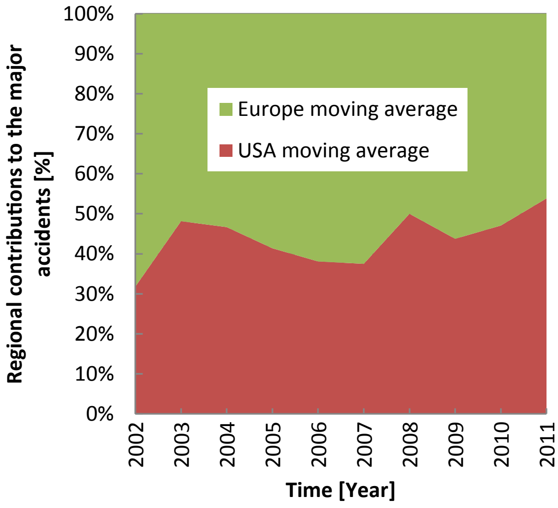

Figure 2: Trends in the proportion of each of the major accidents series over time

As shown in Figure 3, most of the maintenance-related major accidents occurred in chemical manufacturing plants (46%). The chemical plant category includes petrochemical plants. The "Others" category includes waste treatment, fossil-fuel power and food processing plants. The second and third most frequently involved plants are petroleum refinery (15%) and storage/terminals (14%) respectively.

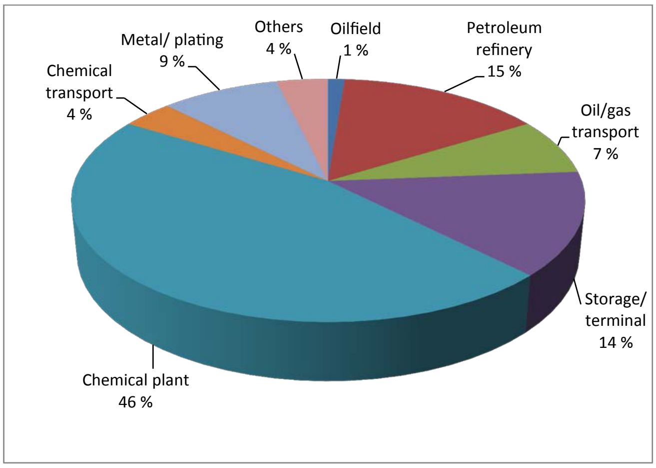

Figure 3: Types of plants where accidents occurred

In Figure 4, it is seen that the frequencies of involvement of hazardous substances are in the following order: toxic substances (26%), petrochemicals (22%) and crude oil/natural gas (18%) etc. The total number of substances involved in the 80 maintenance-related major accidents is 82 because two of the accidents each involved two hazardous substances. The fact that toxic substances (e.g. chlorine) are dangerous when in contact with living species and may tend to be corrosive to containments (leading to release), explosive in pressurized containments or support combustion is probably a reason for their being most involved in the major accidents. It could also be that toxic substances are the most common.

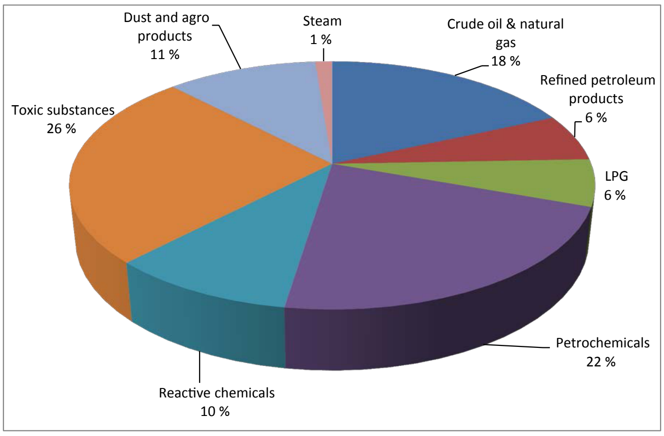

Figure 4: Types of substances stored, handled or processed

According to Table 2, out of the 80 maintenance-related major accidents, "emission/discharge" is involved in the most (60%). This is followed by "explosion" (44%), "fire" (34%) and "structural failure/loss of stability" (3%). Some of the accidents involved combinations of fire and explosion, emission and fire or emission, fire and explosion etc. The structural failure/loss of stability recorded did not result from fire or explosion. The fact that emission/discharge may be toxic, ignitable or explosive probably explains it's most frequent involvement in major accidents. The low number of "structural failure/loss of stability" (only 2) suggests that the structural integrity of the installations have been high enough to withstand the effects of maintenance deficiencies for a long time. Virtually all the cases associated with major damages to structures were as a result of the impact of fire and explosion.

4. Causes of maintenance-related major accidents

In the following subsections, the causes of maintenance-related major accidents will be reviewed based on the Work and Accident Process (WAP) classification scheme (Okoh and Haugen, 2013a). The scheme was developed based on some essential criteria for classification (Lortie and Rizzo, 1999; Kjellen, 1984; Okoh and Haugen, 2013a). The classification scheme consists of both the accident process and maintenance work process parts. The accident process part is related to both the active failure pathway which refers to the direct/immediate route to the manifestation of a major accident and the latent failure pathway which refers to the indirect/dormant route to the manifestation of the major accident (Reason, 1997). The maintenance work process part reflects the various phases of the work process in which something can wrong and it shows what can go wrong in each phase (Hale et al., 1998; Malmén et al., 2010).

Table 2: Type of maintenance-related major accidents

Year	Fire	Explosion	Emission/ Discharge	Structural failure or loss of stability
2000	1	3	5	0
2001	4	3	4	0
2002	2	5	5	0
2003	3	5	8	0
2004	4	3	7	0
2005	2	2	5	0
2006	4	3	1	0
2007	1	1	2	1
2008	2	2	6	1
2009	1	3	2	0
2010	0	3	2	0
2011	3	2	1	0
Total	**27**	**35**	**48**	**2**

4.1. *The work process*

The maintenance work process may be deficient in one or more phases (Okoh and Haugen, 2013a): (1) Deficient planning/scheduling/fault diagnosis, (2) Deficient mobilization or shutdown, (3) Deficient preparation for maintenance, (4) Deficient performance of maintenance work, (5) Deficient startup and (6) Deficient normal operation. The work process aspect identifies the various phases of a work process whose deficiencies can lead to an accident and in what order, for example, deficient planning being undetected during the performance of the maintenance work renders the former deficient and manifests as an accident during normal operation. The work process aspect will enable more specific and effective risk management for a particular kind of phase-wise scenario rather than relying on more general operational information or merely ignoring a phase as not critical to the development of an accident (Okoh and Haugen, 2013a). Analyzing the chain of events from the originating phase through intermediate phases (if applicable) to the manifestation phase gives a better insight into the underlying and contributing causes of the accidents and hence promote prevention efforts (Lortie and Rizzo, 1999).

4.2. *The accident process*

The accident process encompasses the pathways by which both active and latent failures interact and develop into major accidents. Major accidents manifest in active failures and the probability of their occurrence are influenced by the degree of latent failures/conditions. The occurrence of these two types of failures which are described further in the following, give additional insights into the underlying and contributing causes of the accidents.

4.2.1. *The active failures*

The active failure pathway represents the direct/immediate route to the occurrence of a major accident. There are four main active-failure scenarios associated with the causes of maintenance-related major accidents, namely (Okoh and Haugen, 2013a,b): (1) *Lack of barrier maintenance* - Lack of barrier maintenance which allows barriers to be breached by failure mechanisms (*e.g.* unreadable pressure gauge due to lack of cleaning), (2) *Barrier maintenance error* - Maintenance error directly breaching safety barriers (*e.g.* bypassing safety systems without applying suitable compensating measures during critical phases of operation), (3) *New hazard* - Maintenance introduces new hazards, which may be triggered by events (*e.g.* the use of hot tapping in line stopping), and (4) *Initiating event* - Maintenance being an initiating event for an accident scenario (*e.g.* dangerous release due to the wrong valve being operated as part of preparation for pipeline pigging). A maintenance related major accident will occur when "lack of barrier maintenance" or "barrier maintenance error" occurs in combination with "new hazard", "initiating event" or other non-maintenance related causes (Okoh and Haugen, 2013a).

4.2.2. *The latent failures*

The latent failure pathway represents the indirect/dormant route to the occurrence of the major accident (Reason, 1997) and they have been classified into the following (Okoh and Haugen, 2013a): (1) Deficient regulatory oversight, (2) Deficient risk assessment, (3) Deficient implementation of requirements, (4) Deficient Management of Change (MOC), (5) Deficient documentation, (6) Deficient design, organization and resource management, (7) Unbalanced safety and production goals, (8) Deficient monitoring of performance, (9) Deficient audit, and (10) Deficient learning.

4.3. *Occurrence of active failures*

According to Table 3, out of the 80 maintenance-related major accidents, "lack of barrier maintenance" is the most frequent active cause (50%). This is followed by "maintenance being an initiating event for an accident scenario" (34%), "maintenance error directly breaching barriers" (21%) and "maintenance introduces new hazards" (15%). Some of the accidents involved the failure of multiple barriers through several causes.

4.3.1. *Combinations of active failures*

According to Table 4, the most frequent combination of active failures is "Maintenance introduces new hazards - Maintenance being an initiating event" (42% of all the combinations). This combination is highly probable for safety-critical maintenance work in plants with significant amounts of hazardous substances. The new hazards are those generated by maintenance e.g. through the application of new, unvalidated procedures, processes, conditions and equipment or existing undervalidated ones. These may become triggered by events (e.g. certain maintenance interventions) that favor their development to an accident. An example can be seen in the Partridge-Raleigh oilfield explosion and fire in the US in 2006, in which "an open-ended piping left unisolated after a previous maintenance session" *(new hazard)* was in combination with "the act of welding a piping connection to it on resumption of maintenance work" *(initiating event)* (U.S. Chemical Safety Board, 2013). The second most frequent combination is "Lack of barrier maintenance - Maintenance error directly breaching barriers" (32% of all the combinations). An example of this can be seen in the Texas City refinery explosion in the US in 2005, in which "failure to clean sight glass" *(lack of barrier maintenance)* was in combination with "failure to calibrate level transmitter correctly" *(barrier maintenance error)*. This is followed by "Lack of barrier maintenance - Maintenance being an initiating event" (16% of all the combinations) and "Lack of barrier maintenance - Maintenance introduces new hazards" (11% of all the combinations). When "maintenance being an initiating event for an accident scenario" occurs, the percentage of it in combination with "maintenance introduces new hazards" is 30%. When "maintenance being an initiating event for an accident scenario" occurs, the percentage of it in combination with "lack of barrier maintenance" is 11%. When "lack of barrier maintenance" occurs, the percentage of it in combination with "maintenance errors directly breaching barriers" is 15%. When "lack of barrier maintenance" occurs, the percentage of it in combination with "maintenance introduces new hazards" is 5%.

Table 3: Occurrence of active failures

Year	**Lack of barrier maintenance**	**Maintenance error directly breaching barriers**	**Maintenance induces new hazards**	**Maintenance being an initiating event**
2000	4	4	0	2
2001	1	0	3	4
2002	5	0	2	2
2003	3	2	1	6
2004	4	3	1	1
2005	6	4	0	1
2006	2	1	2	2
2007	4	0	0	0
2008	3	3	0	3
2009	1	0	1	3
2010	4	0	1	3
2011	3	0	1	0
Total	**40**	**17**	**12**	**27**

4.4. *Occurrence of latent failures*

According to Table 5, out of the 80 maintenance related major accidents, "deficient design/organization/resource management" is the most frequent latent cause (85%). This is followed by "deficient risk analysis" (70%), "deficient documentation" (51%), "deficient implementation of requirements" (44%), "deficient monitoring of performance" (23%), "deficient management of change" (21%), "deficient learning" (19%), "deficient regulatory oversight" (16%), "deficient audit" (11%) and

Table 4: Combinations of active failures (number of occurrences)

	Maintenance error directly breaching barriers	Maintenance induces new hazards	Maintenance being an initiating event
Lack of barrier maintenance	6	2	3
Maintenance introduces new hazards			8

"unbalanced safety and production goals" (5%). Some of the accidents involved several latent failures. Disregarding the period between 2008 and 2011 for which some accident investigations have yet to be completed, we can see improvements in "risk assessment", "management of change", "monitoring of performance" and "learning" in at least a period of 4 years leading to 2007. However, it can be seen that there was no improvement in "regulatory oversight" in a period of 3 years leading to 2007.

4.4.1. Combinations of latent failures

As shown in Table 6, the most frequent combination of latent failures is "Deficient risk assessment - Deficient design, organization and resource management" (36% of all the combinations). These two sets of elements are such that they can influence each other: Deficient risk assessment may influence deficient design and on the other hand deficient organization and resource management may influence risk assessment. An example can be seen in the DSM Chemical Plant Explosion in the Netherlands in 2003 in which "deficient risk assessment" was in combination with "deficient design, organization and resource management" (Bureau for Analysis of Industrial Risks and Pollution, 2013; Okoh and Haugen, 2013b).

The second most frequent combination is "Deficient design, organization and resource management - Deficient implementation of requirements" (22% of all the combinations). It is obvious that deficient organization and resource management can hamper the implementation of requirements stipulated by regulatory bodies, manufacturers, experts etc. An example can be seen in the Texas City refinery explosion in the US in 2005, in which "deficient design, organization and resource management" was in combination with "deficient implementation of requirements" (U.S. Chemical Safety Board, 2013).

The third most frequent combination is "Deficient risk assessment - Deficient documentation" (21% of all the combinations). Deficient risk assessment may occur in a plant due to lack of procedural risk management strategies in the form of elements of safety management systems being kept and disseminated through soft or print media. An example can be seen in the explosion of a tank in TDI production unit in Italy in 2002 in which "deficient risk assessment" was in combination with "deficient documentation" (Bureau for Analysis of Industrial Risks and Pollution, 2013).

The fourth most frequent combination is "Deficient design, organization and resource management - Deficient monitoring of performance" (11% of all the combinations). Deficient monitoring of performance may be influenced by deficient organization (encompassing communication, coordination etc.) and/or by deficient resource management (encompassing poor hiring, poor training, insufficient manning, insufficient motivation etc). An example can be seen in the Texas City refinery explosion in the US in 2005, in which "deficient design, organization and resource management" was in combination with "deficient monitoring of performance" (U.S. Chemical Safety Board, 2013).

The fifth most frequent combination is "Deficient management of change - Deficient documentation" (7% of all the combinations). Deficient management of change (MOC) will most probably occur in the absence of documented MOC procedures necessary to guide the MOC process. An example can be seen in the BP Amoco thermal decomposition incident in the US in 2001, in which "deficient management of change" was in combination with "deficient documentation" (U.S. Chemical Safety Board, 2013).

When "deficient risk assessment" occurs, the percentage of it in combination with "deficient design, organization or resource management" is 86%. When "deficient implementation of requirements" occurs, the percentage of it in combination with "deficient design, organization or resource management" is 86%. When "deficient monitoring of performance" occurs, the percentage of it in combination with "deficient design, organization or resource management" is 78%. When "deficient documentation" occurs, the percentage of it in combination with "deficient risk analysis" is 68%. When "deficient documentation" occurs, the percentage of it in combination with "deficient management of change" is 22%. When "deficient monitoring of performance" occurs, the percentage of it in combination with "deficient implementation of requirements" is 28%.

Table 6: Combinations of latent failures (number of occurrences)

	Deficient documentation	Deficient design, organisation or resource management	Deficient monitoring of performance
Deficient risk assessment	28	48	
Deficient implementation of requirements		30	5
Deficient management of change (MOC)	9		
Deficient monitoring of performance		14	

Table 5: Occurrence of latent failures

Year	Deficient regulatory oversight	Deficient risk assessment	Deficient implementation of requirements	Deficient Management of Change (MOC)	Deficient documentation	Deficient design, organisation or resource management	Unbalanced safety & production goals	Deficient monitoring of performance	Deficient audit	Deficient learning
2000	0	2	2	0	2	6	0	3	0	0
2001	0	4	3	2	4	5	0	2	1	2
2002	0	6	1	2	5	9	0	1	4	2
2003	3	9	7	3	6	12	1	3	1	2
2004	0	7	3	3	2	6	0	2	0	1
2005	1	4	2	1	3	7	1	2	1	1
2006	1	3	2	1	4	3	1	1	1	1
2007	2	3	3	0	1	3	0	1	1	0
2008	0	5	4	2	5	6	0	1	0	3
2009	1	4	2	1	3	3	1	1	0	0
2010	2	5	3	2	2	4	0	0	0	1
2011	3	4	3	0	4	4	0	1	0	2
Total	**13**	**56**	**35**	**17**	**41**	**68**	**4**	**18**	**9**	**15**

4.5. *Occurrence of accidents in relation to the work process*

According to Table 7, out of the 80 maintenance-related major accidents, "deficient planning/scheduling/failure diagnosis" is the most frequent work-process-based cause (69%). This is followed by "deficient normal operation" (48%), "deficient performance of the maintenance work" (39%), "deficient startup" (13%), "deficient preparation for maintenance" (11%) and the least is "deficient mobilization/shutdown" (9%). Some of the accidents involved several phases of the work process

Table 7: Occurrence of accidents in relation to the work process

Year	Deficient planning/ scheduling/ fault diagnosis	Deficient mobilization/ shutdown	Deficient preparation for maintenance	Deficient performance of maintenance work	Deficient startup	Deficient normal operation
2000	3	2	1	4	0	3
2001	5	0	0	4	0	1
2002	5	0	1	1	0	7
2003	9	2	1	4	3	5
2004	4	0	3	3	0	5
2005	6	2	0	2	2	4
2006	4	0	0	3	0	2
2007	3	0	0	1	0	3
2008	6	0	0	4	1	5
2009	4	0	0	1	2	1
2010	4	1	2	2	1	1
2011	2	0	1	2	1	1
Total	**55**	**7**	**9**	**31**	**10**	**38**

4.5.1. *Combinations of work phases*

In Table 8, it is shown that the most frequent combination of causes in relation to the work process is "Deficient planning/scheduling/fault diagnosis - Deficient normal operation" (33% of all the combinations). Deficient planning/ scheduling/ fault diagnosis can lead to an accident directly in the normal operation phase. An example can be seen in the Imperial sugar refinery explosion in the US in 2008, in which "the failure to plan the maintenance of sugar and cornstarch conveying equipment to minimize the release of sugar dust into the work area" *(deficient planning/ scheduling/ fault diagnosis)* was in combination with "operating in the presence of significant accumulation of sugar dust" *(deficient normal operation)* (U.S. Chemical Safety Board, 2013). The second most frequent combination is "Deficient planning/scheduling/fault diagnosis - Deficient performance of maintenance work" (25% of all the combinations). Situations abound where erroneous plans result in accidents when undetected during the actual performance of the maintenance work in safety-critical operations. An example can be seen in the Partridge-Raleigh oilfield explosion and fire in the US in 2006, in which "deficient planning/scheduling/fault diagnosis" was in combination with "the welding of a piping connection, leading to the accident" (U.S. Chemical Safety Board, 2013). The third most frequent combination is "Deficient performance of maintenance work - Deficient normal operation" (12% of all the combinations). It is also possible to have a work performance phase with failures induced by personnel therein and leading to an accident in the normal operation phase. An example can be seen in the Goodyear heat exchanger and ammonia release incident in the US in 2008, in which "the failure of maintenance workers to reopen an isolation valve" was in combination with "increasing ammonia pressure during process piping cleaning being performed by the operators" (U.S. Chemical Safety Board, 2013). Further more, deficient plan may introduce failures in the work performance phase that will manifest during normal operation as an accident. When "deficient planning/scheduling/fault diagnosis" occurs, the percentage of it in combination with "deficient normal operation" is 49%. When "deficient planning/scheduling/ fault diagnosis" occurs, the percentage of it in combination with "deficient performance of maintenance work" is 36%. When "deficient planning/scheduling/fault diagnosis" occurs, the percentage of it in combination with "deficient startup" is 13%.

When “deficient planning/scheduling/fault diagnosis” occurs, the percentage of it in combination with “deficient preparation for maintenance” is 7%. When “deficient planning/ scheduling/ fault diagnosis” occurs, the percentage of it in combination with “deficient mobilization/shutdown” is 7%. When “deficient performance of maintenance work” occurs, the percentage of it in combination with “deficient normal operation” is 32%. When “deficient preparation for maintenance” occurs, the percentage of it in combination with “deficient normal operation” is 11%.

Table 8: Combinations of work phases (number of occurrences)

	Deficient mobilization/ shutdown	**Deficient preparation for maintenance**	**Deficient performance of maintenance work**	**Deficient start-up**	**Deficient normal operation**
Deficient planning/ scheduling/fault diagnosis	4	4	20	7	27
Deficient mobilization/ shutdown		1	1		
Deficient preparation for maintenance			4		1
Deficient performance of maintenance work				2	10

5. Discussion and recommendations

The main intention in this paper is to identify the most challenging causes of maintenance-related major accidents in the process industries in order to motivate intervention with the most preventive effort. However, potential areas for more usefulness can still be suggested. One of the possible ways in which the outcome of this research may be applied to maintenance management is by adapting it to a process FMEA (Failure Mode and Effect Analysis). A process FMEA is a systematic method that can be used in advance to identify, analyze and eliminate or reduce potential failures from a process (e.g. a maintenance process). It deals with problems emanating from how an item is manufactured, maintained or operated (Rausand and Hø yland, 2004). The style of the suggested FMEA is inspired by an application from the healthcare industry (ISMP, 2005; Cohen et al., 1994; Williams and Talley, 1994) where the FMEA is used to investigate medical processes for potential failures and to prevent the failures by correcting the defective processes proactively. We may identify the suggested FMEA as WAP-FMEA (Work and Accident Process Failure Modes and Effects Analysis), i.e. a FMEA which integrates the maintenance work process with the accident process for the purpose of prevention of maintenance related major accidents. Sample worksheets of the suggested WAP-FMEA are illustrated in Table 9 and Table 10.

Table 9: An illustration of maintenance WAP-FMEA for the prevention of maintenance-related major accidents in an offshore riser system

Process	Potential failure modes	Potential failure causes			Failure effects that can lead to major accidents	Probability* of failure	Severity of* failure effects	Risk* score	Actions for the elimination or reduction of failure modes
		Accident-process related		Work-process related					
		Active causes	Latent causes						
Maintenance process, e.g. Maintenance processes of an offshore riser system – various preventive, repair, replacement and pre-commissioning processes.	Failure to repair, hydrotest, pig or inspect etc.	**Lack of barrier maintenance:** Absence or insufficiency in update of status of maintenance program and administrative tools.	Deficient regulatory oversight, Deficient risk assessment, Deficient Implementation of requirements, Deficient Documentation, Deficient design, organization or resource management, Deficient monitoring of performance, Deficient learning	Deficiencies in planning/scheduling/ fault diagnosis (originating phase of accident), mobilization/shutdown, preparation for maintenance, performance of maintenance work, startup or normal operation (manifestation phase of accident)	Overload, corrosion, material degradation, leak, rupture	0.0249	4 fatalities	0.0996	Review of management policy, audit, etc. Review of the management of resources, information, change etc. Review of maintenance plan/program.
	Welding error, parts mismatch, omission of components and incorrect installation, repair or isolation etc.	**Barrier maintenance error:** Procedures, parts or techniques are inappropriate or applied wrongly to barriers.	Deficient implementation of requirements, Deficient Management of Change (MOC), Deficient Documentation, Deficient design, organization or resource management, Deficient learning	Deficiencies in planning/scheduling/fault diagnosis (originating phase of accident), mobilization/shutdown, preparation for maintenance, performance of maintenance work, startup or normal operation (originating or manifestation phase of accident)	Leak from weld, flange or valve etc.	0.0232	3 fatalities	0.0696	Review of welding procedure specification (WPS), work execution procedure, evaluation of work performance and personnel qualification.

* The figures in the columns are arbitrary values for demonstration purpose only. The probability may be determined from the failure frequency, the severity may be defined in terms of the expected damage and the risk score may be defined as the product of the probability and severity (ISMP, 2005). The ranking is discussed afterwards.

Table 10: An illustration of maintenance WAP-FMEA for the prevention of maintenance-related major accidents in an offshore riser system (Continuation of Table 9)

Process	Potential failure modes	Potential failure causes			Failure effects that can lead to major accidents	Probability* of failure	Severity* of failure effects	Risk score*	Actions for the elimination or reduction of failure modes
		Accident-process related		Work-process related					
		Active causes	Latent causes						
Mainte-nance process, e.g. Mainte-nance processes of an offshore riser system – various preventive, repair, replace-ment and pre-commiss-ioning processes.	Accumulated Ratcheting of bolts in live hydrocarbon piping, presence of maintenance intervention with ignition sources but no flame arrestor	**New hazard:** The resource being used for maintenance introduces hazards which interact with existing hazards or are triggered by events.	Deficient regulatory oversight, Deficient risk assessment, Deficient Implementation of requirements, Deficient Documentation, Deficient design, organization or resource management, Deficient monitoring of performance, Unbalanced safety & production goals, Deficient learning	Deficiencies in planning/scheduling/fault diagnosis (originating phase of accident), preparation for Maintenance, performance of maintenance work, startup or normal operation (originating or manifestation phase of accident)	Leak from flange or valve and ignition of flammable substances	0.0162	3 fatalities	0.0486	Review of safe operating procedure (SOP), evaluation of work performance, personnel qualification, simultaneous operations (SIMOPS), work permit system.
	Loss of containment due to a wrong valve being operated as part of preparations, fire/explosion from maintenance in process area adjacent to riser maintenance area, collision of work-class ROV with riser system.	**Initiating Event:** An accidental maintenance-related event disrupts a planned maintenance, initiating an accident scenario.	Deficient regulatory oversight, Deficient risk assessment, Deficient Implementation of requirements, Deficient Management of Change (MOC), Deficient Documentation, Deficient design, organization or resource management, Deficient audit	Deficiencies in planning/scheduling/fault diagnosis (originating phase of accident), mobilization/shutdown, preparation for maintenance, performance of maintenance work, startup or normal operation (originating or manifestation phase of accident)	Leak, rupture	0.0238	4 fatalities	0.0952	Review of safe operating procedure (SOP), Simultaneous operations (SIMOPS), work permit system or emergency response system.

* The figures in the columns are arbitrary values for demonstration purpose only. The probability may be determined from the failure frequency, the severity may be defined in terms of the expected damage and the risk score may be defined as the product of the probability and severity (ISMP, 2005). The ranking is discussed afterwards.

The illustration of the WAP-FMEA (in Table 9 and Table 10), generally presents a range of possible modes, causes and effects of failure as well as preventive actions in e.g. the maintenance process of an offshore riser system. The list of potential latent causes and work-process related deficiencies were obtained from the observations where they have been linked to different types of active failures. Practically, it is expected that a single failure mode will be treated at a time. The tabulated results in the earlier sections can inform about the probability of failure modes mentioned in Table 9 and Table 10. As regards ranking in order to prioritize preventive efforts, the illustrations in Table 8 and Table 9 indicate a range from highest risk score (corresponding to highest priority) to lowest risk score (corresponding to lowest priority).

Furthermore, the research findings may also find usefulness in maintenance-related, major accident risk modeling applications in the process industries. A typical situation is expressing the likelihood of a particular maintenance-related major accident occurring within a given period. This can be done by using the failure frequency databases of previous similar accidents to establish an annual probability of occurrence (i.e. the statistical probability that the accident will occur during a one-year period) using suitable formulas (Rausand and Hø yland, 2004).

6. Conclusion

In this paper, 183 major accidents in the hydrocarbon and chemical process industries in the period from 2000 to 2011 have been studied in relation to the Work and Accident Process (WAP) classification scheme (Okoh and Haugen, 2013a). The overall objective has been to look at how maintenance influences major accidents, the trend and the degree and distribution of the causes .

It has been found that out of 183 accidents, 80 (44%) are maintenance-related. Most of the maintenance-related major accidents occurred in chemical manufacturing plants (46%). The most frequently involved hazardous substances are toxic substances (26%) and the most frequent type of accident is “emission/discharge” (60%). “Lack of barrier maintenance” (50%), “Deficient design, organization and resource management” (85%) and “Deficient planning/scheduling/fault diagnosis” (69%) are the most frequent causes in terms of the active accident process, the latent accident process and the work process respectively. As regards combination of causes, “Maintenance introduces new hazards - Maintenance being an initiating event” (42% of all the active-failure combinations), “Deficient risk assessment - Deficient design, organization and resource management” (36% of all the latent-failure combinations) and “Deficient planning/scheduling/fault diagnosis - Deficient normal operation” (33% of all the deficient work-phase combinations) are the most frequent.

The results also show a decreasing trend in maintenance-related major accidents in the period from 2002 to 2007 and that the contributions of the US and Europe to the 80 maintenance-related major accidents are about 40% and 60% respectively.

As regards the applicability of the statistical findings, the frequencies can be used to determine probabilities which in turn will be useful in maintenance-related, major accident risk modeling and in the suggested WAP-FMEA (Work and Accident Process Failure Modes and Effects Analysis), i.e. a FMEA which integrates the maintenance work process with the accident process for the purpose of prevention of maintenance related major accidents. The validity of the statistics, however, is constrained by the uncertainty associated with the assumption that future failures will occur at the same rate being established currently based on previous experience.

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