Review of maritime and port-related HNS accidents

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Abstract

This paper provides a worldwide overview of maritime and port-related accidents involving hazardous of noxious substances (HNS). The data mining was carried out as a literature review. The study mainly focuses on liquefied chemicals but also other HNSs and accidents involving hazardous substances in packaged form were considered. Oil and oil products were observed only for comparison and on a very general level. Comparisons were made especially in case response actions were needed. Furthermore, studies focusing on port-related accidents were reviewed in this study. In addition, studies on the costs of chemical accidents were surveyed.

The study revealed that the risk of an HNS accident is highest in seas where the highest tonnes of chemicals are transported, the density of maritime traffic is highest and, of course, in the ship-shore interface where unloading/loading takes place. The data on marine pollution effects and the economic impacts of most transported chemicals is limited. Costs of a chemical tanker accident are almost unstudied, while study showed that the costs of an oil tanker accident could be enormous. Incidents involving chemical spills are statistically much less likely to occur than oil spills. However, chemical cargoes can be more dangerous to humans and property because chemicals can be more combustible, poisonous, irritating and reactive. The most important difference between a chemical and an oil spill may be related to response actions. In case of a chemical accident, the air quality or the risk of explosion should be more carefully evaluated before any response actions are taken. In case of chemical spills, the response is more limited in comparison to oil.

Keywords: Chemical accidents, environment, maritime, port-related, pollution, costs

1. Introduction

Transport and handling of hazardous chemicals and chemical products has increased considerably over the last 20 years, thus increasing the risk of major pollution accidents. Worldwide, approximately 2,000 chemicals are transported by sea either in bulk or in packaged form. Only a few hundred chemicals are transported in bulk, but these make up most of the volume of the chemical sea-borne trade (Purnell, 2009). Chemical releases are thought to be potentially more hazardous than oil. Regarding marine spills, chemicals may have both acute and long-term environmental effects and may not be as easily recoverable as oil spills. In addition, public safety risks are more severe in chemical releases (European Maritime Safety Agency [EMSA], 2007).

The amount of chemicals transported by sea is much smaller than the amount of oil and oil products. However, the risks related to possible oil accidents are easier to identify than the risks caused by chemicals. Although the eventuality of an incident involving hazardous or noxious substances (HNS) and chemicals transport is relatively low, some shipping incidents worldwide, such as the MSC Rosa M in 1997, the Ever Decent in 1999, the Napoli in 2007 and the Princess of the Stars in 2009 have demonstrated that the possibility exists (Mamaca *et al.*, 2009). The problem is the high variety and complexity of the environmental risk profiles and potentials of the chemicals, chemical compounds and other substances. Most shipping accidents have a local impact on the environment through polluting the shoreline in a certain area, but the accidents also have wider effects. Depending on the chemical, different spills of the same size may also have tremendously different effects on the environment.

At their best studies about historical chemical accidents may offer valuable lessons about the reasons leading to the accident, its environmental or health-related consequences or even the costs of the accident. First studies concerning past maritime or port-related HNS accidents were already made two decades ago (Rømer *et al.*, 1993, 1995, Cristou, 1999). More recently, many excellent papers and reports concerning maritime accidents have been written, concentrating mainly on the probability and environmental consequences of accidents (e.g. Marchand, 2002, Wern, 2002, Response to harmful substances spilled at sea [HASREP], 2005, EMSA, 2007, Mamaca *et al.*, 2009). Oil accidents have been studied more than other HNS accidents, but this is simply because of the higher incident numbers and larger spills (Burgherr, 2007). Even chemical or HNS accidents in ports have been studied to a smaller extent, but some papers based on international accident databases exists, answering to questions such as what transport phases are the most dangerous and why accidents happen (Dabra and Casal, 2004, Ronza *et al.*, 2004, Ellis, 2011). One of the most important issues studied is the difference in response actions in the case of oil and chemical accidents (Marchand, 2002, EMSA, 2007, Purnell, 2009). Unfortunately, very few papers related to the costs of chemical vessel accidents have been written so far and these papers have been very theoretical in nature (Talley, 2002, Ronza *et al.*, 2009). On the other hand, it is well-known that expenses of oil accidents can be enormous (Tegeback and Hasselström, 2012, International Tanker Owners Pollution Federation [ITOPF], 2012).

This paper reviews past studies on accidents and presents the state-of-the-art in the field of research of historical HNS accidents based on the literary review made. The study is mainly focused on bulk chemicals but also some accidents involving packaged chemicals were included, and for comparison purposes, also an overview of oil tanker accidents is given. In this study, a special emphasis was placed on the assessment of the environmental impacts of chemical accidents, but also the costs of maritime accidents were surveyed.

2. Methodology

The study provides an overview of several topics related to the maritime transportation of hazardous substances. Firstly, a literature review on maritime accident studies involving hazardous substances, and especially chemicals, was made to establish what kind of studies have been conducted on the topic earlier and what the main results of these studies are. Secondly, for comparison, accidents involving conventional oil and non-mineral oils were surveyed. Thirdly, response actions to chemicals spills were surveyed and compared to those of oil spills. Fourthly, port-related transport accidents were studied based on literature. Lastly, the costs of accidents were surveyed from scientific papers and reports. The literary studies were mainly collected from numerous electronic article databases and using a web search engine. The main focus was set on environmental and human health consequences and risks of hazardous spills, but other impacts, such as their economical impacts, were also studied for this paper.

3. Maritime accidents involving chemicals and other HNS

One of the earliest scientific analyses of the past maritime accidents was made by Rømer *et al.* (1993, 1995). Based on 151 marine accidents involving dangerous goods, Rømer *et al.* (1993) calculated accident frequencies for the different accident types (collisions, groundings, fire/explosions and structural damage). All types of accidents were rare, ranging from 1 x 10-3 to 2 x 10-2. In their analysis, the accidents involving oils were twice as frequent as accidents involving chemicals. In Rømer *et al.* (1995), the consequences measured by the number of fatalities from marine accidents (n=1780) during the transport of dangerous goods were investigated and compared with those from other modes of transport (n=1001). Accidents concerning the marine transport of dangerous goods were found to comprise a larger proportion of accidents with fatalities in the range of 10–50 than other transport modes. Almost all accidents with more than 40 fatalities were collisions and accidents with more than 100 fatalities were collisions between (oil)tankers and ferries. Surprisingly, the cargo type, containment type, geographical location or time period had no effect in this study (Rømer *et al.*, 1995).

Rømer *et al.* (1996) researched, on the basis of 1776 descriptions of water transport accidents involving dangerous goods, the environmental problems relating to releases of this kind. It was found that the most detailed descriptions of environmental consequences concerned oil accidents, although most of the consequences were described as reversible changes. It was shown that crude oil releases, on average, are approximately five times larger than the releases of oil products, and that oil product releases are approximately five times larger than those of other chemicals. Only 2% of the 1776 accidents described in the study contained information on consequences to living organisms, and only 10% contained any information on consequences to ecosystems. A relationship between the minimum kilometres of shore polluted and the tonnes oil released was found in oil accidents. Oil slicks were shown to be five times their breadth in length. Gravity scales used to describe and evaluate environmental consequences were discussed in the study as well.

Gunster *et al.* (1993) studied petroleum and other hazardous chemical spills in Newark Bay, USA, from 1982 to 1991. A record obtained from the United States Coast Guard (USCG) included 1453 accidental incidents that had resulted in the release of more than 18 million US gallons of hazardous materials and petroleum products in the Newark Bay area. Most accidents had occurred with fuel oils and gasoline. The authors reviewed many environmental studies and concluded that with regards to the amount and frequency of these spills, the elimination of entire species and a reduction in biotic diversity have typically been observed among benthic communities after major releases. Many compounds are also long-lived in the environment and thereby pose a chronic threat to aquatic organisms long after the acute initial effects of the spill have abated (Gunster *et al.*, 1993).

There are only very few impact assessment studies for chemical spills in the scientific literature in comparison to those for oil spills. Recently, some good papers and accident analyses concerning chemicals (conventional oil omitted) and other hazardous materials have been published (Marchand, 2002, Wern, 2002, HASREP, 2005, EMSA, 2007, Mullai and Larsson, 2008, Mamaca *et al.*, 2009, Cedre and Transport Canada, 2012). In addition, the Centre of Documentation, Research and Experimentation on Accidental Water Pollution (Cedre) collects information about shipping accidents involving HNS for an electric database by using various data sources (Cedre, 2012). None of the aforementioned sources are, or even try to be, exhaustive listings of all accidents involving chemicals and other hazardous materials, but they include examples of well-known accidents with some quality information. By compiling accident data from the aforementioned sources, 67 famous tanker/bulk carrier accidents involving chemicals and/or other hazardous materials were detected. These accidents frequently involved chemicals or chemical groups like acids, gases, vegetable oils, phenol, ammonia, caustic soda and acrylonitrile. Using the same information sources, 46 accidents involving packaged chemicals or other hazardous materials in packaged form were listed. In comparison to bulk chemicals, it can be seen that the variety of chemicals involved in accidents is much higher in the case of packaged chemicals. In this section, key findings and lessons to be learned in relation to vessel chemical accidents are discussed in more detail, the analysis being based on original key studies.

Marchand (2002) presented an analysis of chemical incidents and accidents in the EU waters and elsewhere, and stated that 23 incidents had information written down on related facts, such as places and causes of accident, chemical products involved, response actions and environmental impacts. In the study, the accidents were categorised into five groups according to how the substance involved behaved after being spilled at sea: products in packaged form; dissolvers in bulk; floaters in bulk; sinkers in bulk, and gases and evaporators in bulk. Based on Marchand's (2002) analysis, most of the accidents happened in the transit phase at sea, that is, while the vessel was moving. Only four accidents happened in ports or in nearby zones. Most of the accidents happened with bulk carriers (62 per cent of all the incidents), and less often with vessels transporting chemicals in packaged form (38 %). Poor weather conditions and their consequences were the main cause of the accidents (in 62 per cent of all the cases). Marchand (2002) highlighted several issues concerning human health risks regarding maritime chemical accidents. In the study it was also pointed out that in most cases of accident, the risks affecting human health usually come from reactive substances (reactivity with air, water or other products) and toxic substances. The evaluation of chemical risks can be very difficult if a ship is carrying diverse chemicals and some of those are unknown during the first hours after the accident.

In a more recent study, Mamaca *et al.* (2009) assessed the same chemical risks as Marchand (2002). Certain substances, such as chlorine, epichlorohydrine, acrylonitrile, styrene, acids and vinyl acetate, are transported in large quantities and may pose a very serious threat to human health, as they are highly reactive, flammable and toxic. Both Marchand (2002) and Mamaca *et al.* (2009) pointed out that the consequences and hazards chemical tanker accidents have had to the environment have varied a lot. Both studies stated that, in light of the accidents, pesticide products are one of the biggest threats for the marine environment. If pesticides enter the marine environment, consequences for the near-shore biota, and simultaneously for the people dependent on these resources, could be severe. On the other hand, even substances considered to be non-pollutants, such as vegetable oils (in accidents like Lindenbank, Hawaii 1975; Kimya, UK 1991; Allegra, France 1997), can have serious effects for marine species like birds, mussels and mammals (Marchand, 2002, Cedre, 2012).

By surveying 47 of the best-documented maritime transport accidents involving chemicals in the world from as early as 1947 to 2008, Mamaca *et al.* (2009) gathered a clear overview of the lessons to be learned. Even though the data was too narrow to be used for any statistical findings, the study presented some good examples of maritime chemical accidents. 32 of those accidents occurred in Europe. The list of chemicals that were involved in the accidents more than once included sulphuric acid (3), acrylonitrile (3), ammonium nitrate (2), and styrene (2). Only 10 of the 47 accidents occurred in ports or in nearby zones. Moreover, 66 per cent of the accidents involved chemicals transported in bulk, whereas 34 per cent involved hazardous materials in packaged form. Primary causes for the reviewed accidents were also studied. Improper manoeuvre was most frequently the reason behind the accidents (in 22 per cent of all the cases), shipwreck came second (20 %), and collision was third (13 %), closely followed by grounding and fire (11 % each). Based on past accident analysis regarding packaged chemicals, Mamaca *et al.* (2009) pointed out that, in light of packaged goods and as a consequence of high chemical diversity present on the vessel, responders must know the environmental fates for different chemicals individually as well as the possible synergistic reactions between them. Even though smaller volumes are transported, packaged chemicals can also be extremely dangerous to humans. This could be seen when fumes of epichlorohydrine leaking from the damaged drums on the Oostzee (Germany 1989) seriously affected the ship's crew and caused several cancer cases that were diagnosed years after (Mamaca *et al.*, 2009). However, these types of accidents involving packaged chemicals have only a localised, short-term impact on marine life. As to accidents caused by fire, there are difficulties in responding to the situation if the vessel is transporting a wide variety of toxic products. It is thus of crucial importance, yet difficult, to have a fully detailed list of the transported products for the use of assessing possible dangers for rescue personnel and the public.

Based on the analyses of the reviewed accidents, Mamaca *et al.* (2009) demonstrated that the highest risk for human health comes mainly from reactive substances (reactivity with air, water or other products). They also noted that many chemicals are not only carcinogenic and marine pollutants, but can form a moderately toxic gas cloud which is often capable of producing a flammable and/or explosive mix in the air. Acrylonitrile is a toxic, flammable and explosive chemical, and if it is exposed to heat, a highly toxic gas for humans (phosgene) is formed. Vinyl acetate, in turn, is a flammable and polymerizable product that in the case of Multi Tank Ascania incident (in United Kingdom, in 1999) caused a huge explosion. Little is known about the actual marine pollution effects of most of these substances. If hazardous chemicals and oil are compared, it can be said that the danger of coastline pollution is a far greater concern for oil spills than it is for chemical spills. On the other hand, the toxic clouds are a much bigger concern in the case of chemical accidents (Mamaca *et al.*, 2009).

In the HNS Action Plan, EMSA (2007) reviewed past incidents involving an HNS or a chemical. About 100 HNS incidents were identified from 1986 to 2006. These incidents included both those that resulted in a spill and those that did not. EMSA (2007) stated that caution should be applied to the data concerning the total sum of the incidents as well as the amount of spills, as there is variability in the reports from different countries. Statistics showed that the principal cause for both release and non-release incidents were foundering and weather (in 22 per cent of all the incidents), followed by fire and explosion in cargo areas (20%), collision (16%) and grounding (15%). The majority of the accidents involved single cargoes (73%) in which most of the material was carried in bulk form (63%). Moreover, 50 % of all studied incidents resulted in an HSN release. As to these release accidents/incidents, most of them happened in the Mediterranean Sea (40%), some in the North Sea (22%) and Channel Areas (20%), whereas only 8 per cent occurred in the Baltic Sea. Foundering and weather were again the principle causes of these incidents of release in 34 per cent of the cases, followed by fire and explosion in cargo areas (18%), collision (14%), and grounding (10%). The majority of the incidents resulting in an HNS release involved single cargoes (78%), of which 61 per cent were in bulk form (EMSA, 2007).

The HASREP project listed major maritime chemical spills (above 70 tonnes) in the EU waters between 1994 and 2004 (HASREP, 2005). The project found 18 major accidents altogether, and most of them occurred in France or the Netherlands. Interestingly, 8 accidents listed in HASREP (2005) were not mentioned in the study of Mamaca *et al.* (2009). The average occurrence of a major maritime chemical accident in the European Union was nearly 2 incidents per year (HASREP, 2005). By comparison, the statistical study made by the U.S. Coast Guard (USCG) in the United States over a 5-year span (1992–1995) listed 423 spills of hazardous substances from ships or port installations, giving an average of 85 spills each year. The 9 most frequently spilled products were sulphuric acid (86 spill cases), toluene (42), caustic soda (35), benzene (23), styrene (20), acrylonitrile (18), xylenes (18), vinyl acetate (17) and phosphoric acid (12). Over half of the spills were from ships (mainly carrier barges), and the rest from facilities (where the spill comes from the facility itself or from a ship in dock). A complementary study made over a period of 13 years (1981–1994) on the 10 most important port zones reported 288 spills of hazardous substances, representing on average 22 incidents each year (US Coast Guard, 1999). Small spillages in Europe were not recorded as carefully because they were not detected and/or there was a lack of communication between environmental organizations and competent authorities (HASREP, 2005). Cedre and Transport Canada (2012) analysed a total of 196 accidents that had occurred across the world´s seas between 1917 and 2010. The substances that were spilled most frequently and in the greatest quantities were sulphuric acid, vegetable oils, sodium hydroxide solutions and naphtha. Quite surprisingly, the study showed that structural damage (18 %) was the main cause of accidents involving hazardous materials, followed by severe weather conditions (16 %), collision (13 %), and grounding (11 %). Loading/unloading was the cause for only 7 per cent of the accidents (Cedre and Transport Canada, 2012).

Mullai (2007) surveyed in his thesis a total of 22 hazardous accidents and incident databases. The study revealed that only the U.S. databases gave thorough information about chemical transportation incidents (incl. accidents, small spills etc.) and the most comprehensive database is the U.S. HMIS (Hazardous Materials Incident System). General statistics showed that altogether 592 accidents or incidents in water transportation of hazardous materials occurred in the United States during the years 2002–2011, and the annual range was between 10 and 105 incidents. Mullai and Larsson (2008) made a risk study on hazardous material supply chain incidents based on the U.S. HMIS database (185,612 incident cases in U.S. in 1993–2004). Incidents observed in this study have occurred in every system of the hazardous materials supply chain, including platforms, all modes of transport, chemical plants, terminals and storages. The results showed that more than half (52.1%) of the incidents are attributed to the transport system. The majority (59.2%) of hazmat transport incidents are reported during the unloading phase, which is overrepresented compared to loading (16.8%) and in transit (17%) phases. The study largely considers incidents happening during maritime transport, which account for 18% of transport incidents. The three most frequent hazmat classes involved in packaged hazmat transport incidents reported were Class 3 (flammable liquids), Class 8 (corrosives) and Class 6 (toxic and infectious substances), which combined accounted for approx. 88% of all classes. The top two hazmat shipping names involved in all transport modes combined and vessel incidents are respectively a) corrosive and flammable liquids not otherwise specified (N.O.S.), and b) phosphoric acid and ammonia anhydrous. The dominant bulk hazmat carried by water is oil and oil products, Liquefied natural gas (LNG) and Liquefied petroleum gas (LPG), which pose fire, explosion, and toxic or environmental pollution hazards. The vast majority of all transport modes combined (93.6%) and vessel (79.6%) incidents have involved hazmat posing fire, explosion, corrosion and toxic as the primary hazards. In many cases, mixtures of hazmat posing more than one kind of hazard have been involved, making the situation more difficult to deal with. The high frequency of the mentioned classes and shipping names is mainly attributed to inherent properties of hazmat and large numbers of shipments. In absolute terms, the FN curves of maritime transport human risks are generally found to be well below the corresponding FN curves of aggregated supply chain human risks (Mullai and Larsson, 2008).

3.1. Oil accidents

Perhaps the most comprehensive study and analysis of accidental oil spills from tankers was conducted by Burgherr (2007). The main source of data in the study was the database ENSAD (Energy-Related Severe Accident Database). ENSAD contains consolidated oil spill data from a wide variety of commercial and non-commercial information sources such as ETC, FACTS, MHIDAS, ITOFF, USGC NOAA, IMO, CEDRE, REMPEC, CTX, OECD etc. According to Burgherr (2007), different databases have different threshold levels to what is considered a severe accident. Based on PSI’s severe accident definitions for ENSAD, an oil spill is considered severe if at least 10,000 tonnes of hydrocarbons is released. ITOPF distinguishes three spill categories, namely <7, 7–700 and >700 tonnes. In the study of Burgherr (2007), spills less than 700 tonnes were excluded because the information available was incomplete and major differences in the quality of reporting occur among countries and terminals.

In total, 737 accidental oil spills of at least 700 tonnes were included in the analysis of the period 1970–2004. The total numbers of spills exhibited a substantial decrease in the 1980s and 1990s compared to the 1970s. This reduction is primarily attributable to spills from 10,000 tonnes to smaller than 100,000 tonnes, whereas spills smaller than 10,000 varied significantly. The number of extremely large spills (over 100,000 tonnes) remained stable over the decades studied (Burgherr, 2007). Altogether 131 severe offshore and 43 severe onshore (at least 10,000 tonnes) oil spills from all sources occurred between 1970 and 2004. Of 737 accidental oil spills, 531 were oil spills from tankers. Out of 531 spills, only 23.4 % resulted in a release of at least 10,000 tonnes, but they accounted for 84.9% of the total spilled volume. Contrary to the increases in oil movement and the popular perceptions after recent catastrophic events, the number and volumes of tanker spills have decreased since the 1970s. For average spilled volumes the reduction was most substantial from the 1970s to the 1980s (56 %) but only 9 % from the 1980s to the 1990s. Spills greater than 100,000 tonnes are scarce events totalling 11 over the whole study period. Accidents of tankers Haven (144,000 tonnes) and ABT Summer (260,000 tonnes) were the most severe cases. The analysis also showed clear differences among country groups with spill numbers and volumes in FOC (flag of convenience) being significantly higher compared to EU25 and OECD countries. Similarly, pre-MARPOL single hull tankers showed to be significantly more accident-prone than MARPOL single hull tankers, accounting for the majority of total oil spilled. Spills with a volume over 100,000 tonnes only occurred with pre-MARPOL tankers, whereas maximum spills for MARPOL single hull (Sea Empress, 74,700 tonnes), double bottom only (Aegean Sea, 70,400 tonnes) and double sides only (Frontier Express, 8,320 tonnes) were significantly lower. Further, accidents with double hull tankers have caused no spills larger than 5,000 tonnes (2001, Baltic Carrier, 2,700 tonnes). The change in the composition of the world tanker fleet has improved the safety of the tankers and the situation is still improving, thanks to MARPOL regulations. Based on that analysis, collision, explosion/fire and grounding cumulative accounted for more than 80 % of spill causes. The author concluded that unfortunately many oil spills still occur within the boundaries of the sensitive Large Marine Ecosystems because the major maritime transport routes pass through them. However, the decrease in total spill volume could reduce overall ecological and sosio-economic consequences of accidents in the future (Burgherr, 2007).

4. Response actions

There are many excellent reviews (e.g. Marchand, 2002, EMSA, 2007, Purnell, 2009) based on lessons learned from past accidents which also contain data about response actions to chemical spills. Even if response actions taken are different for every accident depending on special conditions and the chemicals involved, it is nevertheless possible to demonstrate certain significant or specific elements valid for all chemical incidents at sea (Marchand, 2002).

Firstly, like the information concerning the ship cargo, an evaluation of chemical risks is of primary importance before any operational decisions are made, especially if the ship is carrying a wide variety of chemicals (Marchand, 2002). Following a chemical spill at sea, the response authorities must immediately take measures in order to minimize chemical exposure to the public as well as contamination of the marine environment. The primary factors which determine the severity and extent of the impacts of the accident are related to the chemical and physical properties of the chemicals in question. It should be noted that in the case of oil spills, the hazard to human health is generally considered to be low, and the more toxic and lighter fractions often evaporate before response actions can be started. However, in case of chemical accidents, an initial assessment and monitoring of potential hazards should be undertaken in order to ensure a safe working environment. In this stage, the primary hazards and fate of the chemical in that marine environment are evaluated. The monitoring techniques need to be designed to measure the key parameters that could give rise to a hazard. It should also be noted that in some cases, doing nothing might be the best option, as long it takes place under observation (Marchand, 2002, Purnell, 2009). Le Floch *et al.* (2010) stated that in case of an instantaneous chemical spill, response usually follows three accepted scenarios: 1) response is not possible because the spill occurred in a geographical environment that is incompatible with reasonable response times, 2) response is not possible due to the reactivity of the substances (major, imminent danger), and 3) response is possible. Gases and evaporators, very reactive substances, and explosives are the biggest concern for human health and safety. Several monitoring devices and dispersion models exist which may aid decision making and help to protect responders and the public. The floaters can be monitored by using the same techniques that are used for oil spills. Chemicals that prove to be the most difficult to monitor are sinkers and dissolvers (such as acrylonitrile in the case of Alessandro Primo in Italy in 1991), even if some techniques, e.g. electrochemical methods and acoustic techniques, do exist (EMSA, 2007, Purnell, 2009).

Several international, regional and national authorities have published operational guides to describe the possible response options in case of chemical spills. For example, Cedre and IMO have made manuals providing information about different response techniques that can be used in case of chemical spills (Helsinki Commission [HELCOM], 2002, International Maritime Organization [IMO], 2007, Cedre and Transport Canada, 2012). Usually response techniques depend on the behaviour of a chemical in the environment, and on whether it is released or still contained in packaged form. In practice, the response actions vary substantially. Techniques that are applicable in case of oil accidents may be suitable for only some floating chemicals. However, it should not be forgotten that some floating chemicals can also potentially create toxic and possibly explosive vapour clouds (e.g. diesel, xylene and styrene). If this happens, spark/static-free equipment should be used. Moreover, foams or sorbent materials can also be used near the spill source. Risks associated with evaporators or gases, such as ammonia and vinyl chloride, could be diminished by diluting or using release methods (Purnell, 2009). In shallow water areas, neutralisers, activated carbon, oxidising or reducing agents, complexing agents, and ion-exchangers can be used. Chemicals that are heavier than seawater, in turn, may contaminate large areas of the seabed. Recovery methods that are used include mechanical, hydraulic or pneumatic dredges, but the recovery work is time-consuming and expensive and results in large quantities of contaminated material. Another option is capping the contaminated sediment in-situ (Purnell, 2009).

As Marchand (2002) listed, the time required for response operations can vary from 2–3 months to as much as several years as e.g. in the case of the research carried out on a sunken cargo. Cold weather and ice cover may create further problems to response actions in the Baltic Sea in the winter. The viscosity of chemicals may change in the cold and they may become more persistent. Collecting techniques based on fluid-like masses are no longer effective if fluids change and act more like solid masses. Moreover, it is difficult for a recovery fleet to operate if it is surrounded by ice and snow. If chemicals have spread under the ice cover, detecting the spill is more difficult and the use of dispersing agents is ineffective. However, ice breakers may be used to break the ice cover and to improve mixing chemicals with larger water masses (Hänninen and Rytkönen, 2006).

5. Port-related chemical accidents

Whilst effort has been devoted to analysing the historic safety performance of oil and chemical tankers, little research has been done on port regions. Given their positions in coastal areas and the great variety of substances handled, ports are nowadays very complex systems involving certain risks from the environmental point of view. In addition, ports are usually close to urban centres, and because of these circumstances, the impacts of chemical accidents can be very serious.

In this study, only 5 articles related to past port accidents involving hazardous materials were discovered. Darbra and Casal (2004) conducted a study on 471 accidents that had occurred in seaports worldwide between 1941–2002 based on the Major Hazardous Incidents Database System (MHIDAS) database.Christou (1999) investigated 671 port accidents from the period 1934–1995, using an f-N curve for each transportation mode. Ronza *et al.* (2004) used 828 historical port accidents since the beginning of the 20th century from the MHIDAS database to build an event tree model and then to predict accident frequency. Ellis (2011) studied accidents and incidents occurring during the transport of packaged goods by sea, using mainly the Hazardous Materials Incident System (HMIS), which primarily contains accidents that occurred in the United States. Nowadays, the HMIS contains a total of over 162,000 hazardous material related incidents that have occurred in the US between the years 2002–2011. The portal is provided by the U.S. Department of Transportation. The Pipeline and

Hazardous Material Safety Administration Contribution to accidents of misdeclared or undeclarated hazardous cargo was studied in Ellis (2010).

Christou (1999) studied hazards related to the presence of hazardous materials in the port areas and marshalling yards. Furthermore, data of past accidents in port-related transport interfaces was collected from various sources and analysed statistically. In this study, the investigation of accidents related to transport interfaces revealed that 617 accidents all over the world had resulted in 2,494 fatalities and 17,943 injuries. From those accidents, 54.8 % happened in sea ports, and also over 90 % of fatalities and 30 % of injuries occurred in sea ports. When comparing different decades, it seems that port safety has improved a lot and the number of accidents is clearly decreasing.

Darbra and Casal (2004) analysed a total of 471 accidents involving hazardous substances using the MHIDAS database. Their results indicated a significant increase in the frequency of accidents over time: 83 % of the accidents had occurred in the last 20 years and 59 % in the past decade. However, the reasons to the increase seem to be better data gathering and access to accident information in the last two decades, as well as higher industrial activity in many countries during that time. The most frequent accident type was releases (51 %), followed by fires (29 %), explosions (17 %) and gas clouds (3 %). However, it should be noted that 21 % of accidents were unclassified and, on the other hand, many accidents can be classified in more than one category. Most accidents start with a release followed by fire or explosion. These can be then classified e.g. only into the fire category. Surprisingly, more than half of the accidents occurred during transport. Unloading/loading, storage and process plants also made a large contribution to the total number of the accidents (Darbra and Casal, 2004). The principal origin of accidents in ports was transport with 56.5 % of the cases (173 accidents). Almost 15 % of port accidents happened during loading/unloading, 11.7 % during storage and 10.8 % in process. It should be noted that the transport category includes, in practise, all accidents that occur when moving ships (entering or leaving the port), and in lorries or trains entering or leaving port facilities.

Darbra and Casal (2004) mentioned that it is logical that most accidents happened in transit phase since the function of ports is precisely the movement of goods. However, an analysis of the HMIS data showed quite an opposite view: in this analysis loading/unloading was the most dangerous phase when all transport modes were taken into account (Häkkinen *et al.*, 2010, 2012). Surprisingly, the results of Darbra and Casal (2004) regarding accidents that occurred during transport showed that the majority of the accidents (65 %) took place on ocean-going vessels. The authors stated that this was logical given the intense movements in and out of a port area and the intense ship manoeuvring within it. In the study by Darbra and Casal (2004), pipelines were also considered to be transport category (31 cases), which in many cases are not included in transport. The greatest proportions of accidents occurred with oils (59 %), followed by chemicals (4 %), acids (3 %) and natural gas (3 %). In their study, 40

% of the accidents involved other substances. In many cases there were multiple substances involved and the classification to 4 substance groups is very rough indeed.

According to Darbra and Casal (2004), the MHIDAS database takes into consideration 8 types of cause: mechanical failure, impact failure, human factor, instrumental failure, services failure, violent reaction, external events and upset process conditions. However, 36 % of their cases were not classified into any of these groups. Based on the study, 43.6 % of accidents in ports were caused by an impact or a collision between ships or between a ship and dry land, vehicle collisions etc. This result of Darbra and Casal (2004) can be considered exceptional if compared to other studies, where accidents of a whole chemical supply chain have been studied. In these other studies either mechanical failures or human factors have been the reason in most cases, and the most dangerous transport phases have been unloading and loading, not the in-transit phase (Mullai and Larsson, 2008, Häkkinen *et al.*, 2010). In the study by Darbra and Casal (2004), the proportion of mechanical failures was only 18.1 %, followed by external impact (17 %) and human factor (15.9 %). When considering human factor, the most important mistakes were related to general operation (23 %) and overfilling (11 %).

Ronza *et al.* (2003) made a historical analysis of 828 chemical-related accidents in port areas using the MHIDAS database. Based on the study, the location of the accident was in most cases (40 %) at sea (approach + manoeuvre), whilst only 21 % took place ashore (storage + process + transport). It is worth noting that the remaining 39 % of the accidents occurred at a sea-land interface (loading/unloading + maintenance), which is a particular feature of ports as industrial areas. When accidents were classified in terms of operation, it could be clearly seen that most accidents happened during loading/unloading (34 %), followed by manoeuvre (27 %) and approach (13 %). Only 12 % of accidents happened during storage and 7 % in the transportation phase. This result is opposite to those of Darbra and Casal (2004), but provides more support to other chemical transportation accident analyses (Mullai and Larsson, 2008, Häkkinen *et al.*, 2010, 2012).

5.1 Packaged HNSs in ports

It has been stated that the safe transportation of dangerous/hazardous goods is one of the most serious challenges to container shipping. The ship operator receives the containers closed and sealed and thus cannot confirm with certainty that the contents of a container are properly stowed and secured for transport (Ellis, 2011). Several participants are involved in the packaging, loading and transport of dangerous goods before shipping, and the safety of the port handling and marine transport depend on the reliability of the participants of the whole supply chain. In the study by Ellis (2011), altogether 116 cases were analysed from US and UK databases related to dangerous goods releases from an 11-year period covering the years 1998–2008. The purpose of the study was to identify and categorise the main contributing factors to accidents involving packaged dangerous goods. The majority of releases, estimated at 97 % of the US incidents and 94 % of the UK incidents, did not follow another primary accident type such as a collision. Faults/mistakes that took place during activities such as the preparation of goods for transport, packaging, stuffing containers and loading/unloading the ship, were the main factors contributing to the release of dangerous goods on board of the ship. According to the HMIS data, 91 % of the faults contributing to the release of the dangerous goods were introduced before the container was brought onto the ship. Containment and packaging problems represent the largest category of the reasons (66 %), followed by problems related to loading the ship (25 %). Only 2 % of the releases occurred due to a secondary event, attributed to excessive motions of a ship or storms. For container ship casualties occurring worldwide during the same period, 1998–2008, accidents involving packaged dangerous goods were estimated to account for 15 % of all fatalities. Self-ignition or ignition of incorrectly declared dangerous goods were identified as contributing factors to the fatal accidents. In the second study, Ellis (2010) demonstrated that dangerous goods that have not been correctly declared when offered for transport have contributed to some serious accidents at sea. The safe handling, stowage, and segregation of packaged dangerous goods cannot be carried out if there is no knowledge of the presence of dangerous goods inside the cargo transport unit (container and/or trailer), or if the goods have been incorrectly declared. For example, in the famous accident of Sea-Land Mariner involving fire and explosions, there were undeclared class 9 substances in 20 containers. In Swedish inspections, some deficiencies in documentation were discovered on 21 % of the inspected transport units (Ellis, 2010).

5.2 Domino effects/events

Domino effect or events are perhaps the most feared events related to chemical accidents both in fixed installation and transportation. A domino effect may occur if leakage/spill of a hazardous material leads to the escalation of the incident, e.g. a small leak catches fire and damages a vessel or storage tank through flame impingement, causing it to catch fire and possibly leading to explosions (so called BLEVE). Abdolhamidzadeh *et al.* (2011) studied altogether 224 major domino effects in 6 different industrial accident databases (APELL, COMAH, MARS, CBS, HSE and MHIDAS). Fixed installations account for three-fourths of all past domino events and road/railroad accidents account for the maximum number of domino effects occurring during transportation, while the proportion of shipping was only 13 % of all transportation accidents involving a domino event. Flammables are the types of substance most often involved in domino effect accidents. The most common domino event was vapour cloud explosion. It should be noted that most domino events occurred in the developing countries (Abdolhamidzadeh *et al.*, 2011).

Darbra *et al.* (2010) consulted altogether 5 different databases (MARS, MHIDAS, FACTS, ARIA and MAHB) and analysed 225 accidents involving domino effects. In their study, the accident scenario, the type of accident, the materials involved, the causes and the consequences were analysed. The results of the study revealed that storage areas (like ports) are the most common setting for domino accidents (35 % of all cases). The most frequent causes for domino accidents are external events (31 %) and mechanical failure (29 %). Even 89 % of the accidents involved flammable materials, the most frequent of which was LPG. The most frequent sequences were explosion–fire (27.6 %), fire–explosion (27.5 %) and fire–fire (17.8 %) (Darbra *et al.*, 2010).

6. Costs of HNS accidents

Ronza *et al.* (2009) presented a very typical scenario of a port-related accident, which involved the full bore rupture of a diesel oil loading arm, a situation that could be caused by either a violent and unexpected movement of a (dis)charging tanker at berth or a fault in connecting the arm to the tanker's piping. In their scenario, it was assumed that the duration of the release is 120 seconds and a pool is formed partly on water and partly on the ground. The pool is subsequently ignited. In their scenario, the pool fire caused by the loss of containment of diesel oil is such that the area affected by 99% mortality is 2,100 m2 (radius = 26 m). Assuming a population density of five people/ha, the expected number of fatal victims is 1. They calculated that the economic loss would be over 300 thousand euros. In their scenario, the costs of losing valuable animals are assumed to be 0, because the affected area is not considerable. Additionally, the slick formed by the spill will most probably be confined in port waters. Assuming that the residual amount of diesel oil is 5% of the amount spilled, it can be estimated that the cost of cleaning the water is over 30 thousand euros. Based on their calculations, the total cost of this kind of accident could be over 900 thousand euros including damages to humans, the environment and property, excluding however damages to tanker itself (Ronza *et al.*, 2009).

In case of a severe marine accident, the costs can be enormous. Talley (2002) studied whether there are accident vessel damage cost differentials among container, tanker and bulk vessels. Based on Talley's (2002) calculations, the vessel damage cost per vessel gross ton of a container (tanker) accident is $33.37 ($18.37) less than that of a bulk accident, all else held constant. The damage cost differentials are associated with fire/explosion accidents and human and environmental causes of accident. For loss of life, the values vary considerably depending on the region. The International Maritime Organization (IMO) uses a value of USD 1.5 millions in its guidelines for Formal Safety Assessment (IMO, 2007). In addition, the European Union Project SAFEDOR (2007) suggests a range of USD 20,000 to 70,000 per injury, while the IMO Formal Safety Assessment suggests a value of USD 42,000 per injury. Concerning the cost of pollution, there is currently no consensus at IMO level, but SAFEDOR (2007) provides an average figure of USD 60,000 per ton. This figure does not take into account the associated costs of environmental damage (such as loss of animal life) and other socio-economic factors, since these costs are difficult to estimate. Unfortunately, no studies concerning costs of maritime chemical accidents were found in this study. However, in cases that involved chemicals, most damage costs originate from loss of property/ship and loss of lives. Because in many cases chemicals are unrecoverable, the clean-up costs are not as high as in the case of oil accidents, but a great effort should be targeted at monitoring and risk assessment (see section dealing with response actions).

Tegeback and Hasselström (2012) estimated in their study that if 10,000 tons of oil contaminated a coastline of the Baltic Sea, the costs would be 100–400 million euros including direct (e.g. clean-up), market (e.g. tourism and fisheries industry) and non-market costs (i.e. environmental and other impacts that are not easily measured in a market). Similarly, Halonen (2007) stated that in case of a spill of 30,000 tons of oil, the estimated costs of clean-up could reach 1.5 billion euros. According to ITOPF (2012), the most expensive oil spill in history is the EXXON VALDEZ (Alaska, 1989). Clean-up alone cost approximately US$2.5 billion and total costs (including fines, penalties and claims settlements) have been estimated to be as much as US$7 billion. The AMOCO CADIZ (France, 1978) reportedly cost about US $282 million, of which about half was for legal fees and accrued interest. For the NAKHODKA (Japan, 1997), compensation was settled at approximately US$219 million. Claims are still being processed for the ERIKA (France, 1999), as in October 2010 payments had been made for 5,939 claims, comprising a total of 129.7 million euros. Economically severe accidents (like Flixborough, Pasadena Texas, La Mede in France etc.) also occur at petrochemical, chemical and refinery sites and their costs have ranged between 150–1500 million dollars. These accidents have actually included very few if no casualties, whereas accidents like Bhopal (possibly 4,000 deaths) and Mexico City (more than 500 deaths) are not recorded as high-cost accidents (Fewtrell and Hirst, 1998).

There are very few studies concerning environmental impacts of transport-related accidents involving hazardous materials or the expenses of these environmental damages (Häkkinen *et al.*, 2012, Mullai and Larsson, 2008, Vince, 2008). In the MHIDAS database, only 21 transport-related chemical accidents that caused harm to the environment were listed (Vince, 2008). Similarly, it was found in Häkkinen *et al.* (2012) that in the HMIS database in 2011 there were only 63 reported accidents that resulted in environmental damage, while the total number of accidents recorded in the database was over 14,000 during the same period. It is also important to note that since environmental damages were reported very seldom, the damage costs of those few cases that were reported were remarkably high ($35,786,175).

7. Conclusions

This paper provides an overview of past maritime and port-related HNS accidents worldwide. The results of the study demonstrated that chemical tanker accidents are very rare; however, there is always a possibility that an incident occurs. Many studies have shown that the most commonly transported chemicals are the ones most likely to be involved in an accident. The risk is also different in different sea areas. The risk is highest in water areas where highest amounts of chemicals are transported, the density of the maritime traffic is highest or bad weather conditions exists, as well as on the ship-shore interface in ports where unloading/loading take place. Incidents involving chemical spills are statistically much less likely to occur than oil spills.

Whilst effort has been devoted to analyses of the past safety performance of oil and chemical tankers, little research has been conducted regarding port regions. Ports are usually close to urban centres and because of these circumstances, the impact of chemical accidents can be very serious. Surprisingly, reviewed papers showed that in port or terminal areas the most HNS accidents happen during the transit phase, not during unloading/loading. However, studies considering the whole supply chain usually demonstrate that unloading and loading are the most dangerous transport phases.

Actually, very little is known about the actual marine pollution effect of most of these frequently transported substances. From an environmental point of view, the previous studies highlighted accidents in which pesticides were released into water, but also substances considered as non-pollutants (vegetable oils) seem to have a negative effect on biota in a water environment. When hazardous chemicals and oil are compared, it can be said that the danger of coastline pollution is a far greater concern for oil spills than for chemical spills. Moreover, toxic clouds are a much serious concern in the case of a chemical accident. The evaluation of chemical risks is very difficult when the ship is carrying diverse chemicals and some of them remain unknown during the first hours after the accident. This situation often arises when a vessel is carrying packaged dangerous goods. Maybe the most important difference between a chemical and an oil spill is related to response actions. The air quality or the explosion risks are not usually of any concern for response personnel in case of oil spills, but they should be carefully evaluated if some response actions are taken in cases involving chemical spills.

Data of the marine pollution effects and the economic damages of most transported chemicals is limited, mainly because of the rarity of maritime chemical accidents. The costs of chemical tanker accidents are almost unstudied, while the costs caused by an oil tanker could be enormous. Even though the probability of major chemical tanker accidents is very small, much more studies are still needed on the risks of different chemicals to both the environment and humans, as well as on the economic risks of possible accidents.

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