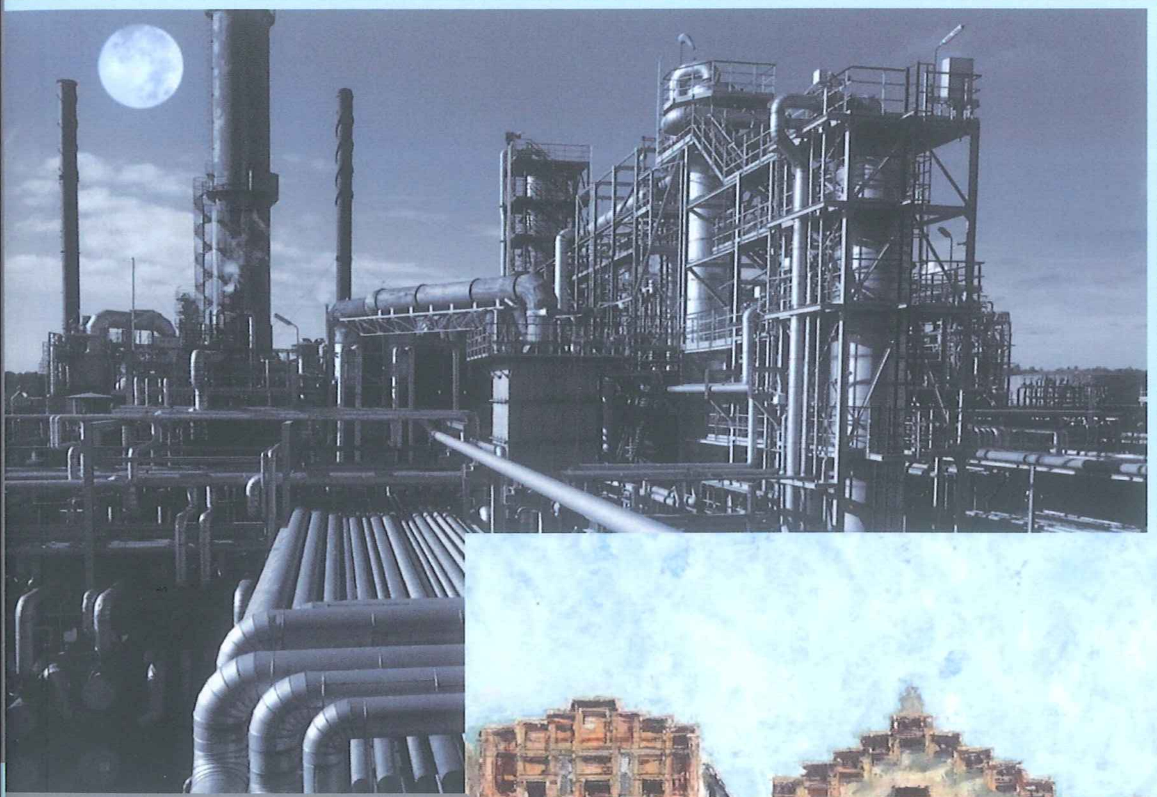
EMChIE 2015

Conference Proceedings

Volume 1

Edited by Christophe Bengoa



7th European Meeting on Chemical Industry and Environment

Tarragona, Spain, 10-12 June 2015

EMChIE 2015
Conference Proceedings

Volume 1

Edited by Christophe Bengoa

Topic 01 Air pollution control and abatement

Topic 02 Methods of testing, validation and monitoring

Topic 03 Particle technology and nanotechnology

Topic 04 Process and environmental applications of microalgae

Topic 05 Process intensification and sustainability in chemical engineering

Topic 06 Risk analysis and loss prevention

7th European Meeting on Chemical Industry and Environment

Tarragona, Spain, 10-12 June 2015

Domino effect accidents in hazardous materials transportation by road and rail (2009)

C. Chanut [1], J. Casal [2], G. Dusserre [1], R. M. Darbra [2]

[1] Risk Department, Laboratoire Génie de l'Environnement Industriel, École des Mines d'Alès, 6 Av. De Clavières. Alès Cedex 30319, France.

[2] Centre d'Estudis del Risc Tecnològic (CERTEC), Universitat Politècnica de Catalunya. Diagonal 647, 08028-Barcelona, Catalonia, Spain.

e-mail: joaquim.casal@upc.edu

Abstract
135 accidents occurred during the transportation of hazardous materials by road or rail and involving domino effect have been analyzed. Only accidents happened after 1st January 1961 have been considered. 45% of them occurred during road transportation and 55% during rail transportation. Accidents involving loading/unloading operations have been also taken into account. Their main features were analyzed: evolution over the time, geographical location, type of accident, substances involved, causes and consequences. The main cause was impact failure, followed by external events and mechanical failure. Differences between developed and developing countries have been identified; the analysis shows an increasing frequency over the years in the developing countries. The domino sequences have also been analyzed. Finally, some conclusions are drawn concerning these results.

Keywords
Road and rail transportation, hazmat, domino effect accidents.

INTRODUCTION

The transportation of hazardous materials by road and rail, which has increased in the past decades, involves often the problem of the proximity to inhabited areas. This is a difference with respect to most process plants, which in many countries have to ensure a certain distance to the urban zones. Besides, in the case of an accident in a plant, often the population has been informed on how to react, whereas in most transportation accidents they do not know how to behave. That is why the consequences can be worse in this kind of accidents.

In this study, accidents which occurred during the transfer activities (loading/unloading) have also been analyzed. These events, which occur with certain frequency, have lower severity than that of transportation accidents, because they occur in fixed installations (storage or process plants) where there are very few employees. However, as transfer is an activity clearly associated to transport, it seems logical to include it in the analysis.

Recent surveys have shown the importance of the domino effect in the severity of the major accidents (Darbra et al., 2010; Abdolhamidzadeh et al., 2011). Besides, the main features of domino accidents have been analyzed in the book "Domino effects in the process industries" (Reniers & Cozzani, 2013). Several historical studies have been performed on this subject: Kourniotis et al. (2000) analyzed 207 accidents, 80 of them involving domino effects; Ronza et al. (2003) studied 108 domino effect events occurred in port areas. Chen et al. (2012) studied 318 domino accidents and drew specific conclusions about the situation in China. Recently, a historical survey has been published with 330 cases analyzed (Hemmatian et al., 2014). Nevertheless, scarce attention has been paid to the specific case of transportation.

Different definitions and interpretations have been proposed for the domino effect; in this study the definition given by Delvosalle (1998) has been chosen: "a cascade of events in which the consequences of a previous accident are increased both spatially and temporally by the following ones, thus leading to a major accident".

ACCIDENTS SELECTION

135 accidents were selected using information from diverse databases such as MHIDAS (2007), RISCAD (2012), FACTS (2010) or ARIA (2012), as well as from other sources. All of them involved domino effect and occurred during the transportation of hazardous materials by road or train, or during the transfer phase. Only events occurred after 1st January 1961 were included; before this date, the main features of transportation were different from the present ones.

45 % of them occurred during road transportation and 55 % during rail transportation; Haastrup and Brockhoff (1990), in a survey on the severity of accidents with hazmat, found the same percentages considering only these two ways of transportation. Oggero et al. (2006) studied all the accidents occurred in transportation by road and rail (not only domino effect) and found that 37% of them occurred during rail and the rest during road transportation. Therefore, it seems that accidents occurred in rail transportation involve more often domino effect than those occurred in road; this can

be explained by the fact that there are often several tank wagons containing hazardous materials, which in case of derailment interact. However, it is interesting to remark that, according to the present data, in developing countries about two-thirds of the analyzed cases occurred in transportation by road (in these countries the road network is usually more important than rail network).

From the total of accidents analyzed, 72.6% occurred in transportation and 27.4% during the transfer phase. Nevertheless, in developing countries, about 55% occurred in transportation and 45% in transfer. During the transfer phase, the human factor is more relevant than in transportation, and in developing countries, generally, operators receive less safety training than in the developed ones.

DISTRIBUTION OF THE ACCIDENTS OVER TIME

The frequency of accidents has kept approximately constant –with some variation– over the years, even though the transportation has globally increased. It can be considered therefore that the situation has improved somewhat, due to the measures taken in many countries on both the transportation and the road and rail tanks conditions.

The location of the accidents has also been analyzed. Two categories depending on the country where they had occurred were considered: 1) Developed countries: European Union and Australia, Canada, Japan, New Zealand, Switzerland, Norway and the United States (84%), and 2) Developing countries: the rest of the world (16%).

With this classification, accidents occur mainly in developed countries. This can be attributed to the higher volume of transportation of hazardous materials in them, as well as to the better access to information on accidents.

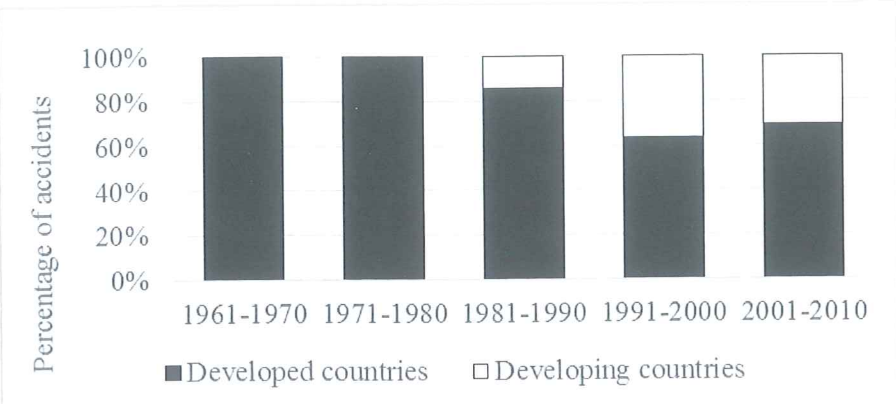


Figure 1. Distribution of transportation domino accidents according to the location.

When the evolution over the time of the accidents in the different parts of the world is analyzed, an interesting situation is found (Figure 1). The proportion of accidents occurred in developed countries has decreased from 1961 to 2000; it seems that the measures taken in these countries have reduced the frequency, leading to a safer transportation. On the contrary, in the rest of the world, the frequency has increased since the 80's, being now around 30%. This gives a clear indication that a special attention should be paid to the situation in the developing countries, where legislation is less strict.

TYPES OF ACCIDENTS AND SUBSTANCES INVOLVED

Accidents can be classified (MHIDAS, 2007) into loss of containment, explosion, fire and gas cloud. The percentages add higher than 100 because some accidents are classified into more than one category. For example, an accident might consist of a fire that then causes an explosion or a release.

Explosion and fire are the most common types, appearing respectively in 84.2% and in 78.4% of cases. It makes sense because in domino effect a first accident, often a fire or an explosion, causes another one. Loss of containment appears in 33.8% and gas cloud in 4.3%.

Sometimes more than one substance is involved in the accident. As a whole, 185 substances were identified in 133 events (in two cases there was no information available). However, this number could be higher because, even if the substance is known for the initiating event, in some cases it is not clearly identified for the following steps. The percentages add more than 100 because of the involvement of more than one substance in many accidents.

LPG is the most common substance (24.8%), followed by gasoline (9.8%), vinyl chloride (7.5%), ethylene oxide (5.3%), chlorine (3.8%) and ammonia (3.8%). Other liquid hydrocarbons were found such as crude oil and naphtha; hydrocarbons were involved in 56 accidents (42% of all cases).

GENERAL AND SPECIFIC CAUSES OF THE ACCIDENTS

Accidents have been classified according to eight types of causes: mechanical failure, impact failure, human factor, instrumental failure, services failure, violent reaction, external events and upset process conditions. 22.2% of accidents have not been classified in any of these categories: they are not taken into account for this part of the study.

Some accidents have more than one general cause: this is the reason why the percentages add more than 100 (Table 1). Impact failure and external events are the most common causes. Human factor is the fourth main cause; however, in the rest of the world this cause becomes the main one with 42.9% of the accidents. It seems clear that this situation could be changed by improving the safety training of operators in these countries, and by a more strict regulation of hazmat transport.

Table 1. General causes of the accidents.

General cause	No. of accidents	Overall percentage	EU %	Other developed countries %	Rest of the world %
Impact failure	75	69.4	64.7	76.6	35.7
External events	38	35.2	17.6	42.9	14.3
Mechanical failure	31	28.7	17.6	28.6	42.9
Human factor	14	13.0	11.8	7.8	42.9
Violent reaction	3	2.8	0.0	3.9	0.0

POPULATION AFFECTED

In 38.5% of accidents analyzed there is no information about the number of deaths; probably there were no fatalities. They have not been considered for this part of the study.

Four categories have been established to classify the accidents as a function of the number of deaths: 0, 1-10, 11-100 and 101-1000. In more than 90% of the cases, there were less than 10. In particular, in 49.4% there were no fatalities. In 42% of the accidents there were between 1 and 10 deaths. Only one accident caused more than 100 fatalities: 320, after a train derailment in Iran, 2004.

The four more severe accidents occurred in developing countries and caused 320, 76, 63 and 46 fatalities, respectively, whereas in developed countries the worst case caused 16 fatalities. According to these data, accidents in developing countries would clearly have worse consequences on people.

The number of deaths does not decrease over the time; indeed, there were 607 deaths since 1961 but more than a half (379) died after 2001.

A value which can show the differences between developed and developing countries is the number of fatalities per accident. Studying all cases, the ratio between the number of fatalities and the number of accidents was found equal to 7.6. However, the ratio is found to be only 1.4 for the developed countries but 35 for the developing ones. This means that when an accident with domino effect in a developing country occurs, often it involves a significant number of fatalities; if the exceptional accident of Iran is withdrawn, still a worrying ratio of 15.6 fatalities per accident is found.

The mortality statistics can be used to obtain social risk curves using accumulated frequency-number of deaths graphs, which relate the number of deaths in a particular accident to the relative probability that there should occur this number of deaths (Figure 2). The value of 1 on the y-axis is the value arbitrarily assigned to all the accidents that involve at least one death. The slope of this curve indicates how the probability of an accident is reduced as a function of severity.

The b value of a curve $p = N^b$ was found to be -0.74. This means that the probability of an accident causing 10 or more deaths is 5.5 times higher than the probability of another one which causes 100 or more deaths. This ratio had been found to be 6.5 for all accidents involving domino effect according to the previous study from Hemmatian et al. (2014). Therefore, it seems that accidents in transportation are most severe in terms of fatalities. This can be explained by the fact that accidents during transportation can occur everywhere, affecting the surrounding population. On the contrary, accidents happening in plants should not affect the external population due to the legislation requirements which establish a safety distance to the urban zones.

A comparison between road and rail transportation shows that the severity of these two ways of transportation is similar: the slope is -0.71 for road transportation and -0.77 for rail transportation.

Furthermore, accidents in this survey seem to have more fatalities than other studies about general accidents (Vílchez et al., 1995, Carol et al., 2002); that would mean that the domino effect increases the severity. Kourniotis et al. (2000) compared the severity of accidents with and without domino effect: they also found that those implying domino effect are more severe. Darbra et al. (2010), from a comparison with the results of Vílchez et al. (1995), drew the same conclusion. Indeed, Darbra et al. (2010) found b = -0.74 studying only domino accidents, whereas Vílchez et al. (1995) found b = -0.84 studying all types.

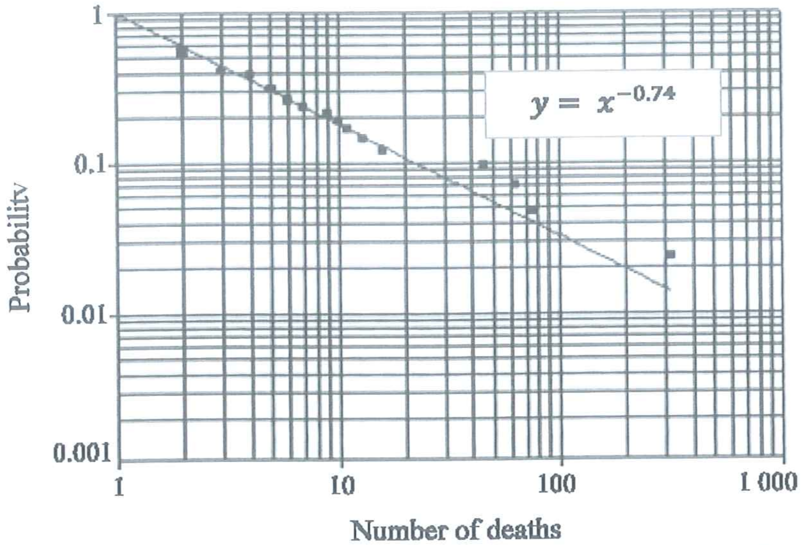


Figure 2. Accumulated probability as a function of the number of deaths.

As already mentioned, accidents in developing countries seem to be more severe; Figure 3 shows the corresponding p-N curves. This could be explained by differences of quality of roads, rail tracks and vehicles, as well as on traffic regulations.

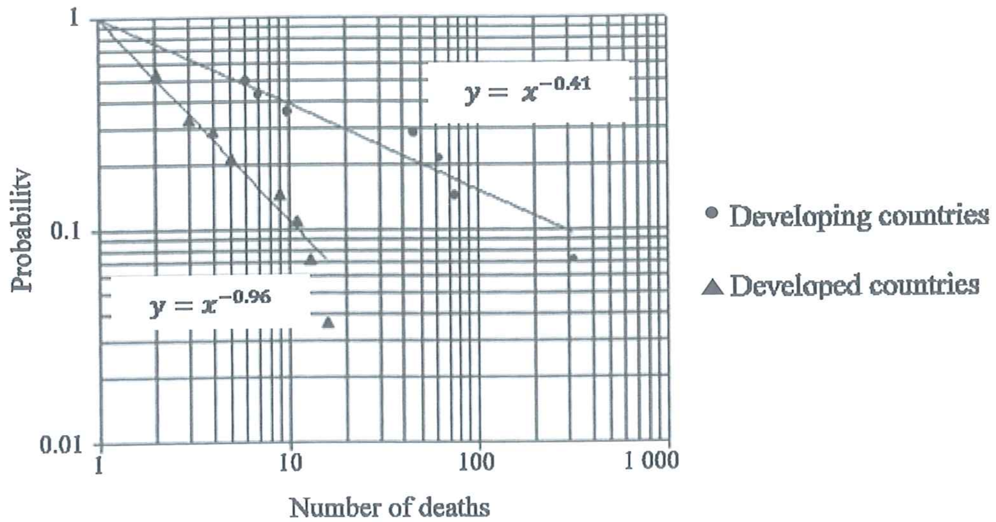


Figure 3. Accumulated probability as a function of the number of deaths for developed and developing countries.

DOMINO SEQUENCES

A practical way to analyze the domino accident sequences is the relative probability tree, in which each sequence is represented as a branch and its relative probability of occurrence can be easily calculated by a statistical treatment.

The event tree is represented in Figure 4. The number of accidents and the relative probability of occurrence (in brackets) are included in each branch. The relative probability was calculated by dividing the number of accidents by the number at the previous level. The overall probability value of each sequence is represented at the end of the branch.

31.9% of accidents started by an explosion and 68.1% by a fire. The most common sequence (58%) was a fire followed by an explosion. When the primary event was a fire (68.1%), the secondary events were an explosion (91.3%), a fire (3.3%), a release (3.3%) or an explosion with a release (2.1%). In this case, the most common three-step sequence was fire → explosion → fire (3%).

When the primary event was an explosion (31.9%), the main secondary event was a fire (83.7%), followed by a release (9.3%), a fire with a release (4.7%) and another explosion (2.3%). In this case, the most common three-step sequence was explosion → fire → explosion (11.9%).

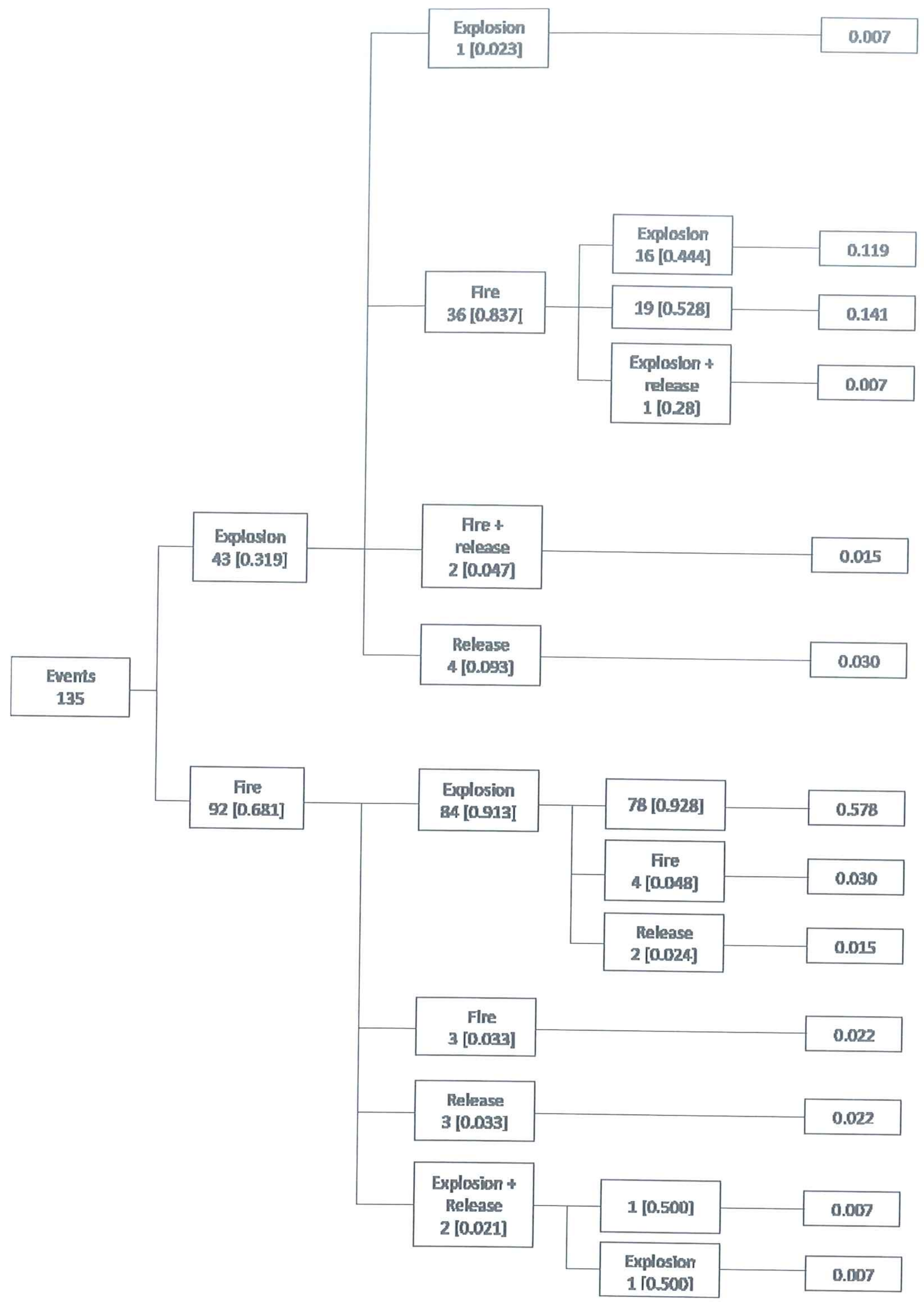


Figure 4. Relative probability tree (relative probability in brackets).

111 accidents included primary and secondary events ("two-step") and 24 included besides a "third step". Therefore, the ratio between "two-step" and "three-step" has been found to be 4.6. In the previous studies from Darbra et al (2010) and Hemmatian et al. (2014), this ratio was 6; this would indicate that in transportation of hazardous materials, there are more "three-step" cases than in other accidents.

Nevertheless, Chen et al. (2012) found a ratio of 3; they explained the difference with the ratio of 6 found by the aforementioned authors by the fact that they analyzed a significant number of accidents occurred in China and other developing countries: in this part of the world, these accidents have a longer chain of domino effects, with worse consequences. Abdolhamidzadeh et al. (2010) found a ratio of 2.2 in a study based on only 73 cases; this difference could be explained by a reduced set of data, based on very specific sources.

CONCLUSIONS

The accidents analyzed show a higher frequency in rail transportation than in road transportation: this is probably due to the fact that often several tank wagons containing hazardous materials are transported by rail, with the consequent probable domino effect in case of derailment; instead, road accidents usually involve a single road tanker. However, in developing countries about two thirds of accidents occurred in road transport, as in them this mean of transport is much more common than rail. As also noticed in previous surveys, transfer events keep showing a significant contribution (27%).

The overall frequency has not changed essentially over the years, even if the transportation of hazardous materials is continuously increasing. However, when analyzing the information in detail, this frequency has decreased in developed countries and has increased in the developing ones during the last thirty; this is due probably to a significant increase in the transportation in these countries, which have a less strict regulation and worse transportation routes.

Explosions and fires are the most common events, a logical consequence of the fact that 91% of the substances involved were flammable. Concerning the causes of the accidents, the most frequent one is impact, usually associated to a derailment or a road accident. Another important cause is human factor: originating 13% of all domino accidents, this percentage increases up to 43% in developing countries; this suggests that there is a significant potential improvement of this aspect through training of the involved people.

Concerning the severity, a strong difference between developed and developing countries is found: the probability that an accident with 10 or more fatalities will occur is 9 times greater than that of an accident with 100 or more deaths for a developed country; instead, it is only 2.5 greater in the developing ones.

The analysis of domino sequences has shown that 68% were initiated by a fire and the rest of them by an explosion. As compared with accidents occurred in fixed plants, in those occurred in transportation "three-step" sequences are more frequent.

Overall, this survey indicates that the measures taken in developed countries have led to a reduction of the frequency of transportation domino accidents. Measures should be taken in developing countries to reach better safety conditions: increase of operators safety training, implementation of transport regulations and –more difficult– improvement of transportation routes.

ACKNOWLEDGEMENTS

The authors thank the Spanish Ministry of Science and Innovation (project no. CTQ2011-27285) and the Autonomous Government of Catalonia (project no. 2009 SGR 1118) for sponsoring this research.

References

Abdolhamidzadeh B, Abbasi T, Rashtchian D, Abbasi SA. Journal of Hazardous Materials 182 (1010) 416-426.
Abdolhamidzadeh B, Abbasi T, Rashtchian D, Abbasi SA. (2011). Journal of Loss Prevention in the Process Industries 24 (2011) 575-593.
ARIA (Analysis, Research and Information on Accidents). French Ministry of Ecology, sustainable development and energy (2012).
Chen, Y., Zhang, M., Guo, P., & Jiang, J. Procedia Engineering 45 (2012) 152-158.
Darbra, RM, Palacios A, Casal J. Journal of Hazardous Materials 183 (2010) 565-573.
Delvosalle, C. A methodology for the identification and evaluation of domino effects. (1998) Brussels.
Failure and Accidents Technical information System (FACTS) (2010). TNO industrial and external safety.
Haastrup P, Brockhoff L. Journal of Loss Prevention in the Process Industries 3 (1990) 395-405.
Hemmatian B, Abdolhamidzadeh B, Darbra RM., Casal J. Journal of Loss Prev. in the Process Industries 29 (2014) 30-38.
Kourniotis SP, Kiranoudis C, Markato NC. Journal of Hazardous Materials 71 (2000) 239-252.
Major Hazardous Incident Data Service (MHIDAS). In AEA Technology. London: HSE-Health and Safety Executive. (2007) (United Kingdom).
Oggero A, Darbra RM., Muñoz M, Planas E, Casal, J. Journal of Hazardous Materials 133 (2006) 1-7.
Reniers G, Cozzani V. (Eds.). Domino effects in the process industries. Modelling, prevention and managing. Amsterdam Elsevier (2013).
RISCAD (2012). Available from: www.riscad.db.aist.go.jp/. Accessed 23.06.14.
Ronza A, Félez S, Darbra RM, Carol S, Vílchez JA. Casal, J. Journal of Loss Prevention in the Process Industries 16 (2003) 551-560.
Vílchez JA, Sevilla S, Montiel H, Casal, J. Journal of Loss Prevention in the Process Industries 8 (1995) 87-96.