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Analysis of Risks Associated with Hazardous Materials Transportation in the French Chemical Industry

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This article focuses on the risks associated with Hazardous Materials Transportation (HazMaT) events in the French chemical industry between 1981 and 2022. The study aims to analyze and assess the causes and consequences of past events using the ARIA database, which lists over 54,000 events that have taken place in France and abroad. The severity of events is classified into five categories, from near misses to catastrophic events. The study highlights the importance of risk analysis/assessment and lessons learned from past events in managing natural and technological risks.

1. Introduction

Chemical industries are subject to significant debate because of the human, environmental, and economic risks they may pose (Dakkoune et al., 2018a). Due to the severity of the consequences of these events, regulatory authorities have developed regulations to mitigate the adverse effects of industrial accidents.
The Seveso directive stands as the most widely recognized European directive addressing risks related to industrial installations. However, regulations can differ across EU member states. In France, for example, the Environmental Code (Légifrance, 2022) which is a law that defines the obligations to be followed when reporting an industrial accident. Moreover, the academic community has also shown interest in these concerns regarding industrial risk. Among the methodologies developed: risk analysis/assessment (Khan and Abbasi., 1998) and lessons learned from past events (Elliott et al., 2003, Dakkoune et al., 2018b) have been prominent. Numerous studies have focused on the lessons learned approach regarding the Hazardous Materials Transportation (HazMaT), drawing on scientific articles (Ekut et al., 2007; Dita et al., 2016).
Despite several scientific studies having been conducted, no study has been found that specifically focuses on analyzing and assessing the risks associated with past HazMaT events in relation with the number of chemical establishments in France. The importance of the French chemical industry to its economy cannot be overstated. It currently ranks sixth globally in terms of chemical production and was the second-largest producer in Europe in 2021 (FranceChimie, 2023). This study aims to analyze and assess the risks associated with Hazardous Materials Transportation (HazMaT) events in France. To achieve this, a comprehensive analysis and evaluation of the causes and consequences of events that took place in the French chemical industry between 1981 and 2022 was conducted, using data from the ARIA database.

2. Methodology

2.1 Description of ARIA database

The ARIA database has been used in many scientific studies, showing its relevance and usefulness in the field of chemical safety (Dakkoune et al., 2018b; Casson Moreno and Cozzani., 2015). The ARIA database records events that have caused or have the potential to cause harm to public health, safety, or the environment. These events are mainly related to industrial activities that fall under the legislation on classified facilities.

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The database lists over 54,000 events that have taken place in France and abroad, which amounts to roughly 1,900 new events each year as of now.

2.2 Data Selection

To analyze information contained in the ARIA database, the official website provides "Advanced Search" and "Simple Search" tools. The "Advanced Search" tool categorizes filters into two groups of criteria: "General Criteria" and "Event-specific Criteria". By combining these criteria, information within the platform can be segmented and refined for a more comprehensive analysis of the data published in the database. On the other hand, the "Simple Search" tool is a quick filtering option for information, using keywords to obtain reports of events where the word appears.

2.3 Trends of events

Between 1981 and 2022, the ARIA database has recorded a total of 55,932 events worldwide, with 49,209 occurring in France, out of the 49,209 events that occurred in French chemical facilities, 180 were linked to the (HazMaT).

2.4 Definitions

The severity of events can be classified into five categories based on the definition proposed by (Rathnayaka et al., 2011), which was later adopted by (Dakkoune et al., 2018b). However, in this study, the criteria used to classify events into each category were refined by specifying the number of serious injuries and fatalities in each category according to (Mannan., 2005).
This severity classification is essential because it allows events to be grouped according to their severity, from the most severe to the least severe. Table 1 presents the five different severity categories (C1 to C5) that are ranked in ascending order, so that an event's severity increases as one moves down the first column. Each category is directly linked to five types of consequences: human, environmental, production, property, and business reputation. These types of consequences are placed in the appropriate severity category.

Table 1:Consequence class for each event

Event	Consequences					Severity class
	Human	Environment	Production	Property	Reputation	
Near miss	No injuries	No impact	No loss	No effect	No impact	C1
Mishap	Minor health effects	Minor damage	Production loss Work hours loss	Minor damage	Minor impact	C2
Incident	Injuries (<5 employees) with public hospitalization	Localized damage	Significant work days loss	Major damage	Considerable media reaction	C3
Accident	Death (1 or 2 employees)/ serious injury (>5 employees)	Short-term environmental damage	Work lost (between 1 and 3 months)	Serious damage	Report in the national media	C4
Catastrophic	Deaths (>3 employees)/ Public fatality and injuries (>5)	Environmental damage	Work Lost (>3 months) or permanent shut down of the plant	Catastrophic damages	Intense international media reaction	C5

3. Results and Discussion

Figure 1 presents the distribution of events related to the Hazardous Material Transportation (HazMaT) according to their severity, based on the ARIA database. The events were classified according to the criteria outlined in Table 1. It should be noted that no events were identified in the near-miss category (C1) (near-misses are not recorded in the ARIA database). Mishap category events (C2) represent the highest percentage (60%), followed by incidents (C3) (28%), accidents (C4) (11%), and finally catastrophes (C5) (1%).

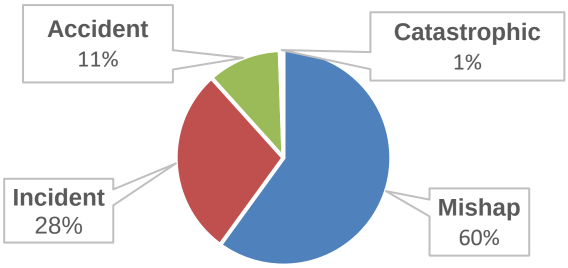

Figure 1: Distribution of HazMaT events by consequences in France: ARIA database (1981-2022)

3.1 Hazardous Phenomenon

Figure 2 shows the distribution of HazMaT events by hazardous phenomenon, based on reports published in the ARIA database. The release of hazardous materials was the most frequent hazardous phenomenon, accounting for 61% of events, followed by fires (22%) and explosions (9%).

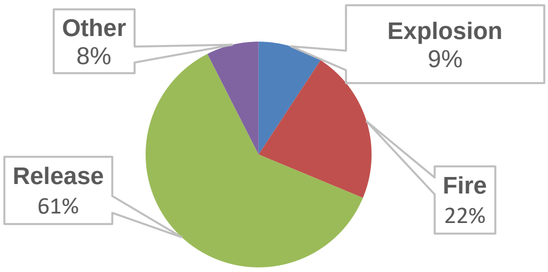

Figure 2: Distribution of HazMaT events by hazardous phenomenon: ARIA database.

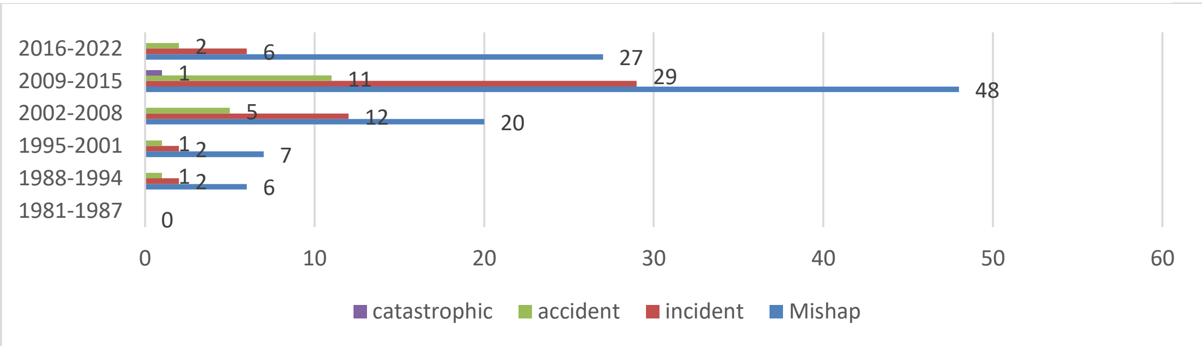

Figure 3: Distribution of HazMaT events by period: ARIA database.

Figure 3 presents the temporal evolution of events associated with Hazardous Material Transportation (HazMaT) recorded in the ARIA database. No HazMaT event was reported between 1981 and 1987, but their number increased significantly from 1988 to 2015. Then, a decrease was observed from 2016 to 2022. This decrease may be due to some events not yet being recorded in the ARIA database, but it could also be attributed to the confinement period imposed by the Covid-19 pandemic, which led to a significant decrease in industrial activity (Guerini et al., 2020).

Figure 4 depicts the distribution of hazardous material transportation (HazMaT) accidents by chemical industry sector between 1981 and 2022. The transportation sector (rail/road/water, pipeline) was the most affected, accounting for 76.11% of HazMaT accidents (137 events). The second largest sector affected was handling and storage centers with 8% of HazMaT events (16 events). Together, these two sectors represent 84.11% of HazMaT events during the period from 1981 to 2022.

Figure 5 presents the human consequences of events involving the transport of hazardous materials in the chemical industry sector between 1981 and 2022. Out of the 180 recorded events, 71 resulted in injuries and fatalities, totalling 164 injuries and 33 deaths.

The transportation sector (rail/road/water, pipeline transport) recorded the highest number of deaths with 29, followed by the (sanitation/waste management) sector with 2 deaths.
The most affected sectors in terms of injuries are transportation (rail/road/water, pipeline transport), with 117 injuries, handling and storage with 23 injuries, and sanitation/waste management with 10 injuries.

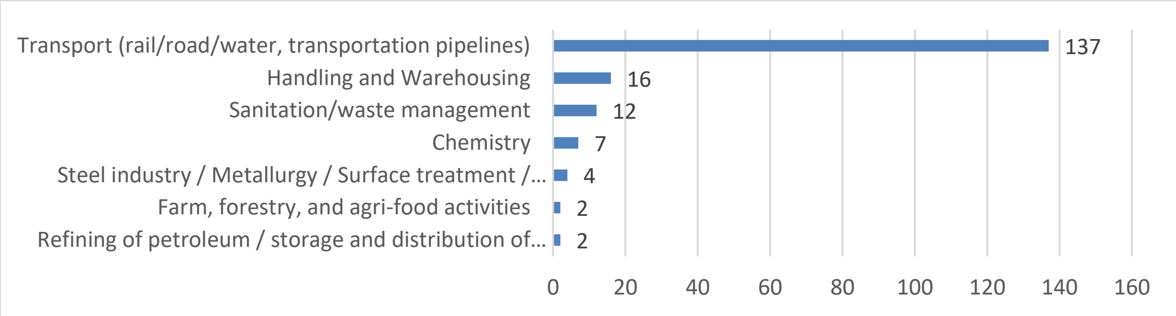

Figure 4: Distribution of HazMaT events by industrial sectors

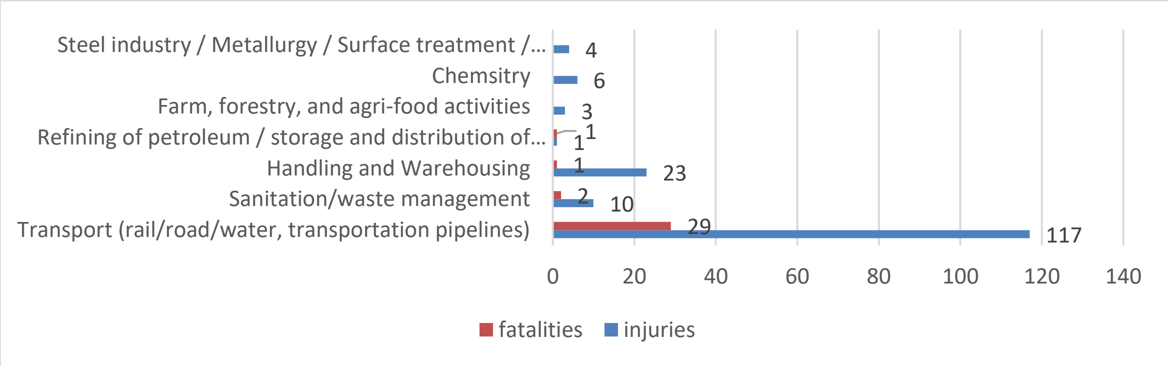

Figure 5: Number of injuries and fatalities by type of French chemical industry for the period 1981-2022

Table 2: Primary and specific causes according to the ARIA database

Primary causes	Specific causes	No. of events	% of category
HazMaT by vehicles (129)	Traffic accident	129	100
	Loss of containment	70	59
	Rupture	26	22
	Failure	5	4
Equipment failure (119)	Deformation, weakening	3	2
	Damaged seal	2	2
	Clogging	1	1
	Other	12	10
	Action not required	44	61
Human (72)	Wrong action	24	33
	Action not performed	4	6
External causes (11)	Weather phenomenon	10	91
	flooding, submersion	1	9
Chemical reactivity (10)	Product decomposition, parasitic reactions	5	50
	Mixing of incompatible products	3	30
	Other	2	20

3.2 Causes of Events

The understanding of the root causes of such events is crucial in order to prevent them in the future, as highlighted by us. The same event can be contributed by several scenarios. In this work, the initial causes will be classified into 5 distinct categories: causes related to installation and equipment, human causes, external causes, HazMaT by vehicles, and Chemical reactivity. These five categories represent the different factors that can lead to the observed issues.

Table 2 presents an analysis of the root causes behind HazMaT-related events in France between 1981 and 2022. The total number of HazMaT-related events recorded in ARIA is over 180, owing to the fact that some events were triggered by multiple root causes, thereby accounting for the high number of causes.

Table 2 indicates that out of all the events recorded, 38% are due to HazMaT by vehicles. Equipment failure is the second most frequent cause of events, accounting for 35% of recorded events, while human interventions are responsible for 21% of HazMaT -related accidents.

3.3 Specific Causes

Table 2 shows that the specific causes of events are related to their corresponding root causes. Analyzing these specific causes allows for a precise determination of the origin of each event, thus providing a better understanding of their nature.

Traffic accidents represent the most frequent specific cause of HazMaT events by vehicle, accounting for approximately 100% of this category. On the other hand, for Equipment failure, loss of containment (58.82%) and rupture (21.84%) are the most common specific causes. Regarding chemical reactivity, decomposition of products and parasitic reactions are the most frequent specific cause, accounting for approximately 50%. Analyzing this data provides a better understanding of the root causes of each HazMaT -related event, thus enabling effective prevention measures to be implemented.

3.4 Risk Assessment

The risk assessment in this study was conducted using a risk matrix, which allowed classifying the risks associated with HazMaT between 1981 and 2022 according to their severity. The methodology used for this classification is semi-quantitative and based on (Di Padova et al., 2011) methodology adapted from the ISO 17776 (International Organization for Standardization (ISO), 2000) methodology. The risk matrix made it possible to calculate the probability and consequences levels of risks in order to classify them in order of importance.

As shown in Table 1, the severity of risks was divided into five categories: Near miss (C1), Mishap (C2), Incident (C3), Accident (C4), and Catastrophic (C5). The frequency of events for each category (frequency) was estimated based on the works of (Casson Moreno and Cozzani 2015), and (Casson Moreno et al., 2016), and calculated using equation (1), by dividing the number of each event by the total duration of the study (41 years) and the estimated (number of chemical industries in France (3,300 according to the Ministry of Economy, Finance, and Industrial and Digital Sovereignty).

$$frequency = \frac{\frac{Number\ of\ each\ event}{Total\ duration\ of\ the\ study}}{estimated\ number\ of\ chemical\ industry\ in\ France} \qquad \text{Eq (1)}$$

The results of the frequency calculation are summarized in Figure 6, and are divided into five categories ranging from the lowest to the highest frequencies.

Frequency Severity	$F<10^{-5}$	$10^{-5}<F<10^{-3}$	$10^{-3}<F<10^{-2}$	$10^{-2}<F<10^{-1}$	$F<10^{-1}$
C1					
C2		$7{,}9 \times 10^{-4}$ (108 events)			
C3		$3{,}37 \times 10^{-4}$ (51 events)			
C4		$1{,}4 \times 10^{-4}$ (20 events)			
C5	7.39×10^{-6} (1events)				

Figure 6: risk matrix

The Figure 6 illustrates the risk matrix, a key tool for assessing the level of risk associated with HazMaT by combining frequency and severity indices (ranging from C1 (low severity) to C5 (very high severity)). It is composed of three colors: green for normal situations, yellow for situations requiring increased vigilance and implementation of safety barriers, and red for unacceptable or degraded situations requiring immediate intervention. Events identified in the yellow and red zones should be prioritized for risk minimization.
The risk matrix displays events categorized within the yellow and red zones, 72 events, indicating risks of moderate and high severity.
It is important to note that risks located in the yellow zone should be closely monitored and appropriate risk reduction measures should be put in place to minimize their potential impact. Although these risks are not considered the most critical, they can still cause significant damage if not managed adequately.

4. Conclusion

This article presents an analysis of hazardous materials transportation events in France from 1981 to 2022 using the ARIA database. Events were classified based on their severity, hazardous phenomenon, industrial sector, and human consequences. The distribution of events by severity shows that the majority of them are mishaps (C2). Releases of hazardous materials were the most frequent hazardous phenomenon, representing 61% of the events, followed by fires and explosions. The transportation sector (rail/road/water, pipeline) was the most affected, accounting for 76.11% of HazMaT events. In terms of human consequences, 71 events resulted in injuries and fatalities, totaling 164 injuries and 33 deaths. The causes of these events are diverse, ranging from technical and physical causes to human and organizational factors. This study highlights the imperative need to enhance transportation safety, given that it is one of the vulnerable sectors prone to severe accidents involving HazMaT.
It is crucial to understand the causes behind these events in order to prevent them or mitigate their consequences effectively. Indeed, identifying potential vulnerabilities, systemic problems or human factors that contribute to such events can contribute to the development of targeted preventive measures, improved safety protocols and sound contingency plans, in order to minimize the occurrence and impact of future incidents.

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