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Investigation Of Safety Barrier Role In Hydrogen Related Undesired Events

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Abstract

Hydrogen is the leading candidate for achieving the goal of decarbonization and making countries energy-independent in the long term. However, spreading hydrogen in different sectors faces various issues, including safety: its flammability characteristics and the ability to permeate and embrittle most metallic materials raise concerns. Safety functions are of the utmost importance in managing conditions that can be hazardous. Preventing an event or controlling or limiting its consequences through safety barriers is possible. They also represent a means to increase a system's resilience, enabling quicker reactions or preventive actions. The lack of them and their wrong installation and/or improper use can be crucial in developing undesired events. This study aims to understand the role of safety barriers in several hydrogen-related undesired events in the past. The available descriptions of past events can provide valuable information, but the number of records makes manual data extraction challenging. First, a set of safety barriers relevant to hydrogen events is developed, extracting information from the ARAMIS project deliverables. Subsequently, the HIAD 2.0 database is analyzed to find any connection with the safety barriers dataset through text comparison, leading to new information mining.

Keywords: hydrogen safety, safety barriers, accident analysis, resilience, Natural Language Processing.

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1. Introduction

The need to face global warming and climate change is ever more urgent, and the global community is putting much effort into addressing this challenge, investigating several strategies and opportunities. Hydrogen has emerged as a valuable solution to ensure a versatile, effective, and clean energy future since its combustion is carbon neutral. As of now, it has been used in refining, in the chemical industry as a feedstock, and in the steel industry as a reducing agent (IEA, 2023). New potential applications advantageous for the decarbonization goal are its usage as fuel in hard-to-abate sectors, such as glass or aluminium manufacturing, and its usage for transportation, such as aviation, cars, buses, and trucks.

Nevertheless, besides the technical issues in scaling up production and transportation, one of the major bottlenecks of the hydrogen rolling out in several sectors is represented by safety aspects. Hydrogen is the smallest existing substance; it is colorless and odorless; it is highly explosive and flammable (4 – 75 % in air) and has low minimum ignition energy (0.02 mJ) (Nicoletti et al., 2015).

Moreover, hydrogen has the capability to embrittle and permeate most of the metallic materials used for containment in transportation and storage (Abohamzeh et al., 2021). Hence, hydrogen-induced material failures, also known as Hydrogen Damages (HDs) are one of the leading causes of hydrogen loss of containment (LOC), representing the critical event (CE) in the bow-tie diagram (Ustolin et al., 2020).

Introducing a hazardous substance such as hydrogen in a plant inevitably requires of being aware of the risks that can arise and ready to tackle dangerous situations. Safety devices and operations to prevent or mitigate possible accident scenarios are significant means to avoid or manage them.

Figure 1 graphically shows how safety barriers can affect the development of events using the terminology clearly expressed in the deliverables of the ARAMIS project (Delvosalle et al., 2006). The left part of the diagram is the well-known fault tree, which is divided into three levels: the Detailed Direct Causes (DDC), the Direct Causes (DC), and the Necessary and Sufficient Causes (NSC). Moving from left to right, the level of technicality increases: in the last level, only the technical aspects are considered, while in the first level, human behavior and organizational aspects are also considered. The event tree represents the right part of the diagram, and it is organized in Secondary Critical Event (SCE), Tertiary Critical Event (TCE) and Dangerous Phenomena (DP), which are fires, missiles ejection, overpressure generation, toxic cloud, and so forth.

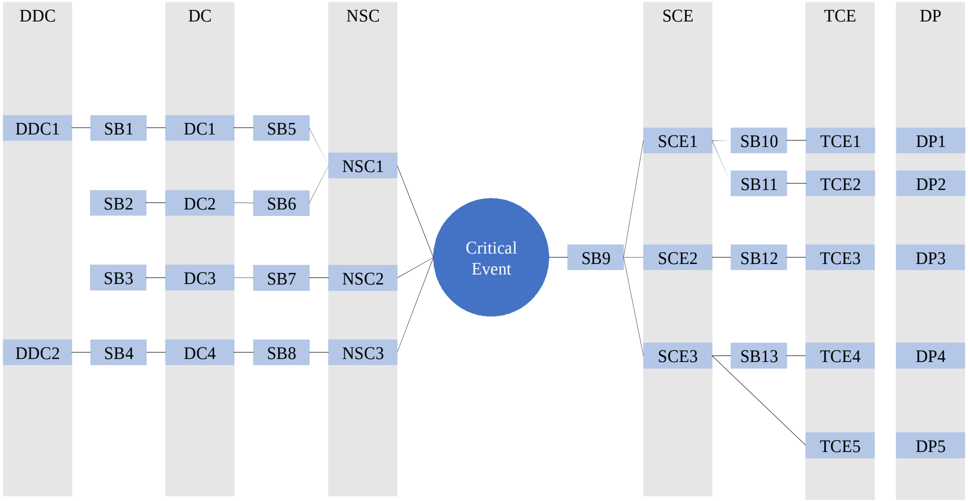

Fig. 1. Schematic representation of safety barriers in the bow-tie diagram. DDC is Detailed Direct Causes; DC is Direct Causes; NSC is Necessary and/or Sufficient Causes; SCE is Secondary Critical Event; TCE is Tertiary Critical Event; and DP is Dangerous Phenomena.

Incorporating safety barriers into a system allows the success of the safety functions, which aim to avoid an event or to control or limit the consequences of the event. They can contribute to reducing the frequency of an event or mitigating the consequences of dangerous phenomena. In this way, the resilience of the system ("the capability of recognizing, adapting to, and coping with the unexpected" (Woods, 2017)) is intrinsically increased. Hence, identifying a proper set of safety barriers is essential in the design phase of the plant. In addition, the REWI methodology ("Resilience-based Early Warning Indicators") (Øien et al., 2012) represents an appropriate tool to assess the performance of the barriers as shown in several studies (Hosseinnia Davatgar et al., 2021; Bucelli et al., 2017; Thieme and Utne, 2017). According to this methodology, collecting information about the quality of the barriers can help achieve knowledge and experience about risks and hazards.

Learning from past events has always been crucial to the process safety industry. Over the years, this strategy has been adopted in the chemical and petrochemical sectors (Tamascelli et al., 2022; Zhao et al., 2014). Considering the emerging nature of the hydrogen systems, learning from past events is even more essential.

Analyzing undesired events is extremely valuable because it helps understand what went wrong and what is crucial for a plant to work safely.

Combining the importance of the analysis of past errors and the criticality of safety barriers, the objective of this study is to analyze a selection of undesired events in which hydrogen was involved to mine information about the presence of the safety barriers and their eventual failure. Although the number of records of hydrogen-related undesired events is not high, reading those reports is still time-consuming. For this reason, an automated approach that considers the list of safety barriers depicted in the ARAMIS project is proposed, making this study one of the pioneers of this procedure with hydrogen events.

The expected result would be a dataset of safety barriers and specific information about which barriers are particularly critical and relevant to emerging hydrogen-based industries.

This paper is structured as follows. The "HIAD 2.0 database" section first describes the collection selected for the analysis in this study and then summarizes the studies carried out by other researchers on the same database.

The “Methodology” section explains the procedure adopted in this study: the extraction of the safety barriers from the ARAMIS document and the finding of matches with the records in the database are delineated. The “Results and Discussion” section shows and comments on the outcomes of the study, highlighting the limitations of this work and underlining the future steps of this research with the corresponding challenges. Finally, the “Conclusion” section summarizes the study.

2. HIAD 2.0 database

The Hydrogen Incident and Accident Database - HIAD - was announced for the first time (Kirchsteiger et al., 2007) to contribute to safely introducing hydrogen technologies and applications in the framework of the HySafe, an European Commission co-funded Network of Excellence (NoE) project. The primary purpose was to facilitate the understanding of hydrogen-related undesired events. A tricky part of the risk assessment is hazard identification, especially when the technology under analysis is not well-established and developed. Hence, the original objective of the database was to serve as an essential data source for the quantitative risk assessment (Galassi et al., 2012). Over the years, this database has been populated, but it was not possible to reach the initial goal due to the lack of information. An updated version, HIAD 2.0, was developed to fulfill a different purpose: a tool to promote sharing lessons learned (Melideo et al., 2019).

As of its most recent update in July 2023, the database contains records of 689 events collected from several generic databases, most of all the French database ARIA events, or the English database of the Institution of Chemical Engineers (IChemE, 2023) and provided by scientific articles (Wen et al., 2022).

The database is provided through five categories: “Events”, “Facility”, “Consequences”, “Lessons Learnt”, “Event Nature”. Each category represents a sheet in the Excel file, and it is further divided into several columns, which help characterize the event. “Event initiating system”, “Causes”, “Causes comments”, “Components involved”, “Number of fatalities”, “Lessons learnt”, “Release type” are only a few of the 96 total columns. All the events are associated with an Event ID, a title, a complete description, and an index, a quality indicator ranging from 1 to 5. The higher the value of the indicator, the higher the quality of the information provided with the event.

The investigation of this database has already come up with some insights into the system design, the system manufacturing, installation, and modification, the human factors, and the emergency response (Wen et al., 2022). Another study applied a Business Analytic approach to extract statistical information regarding the events that occurred in different industrial sectors, countries, and location types (Campari et al., 2023a). In addition, it analyzed the material incompatibility in more depth, highlighting the role of hydrogen-induced failures (Campari et al., 2023a). The analysis of this database also led to emphasize the necessity of collaboration and data sharing to accelerate the safe use of hydrogen (Baboi et al., 2023).

A structured repository tool called HIRA (Hydrogen-related Incident Reports and Analyses) has been developed from HIAD 2.0 (Campari et al., 2023b). The exploration of the latter provided awareness of the maintenance role in the hydrogen undesired events (Collina et al., 2023): this study showed how maintenance could be involved in several events, either because of lack of maintenance or because of errors during maintenance operations.

3. Methodology

This study aims to investigate the participation of safety barriers in hydrogen-related undesired events collected in the HIAD 2.0 database. In the current database version, any references to this are presented as columns in the structure described in the section above. Figure 2 shows the methodology adopted in this work, which allows adding an eventual further column in the database without reading all the recordings but adopting a more automated approach, thus helping save time.

The core of the study is the comparison of two datasets based on the finding of eventual matches in the text. Initially, the procedure follows two parallel paths to obtain these two datasets. On one side, HIAD 2.0 has to be prepared for the analysis; among all the available fields, “Event full description”, “Cause comments” and “Lessons learnt” are the columns selected for this study because they are the ones with more text. The text is slightly pre-processed through the Natural Language Processing techniques to the extent required to make it comparable with the output of the parallel path on safety barrier selection: lowercasing all the characters, deleting punctuations, and correcting some typos are necessary.

On the other side, a proper dataset of safety barriers is developed. One of the deliverables of the ARAMIS project provides a non-exhaustive list of safety barriers (Delvosalle et al., 2006), divided into ones contributing upstream of the critical event and others contributing downstream of the critical event. In the document for each safety function, some safety barriers are mentioned. Compiling the information from this document leads to the production of a draft of the dataset, which is processed to drop the duplicates and to prepare the text for the same reason as the HIAD 2.0 pre-processing. For completeness, all the procedures are applied through Python scripts.

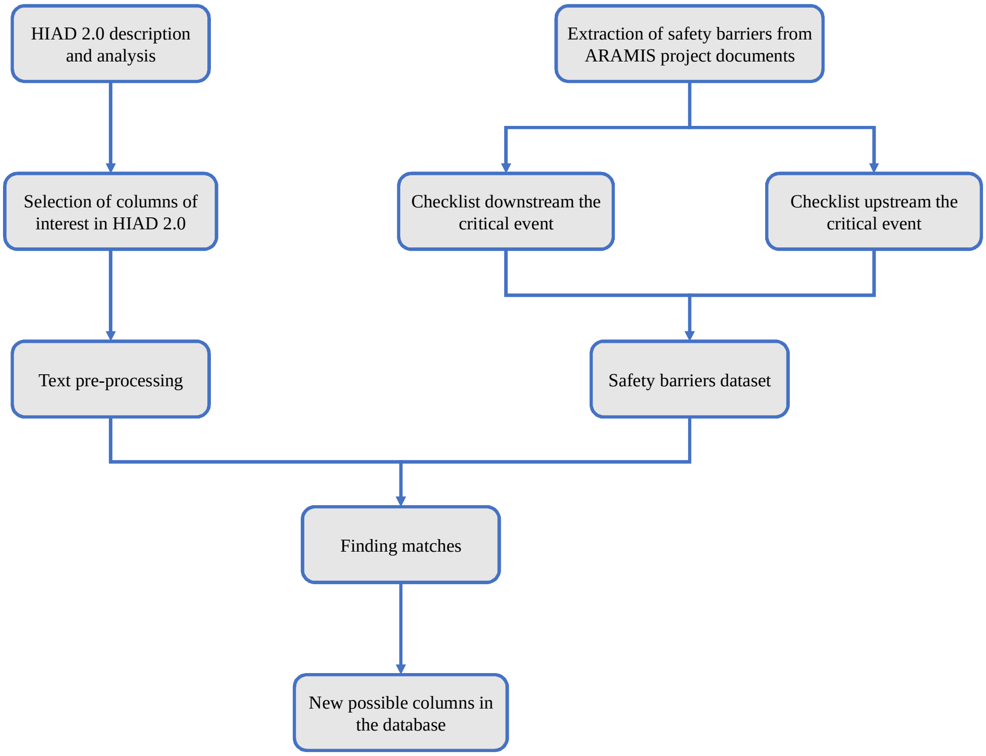

Fig. 2. Schematic methodology for this study.

4. Results

The analysis is carried out on the text of the columns “Event full description”, “Cause comments” and “Lessons Learnt” as stated in the methodology. The data quality of the records is heterogeneous: 339 events have an indicator of ‘2’, 198 events have ‘3’, 70 events have ‘4’, and 82 events have ‘5’. All the events have a complete description, and the cause comments are missing in 195 records. On the other hand, the column in which lessons learned are exploited stands out when compared with the others: only 333 records have the associated column, which is less than 50%. The three columns have been merged into one and pre-processed for the study.

In the framework of the ARAMIS project (Delvosalle et al., 2006), the MIRAS method – “Methodology for the identification of reference accident scenarios” – considers the safety systems installed on and around the equipment to identify the reference accident scenarios taking into account the real system. The safety system influences the possibility of the occurrence of critical events. Safety barriers are the means of the safety system, leading to the application of safety functions, which are technical or organizational actions to prevent an event or control or limit its consequences. This document provides a non-exhaustive list of safety barriers to implement in a system.

First, the collection of the safety barriers from this list was prepared based on the information from the original deliverable of the project as two different text files: safety barriers before the critical events derive from the fault tree and are responsible for preventing the event; safety barriers downstream the critical event have a role in the event tree and are responsible for controlling, limiting the event and preventing the escalation of dangerous scenarios. From merging these two files and the pre-processing step, which allowed the drop of the duplicates and lowercase of the text, a new dataset of 614 entries has been created to use as input for the matching findings: 489 from the upstream of the critical event, and 125 from the downstream. After arranging the two datasets, the texts can finally be compared.

The matches were found in 332 records. Some records showed more than one safety barrier, as depicted in Table 1, the range varies between one and seven matchings. Fifty-two safety barriers from the dataset were found in the database text.

Table 1. Number of records with a specific number of safety barriers cited in the text.

Number of cited safety barriers	Number of records
1	151
2	92
3	48
4	21
5	11
6	8
7	1

The analysis revealed that the maximum number of safety barriers in one event is seven, as Table 1 shows. The event ID698 was a primary explosion of a flammable vapour cloud leaked from a reactor, followed by multiple other explosions and fires in a polyethylene manufacturing plant. The safety barriers listed in Table 2 either failed or were not present. The incident occurred during the maintenance operation of cleaning up the settling branches connected to the manufacturing reactor. An effective permit system was not enforced for the control of maintenance activities. An isolation valve did not work correctly since it was meant to be closed, but it was open. The workshop lacked gas detectors, an emergency shutdown was impossible because of the insufficient separation distances between process equipment, and the ventilation was not arranged. The simultaneous failure or lack of these safety barriers led to 23 fatalities and 314 injured workers.

Table 2. Example of the results of the analysis.

Event ID	barrier 1	barrier 2	barrier 3	barrier 4	barrier 5	barrier 6	barrier 7
698	isolation valve	ventilation	detector	permit system	clean up	maintenance	emergency shutdown procedure

Table 3 shows a selection of illustrative analysis results: for each safety barrier, the number of times appearing in the database and the records in which they are mentioned are expressed. The role of the selected safety barriers is also represented in Figure 3.

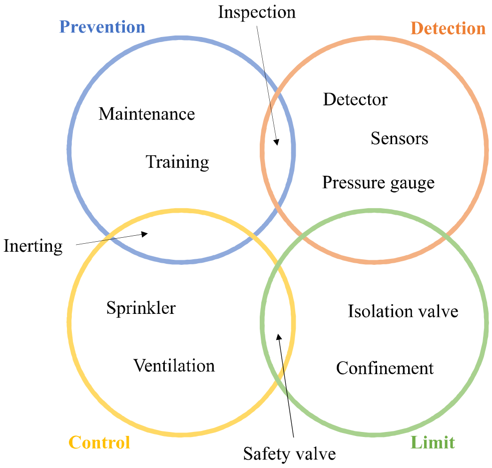

Fig. 3. The role of the mentioned safety barriers in the events.

Table 3. Representative results of matching findings.

Safety Barrier	Typology	Count	Event IDs
maintenance	upstream CE	122	18, 30, 44, 47, 52, 84, 85, 87, 92, 94, 101, 110, 114, 117, 168, 185, 189, 192, 206, 207, 209, 214, 217, 220, 223, 242, 246, 247, 249, 256, 301, 341, 351, 410, 411, 478, 485, 490, 494, 505, 525, 542, 547, 552, 553, 561, 562, 563, 600, 601, 612, 615, 621, 622, 631, 638, 673, 675, 685, 686, 698, 711, 716, 717, 743, 744, 748, 750, 759, 760, 773, 785, 787, 789, 810, 844, 854, 863, 871, 883, 886, 887, 891, 897, 900, 906, 912, 917, 921, 922, 924, 925, 933, 935, 937, 939, 943, 944, 950, 951, 958, 959, 973, 975, 978, 979, 987, 988, 994, 1012, 1017, 1021, 1023, 1024, 1029, 1034, 1035, 1037, 1045, 1046, 1047, 1050
inspection	upstream CE	94	17, 30, 52, 86, 87, 102, 114, 180, 214, 218, 241, 247, 271, 301, 306, 401, 429, 496, 501, 510, 522, 526, 531, 568, 571, 601, 615, 648, 651, 675, 678, 681, 686, 688, 689, 728, 743, 748, 758, 759, 765, 766, 771, 772, 796, 798, 802, 807, 810, 832, 835, 838, 840, 847, 849, 884, 885, 887, 892, 905, 908, 915, 922, 924, 925, 926, 947, 952, 958, 965, 969, 973, 975, 981, 983, 984, 987, 1023, 1024, 1032, 1034, 1035, 1037, 1040, 1042, 1043, 1045, 1047, 1049, 1050, 1053, 1056, 1058, 1060
training	upstream CE	50	29, 44, 57, 116, 167, 185, 204, 206, 216, 218, 225, 228, 234, 246, 345, 380, 385, 429, 475, 494, 538, 547, 563, 599, 650, 700, 760, 764, 789, 846, 885, 886, 904, 913, 915, 916, 922, 943, 951, 959, 973, 990, 1003, 1006, 1033, 1036, 1043, 1044, 1047, 1053
detector	downstream CE	26	28, 34, 57, 87, 206, 252, 547, 569, 618, 673, 698, 765, 781, 785, 807, 888, 906, 913, 919, 938, 941, 944, 953, 965, 972, 1015
sensor	downstream CE	19	10, 28, 86, 87, 179, 229, 380, 401, 672, 785, 786, 844, 918, 941, 942, 972, 1024, 1029, 1034
ventilation	downstream CE	15	46, 305, 494, 496, 499, 616, 698, 703, 821, 927, 944, 951, 972, 1011, 1052
isolation valve	downstream CE	11	16, 167, 229, 382, 562, 650, 698, 716, 720, 844, 1058
sprinkler	upstream CE	11	81, 207, 525, 650, 722, 746, 748, 871, 1012, 1021, 1024
safety valve	upstream CE	9	58, 189, 249, 262, 349, 402, 496, 944, 1002
pressure gauge	upstream CE	8	33, 189, 248, 275, 429, 653, 730, 1036
inerting	upstream CE	7	186, 207, 785, 815, 871, 933, 1030
confinement	downstream CE	6	60, 336, 547, 766, 843, 936
preventive maintenance	upstream CE	6	189, 207, 249, 490, 871, 973
pressure sensor	upstream CE	4	10, 86, 87, 918
plant inspection	upstream CE	4	87, 648, 686, 947
visual inspection	upstream CE	4	241, 758, 835, 981

5. Discussion

The results showed that only fifty-two safety barriers from the dataset were found in the database text. This result shows the first drawback of the analysis: finding the exact correspondence in the text is not easy, especially regarding the safety barriers upstream of the critical event. In some cases, the safety barriers are not represented by a simple word or a union of two words but by almost a sentence, making matching the text challenging.

Maintenance (or preventive maintenance) is the safety barrier indicated in most events, and it could be essential in preventing events, as shown in Figure 3. According to previous studies (Collina et al., 2023), maintenance can be involved in the sense of lack of maintenance or errors during maintenance operations, as for the event in Table 1. The distinction between maintenance and inspection is nuanced. Inspections (visual or plant inspection) are essential safety measures, and their absence has contributed to numerous accidents. The role of this measure can be classified either as prevention or detection. Hydrogen can easily interact with most metals: hydrogen-induced Damages (HDs), such as hydrogen embrittlement or high-temperature hydrogen attack, are well-known phenomena in material science. An in-depth analysis of the HIAD 2.0 database (Campari et al., 2023a) already showed that they were responsible for several events, and the lessons pointed out that most of these could have been avoided through appropriate inspection activities. The lack of training of the operators is also a common cause in the development of the events: for instance, event ID29 had pump failure as the initial cause, but there was an escalation of the event because the operators were inadequately trained, and they did not recognize that an accident was occurring. In other cases, such as Event IDs 47, 117, and 773, the lack of training led to errors during maintenance. Event ID252 was an explosion after a hydrogen release, which was not detected on time due to the absence of detectors. Most of the events that found a match with the word ‘sensor’ were not caused by failure or lack of sensors; many records mention this word for other reasons. Event ID401, for instance, was a leakage detected by the gas sensor, which shut down the plant, avoiding further event development: in Figure 3, sensors detect and limit the event.

Furthermore, in the ‘lessons learned’ field of the event ID698, there is information on a lack of ventilation in the plant, which was not the root cause of the event but contributed to its escalation, failing to control the scenario. The event ID16 describes an explosion in an aerospace company in the United States: in this case, an isolation valve failed open, permitting hydrogen under pressure to enter a pipe not designed for such high pressure. The sprinkler system was highly effective in the event ID81, which was characterized by a release of hydrogen and butane: as the release occurred, the sprinkler was activated, and the ignition was avoided, keeping the event under control. On the other hand, event ID1012 describes an event in which the sprinkler system was the key to the incident: hydrogen accidentally entered the sprinkler piping, mixing with air and forming a flammable mixture, which exploded. Safety valves are fundamental to limiting and controlling events. Still, the event ID944 underlines the criticality of the safety valves: in this case, the release occurred in a laboratory where a relief valve opened and released 340 g of hydrogen. Finally, the lessons from the event highlight that a safety valve is not a safety feature if the release is not directed in a safe location. In fact, in other cases, the word safety valve appears in the description because it is the source of the releases (i.e., ID189, ID249). A leakage in a plant in a petrochemical industry occurred due to the rupture of a pressure gauge, which has the role of detecting process deviation, as described briefly in the event ID33.

Event ID871 shows a lack of nitrogen inerting in the exploded reactor. The direct cause of the event ID936 was the loss of confinement of a cell of a chlorine electrolyzer; no other information is provided to better understand the role of the confinement. In all the other events in which the word ‘confinement’ does not appear because of failure or success in limiting the event: other meanings of the same word led to the matching with six records without any relevance, which is one of the most significant limitations of this analysis. The explosion described in the event ID86 highlighted the necessity of installing a pressure sensor in the plant, to detect and limit the event.

Besides the issue of other meanings of the words, this study also showed other limitations. The matching of the words does not allow the understanding of which was the problem of the safety barrier. Sometimes, the safety barrier was not even present, and in some other cases, the safety barrier did not work correctly, or its failure was the primary cause of the undesired events. Furthermore, in some records, the safety barriers are mentioned as successful for the non-escalation of the event. Despite the limitations of this work, it can be considered one of the first studies using an automated approach to extract information carried out on hydrogen-related events.

To accelerate the spread of hydrogen technologies, every piece of information that can be extracted from accident reports is valuable. For this reason, methods to mine information from the reports as quickly as possible are investigated.

Following the trend of applying supervised machine learning to classify incident text data (Tixier et al., 2016; Nakata, 2017), a pioneer study on hydrogen events used this approach to classify information in the database (Campari et al., 2023b). This study also attempted to retrieve data about the operational status of the facility. However, the performance of the analysis was not considered satisfactory, partially due to the small number of events considered. The supervised approach is applicable only if the required output of the dataset is provided and the training of the model is possible. Otherwise, other approaches are preferable:

- Text clustering algorithms lead to the possibility of grouping accidents based on similarities. For the first time, the Occupational Safety and Health Administration (OSHA) employed the unsupervised approach (Chokor et al., 2016) to categorize incidents based on the description of the reports. A similar approach was used in another study to extract contributing factors and causality of pipeline incidents (Liu et al., 2021).
- Co-occurrence network analysis allows the reveal of word-word relations. This process showed strong performance in extracting information after the clustering creation (Liu et al., 2021).

The application of these techniques can be tested in the database used in the current study: it would be worthwhile to explore the capability of Natural Language Processing (NLP) to extract valuable information from the hydrogen-events database. The criticality of such analysis would be the step of text cleaning. A list of stopwords from the NLTK corpus (Bird, 2006) may be considered. Nevertheless, the noise removal step is not sufficient to prepare the text; an additional filter is required as the last step of text pre-processing. A list of filtering words can not be decided in advance, but it should be prepared during the analysis through the analysis of the bag of words.

The importance of this approach is the potential to combine more sources of information without increasing the time spent on the analysis, such as the Hydrogen Incident Reporting Tool (H2Tools), but also the possibility of including recordings in other languages (KHK, 2020), making some NLP tools helpful in the analysis.

6. Conclusion

The ambition of employing hydrogen in various new applications requires acquiring knowledge from previous hydrogen-related undesired events. This study investigated the most popular collection of hydrogen records, the HIAD 2.0 database. The proposed approach applies an automated procedure to obtain information about the role of safety barriers, which are extremely valuable tools to manage control and mitigate the possible outcomes of any hydrogen event. In this way, it was possible to check if safety barriers from a list of 614 data previously extracted from the documentation of the ARAMIS project had a specific role in the 689 events of the selected database. The analysis showed the possibility of gaining new information for 332 events. The most frequent barrier seems to be maintenance, which is expected, considering that the latest studies on the same database revealed the criticality of maintenance operations.

This approach facilitated the information mining from the H_2-related events. Still, it manifested some limitations, such as the mismatching of safety barriers in cases where the words appear in the text with other meanings or the incapability of understanding equally quickly the problem behind the safety barrier and the contribution to the event. The consideration of other databases, together with the application of unsupervised learning techniques, could further develop this study.

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