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Fire in waste treatment plants in Piedmont Region: case studies and comparison

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Abstract
Following several outbreaks of fires within waste treatment and storage facilities, which have occurred in Italy over the last decade, in 2018 Law n. 132 was enacted in order to introduce new regulatory obligations for operators regarding the drawing up of Internal and External Emergency Plans, in analogy with major-accident hazards establishments under European Directive 2012/18/EU (Seveso III Directive). The study begins with the need of Arpa Piemonte to investigate and characterize the phenomenon of fires in waste treatment and storage facilities, with particular focus on regulatory aspects and the obligations of operators. In 2022, a source-term model was implemented to calculate fundamental parameters such as thermal power, average temperature, and flame height, which are useful for studying the dispersion of combustion fumes into the environment. The study was subsequently expanded with the application of the guidelines established by the External Emergency Plan, defined in Italy by the DPCM of August 27, 2021, to a real case in order to determine the safety distance through fire risk assessment. The obtained results will then be compared with modeling simulations to verify consistency.

1 Introduction

Fires in industrial sites represent one of the most significant events, as, in addition to thermal effects, they generate toxic scenarios related to combustion fumes. The main substances emitted during these fires include, for example, CO, NO2, H2S, NH3, HCN, Cl2, formaldehyde, SO2, CO2, HCl, HF, PCDDs, and PCDFs, all of which have significant effects on human health and the environment. Therefore, it is important to analyse the dynamics of complex fires, as it allows for the identification of key factors in the propagation of the fire and its thermal and toxic consequences.

The Regional Agency for Environmental Protection of Piedmont (Arpa Piemonte), within the framework of its institutional activities established by Regional Law no. 18/2016 [1], intervenes in cases of anthropogenic or natural emergencies, conducting sampling and measurements of pollutants emitted that may impact one or more environmental matrices (air, water, soil). This project begins with the need of Arpa Piemonte to investigate and characterize the phenomenon of fires in waste treatment and storage facilities. The final aim will be to evaluate the fallout areas of fumes and the safety distances downstream of a fire, with a specific focus on the fire phenomenon in warehouses. In 2022, the Agency had already investigated the phenomenon, focusing on the characterization of the source term model to calculate key parameters such as thermal power, average temperature, flame height, and smoke composition [2]. To validate the model, the pile fire, implemented in Excel, was compared with a pool fire simulated using the PHAST software. The results obtained from both models (Excel and PHAST) were compared using the same substance, methanol, and a sufficiently low error was observed, confirming the validity of the developed model.

The study was subsequently expanded with a historical analysis of incidents, followed by the implementation of the guidelines for the External Emergency Plan (so called DPCM of August 27, 2021) [3]. Specifically, the study involved a historical analysis of incidents that occurred in Piedmont to collect significant data on the types of activities most involved in fires and the geographical areas most frequently affected by such events. This analysis allowed for the creation of a detailed framework, highlighting the distribution of incidents across the territory, and providing information to understand the dynamics of specific risks related to fires in local contexts. To investigate the study further, the attention was focused on four fire cases occurring in different industrial settings, examining the impact of pollutants emitted into the atmosphere during the incident and the locations where sampling was conducted to analyze toxic dispersions.

The aim of this study was to evaluate the reliability of the index-based method outlined in the guidelines for the External Emergency Plan, applied as a risk assessment tool for warehouses, with the intention of comparing the results obtained with those derived from field sampling. This method allowed for a semi-quantitative assessment of risk factors, considering key variables such as stored materials, building configuration, and the effectiveness of active and passive protection systems in place at the facility.

Finally, the application of two modeling software tools was introduced, which will be implemented in the next phase of the study to simulate the propagation and dispersion of combustion fumes. The results obtained from the model will then be compared with those from the simulations to verify the consistency between the different approaches.

2 Historical Analysis in Piedmont

Arpa Piemonte, as part of its institutional activities defined in Regional Law No. 18/2016, manages an on-call service for emergency interventions of both anthropogenic and natural origin, conducting environmental sampling during fires. During these events, substances defined as "tracers" are analysed to identify and characterize the fires and assess their impact on the environment and public health [4]. To manage the emergency activation service, since 2014, the Agency has developed the "Ispezioni non programmate" application, which allows for the registration of reports related to various types of events, such as pollution, ionizing radiation, fires, and waste abandonment, by citizens, operators, and other emergency entities. The application has enabled the creation of a database containing 436 records related to fire reports in Piedmont between March 2014 and October 2024, aiming to simplify a systematic analysis of each report to highlight possible trends. Each report is registered as a record that includes various information: the report ID, used as a unique identifier to track and manage each event; the territorial department (North West, North East, South West, South East) in which Arpa Piemonte is divided; the report date, the entry date, and the status of the case. Data related to the reporting entity and its qualification are also recorded, specifying the organization or individual who made the report, the reporting method, and a description of the event. Data analysis revealed that the current database structure may not fully meet the specific needs of the study, particularly regarding data extraction and analysis. The review of the database led to a new structure with additional fields to improve event description, including details on the type of activity, location, and materials involved. Duplicate records were eliminated, and a “unknown” category was added for incomplete data. The updated database contains 361 events, with graphical analysis to identify trends and correlations. The activities have been classified to distinguish the context of the fires, including categories such as industrial plants, waste treatment and storage facilities, agricultural activities, warehouses, and a generic "other" category. The combusted materials are subdivided into specific categories for analysis: chemicals, waste, asbestos-containing structures, vehicles, electronic devices, wood, tires, and combinations of these.

2.1 Results and Discussion

Figure 1, which represents the trend of fires divided by department from March 2014 to October 2024, shows no linear or cyclical trend in the number of fire events. The department with the highest number of fires is the North West, followed by the South East, North East, and finally the South West. In general, the data show significant annual variability, with fluctuations suggesting an episodic behaviour rather than a stable or regular pattern in the number of fires. The oscillations in the annual values indicate that fires do not follow a continuous trend but rather occur discontinuously, with periods of increase deviating from historical averages.

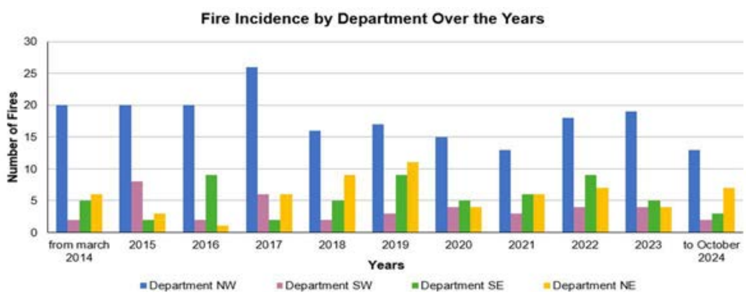

Fig. 1. Trend of fire incidents across the four ARPA Piemonte Departments from March 2014 to October 2024.

Figure 2 shows the distribution of activities recorded in the updated database, providing a detailed overview of the main categories. The analysis highlights that the "other" category is the most represented, with 36% of the 361 reports. However, excluding this category, it emerges that the most affected activities are industrial plants and those dedicated to waste treatment and storage.

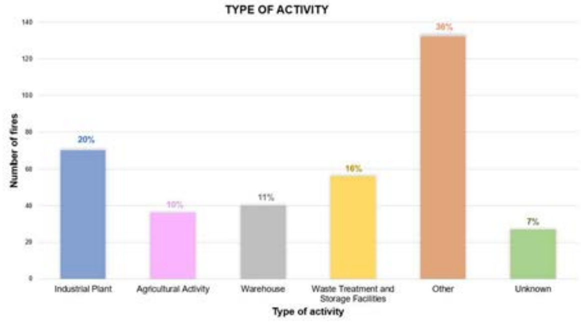

Fig. 2.Distribution of activity types involved in the 361 fires studied.

To focus the analysis on the most affected productive activities, the distribution of fires involving such activities, divided by province, is graphically represented in Figure 3. The data show that the province of Turin records the highest number of events, followed by Biella and Novara for industrial plants. Similarly, for waste treatment and storage facilities, the data indicate that the province with the highest number of incidents is Turin, followed by Alessandria and Cuneo.

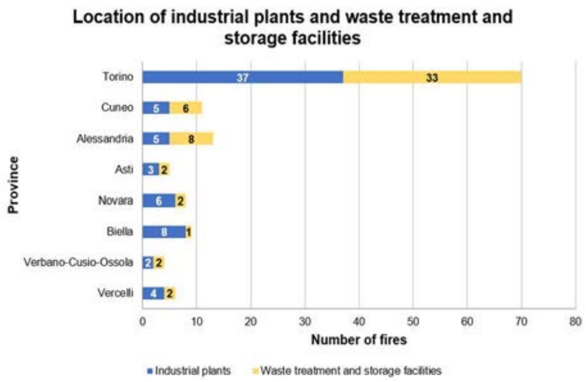

Fig. 3.Distribution of the number of fires in industrial plants and waste treatment and storage facilities, divided by province.

Regarding the combustible materials involved in the fire events analysed, the analysis shows that, excluding the "unknown" category, the most affected materials are waste and chemicals. Concerning the reporting entity, the data analysis reveals that the major sources are 118 (Emergency Health Service) and the Firefighters, which account for the majority of the reports. To a lesser extent, notifications are recorded from 112 (Single Emergency Number) and Arpa Piemonte operators themselves.

3 Analysis of Incidents

Four fire events that occurred in recent years across the various territorial departments were analyzed, with a particular focus on the results of the analyses conducted by the Agency personnel during the emergencies:

- North-West Department: An analysis was carried out on a fire at a facility that processes non-hazardous special waste, specifically plastic material from separate waste collection.
- North-East Department: The fire at a chemical plant specializing in the production of release agents, lubricants, and technical solutions for the molding sector was selected for analysis.
- South-West Department: The fire at a storage warehouse containing various materials, including plastic, clothing, electronic components, and toys, was analyzed.
- South-East Department: Two fires in a non-hazardous waste storage and disposal facility were considered.

An analysis revealed that the reports drafted following the Agency personnel interventions focus on the measurements of toxic fumes resulting from combustion, carried out in accordance with the technical procedure U.RP.T170 [5]. From the analysis of the reports, it emerges that, in line with the technical procedure, ARPA uses a sampling methodology that covers a comprehensive range of substances typically produced during fires. This approach was chosen because, in an emergency situation, it is impossible to predict the combustible material involved, which may vary depending on the type of structure and the materials present. However, a critical aspect highlighted in the reports is the lack of adequate information on the specific chemicals involved in the fire and the exact dimensions of the affected structures. This lack of detail prevented the comparison of the collected data with the guidelines for the External Emergency Plan and made it difficult to carry out simulations using modeling software.

4 Case Study: Tire Storage Warehouse

The historical analysis has highlighted that waste treatment and storage facilities are among the most affected by fires, in line with the numerous incidents recorded in Italy over the last decade. In response to this issue, in 2018 Law n. 132 [6] was introduced, imposing new regulatory obligations on operators regarding the preparation of Internal and External Emergency Plans, similar to the regulations for establishments at risk of major accidents, in accordance with European Directive 2012/18/EU (Seveso III Directive) [7]. Following Law no. 132/2018, an index-based method was developed, as described in the guidelines for the External Emergency Plan, formalized by the DPCM of August 27, 2021, specific to waste treatment and storage facilities. This study aims to assess the smoke fallout areas and safety distances downstream of a fire by preliminarily applying the index-based method to a real case. However, the lack of necessary input data for an adequate characterization of the fire source, as outlined in paragraph 3, has limited the

(1)

use of reports for case study applications. To overcome this limitation and simulate realistic scenarios for facilities in the Piedmont region, reference has been made to risk analyses of establishments subject to the Seveso regulations, for which the "Industrial Plants and Energy" structure has data. In particular, as a representative example, a fire in a tire storage warehouse was selected as a case study, for which useful information is available to reconstruct a realistic event model. Following a bibliographic analysis of fires in tire storage warehouses, it was decided to treat tires as a solid waste in order to estimate the fire risk and corresponding attention distance using the index-based method. This choice is justified by the complex and variable composition of tires, which consist of a mixture of natural and synthetic rubber, carbon black, steel, sulfur, aromatic oils, and various chemical additives, characteristics that make them similar to mixed waste. The index method, specific to waste treatment and storage facilities, allows for a semi-quantitative risk assessment by associating the results with different levels of hazard. This approach provides a foundation for designing mitigation and prevention strategies, thus improving the safety of warehouses and reducing the risks associated with fires involving complex materials such as tires. The method involves assigning specific scores to both the risk factors and the prevention and protection measures present in the facility, also considering potential threats to human health and the surrounding environment. The fire risk index (IR) is calculated according to the formula:

$$IR = Pr + Pt - FC + FD$$

The storage risk index (Pr) is determined by the specific fire load (q_f), which depends on various factors: the mass of the combustible material (g_i), its calorific value (H_i), the surface area of the operational zone (A), and parameters that consider, for example, the participation in combustion ($m_i$and Ψ_{i}). The index method includes a table that associates each value of $q_f$with the corresponding Pr index. The waste treatment risk index (Pt) is based on the operations and processes within the facility. The credit factor (FC) considers the protective measures adopted, such as extinguishing systems and physical barriers, while the debt factor (FD) evaluates the hazard to health and the environment in relation to the facility's proximity to sensitive areas. The resulting value from the risk index (IR) is then associated with a qualitative risk level, ranging from low to high, with intermediate categories such as low-medium, medium, and medium-high. Each risk level is associated with an attention distance, which represents the maximum distance between the boundary of the storage or waste treatment facility and the boundary of the relevant sensitive target area, or the end of a significant element.

Table 1 - Attention Distance Based on the Risk Level

IR	Risk Level	Attention Distance [m]
0-400	Low Risk	100
401-700	Medium-Low Risk	200
701-1100	Medium Risk	300
1101-1500	Medium-High Risk	400
>1500	High Risk	500

a. Application of the index method

A case study was selected regarding a warehouse containing 72000 kg of tires, with a total surface area of 108 m². The lower calorific value of the stored materials, equal to 25 MJ/kg, was derived from data provided by [8]. For the calculation of the specific fire load, not only these parameters were considered, but also the combustion participation factor and the participation limitation factor, both set to 1, in accordance with the provisions of the index method. The value of the specific fire load was determined using the following relationship: (2)

$$q_f = \frac{\sum_{i=1}^{n} g_i \cdot H_i \cdot m_i \cdot \Psi_\mathrm{i}}{A} \left[\frac{MJ}{m^2}\right]$$

Two scenarios were analyzed: the first considers the actual conditions of the facility with the full implementation of prevention, protection, and safety measures; the second is a simplified scenario limited to basic measures, i.e., without any improvement interventions or advanced implementations of prevention, protection, and safety measures. In both cases, for the FD parameter, the proximity of a watercourse to the distances indicated in the General Regulatory Plan (PRG) was taken into account.

In the case study with complete prevention and protection systems, the analysis resulted in a risk index of 1045, placing the warehouse in a medium-risk category (Table 2). This value was obtained by considering various parameters and indices, which reflect the specific situation of the warehouse and the security measures in place. A risk index of this magnitude implies that, although prevention and protection measures are implemented, some vulnerability remains.

In the case where only basic prevention and protection systems are in place, the prevention measures (Pre) were defined by considering only the obligations set forth in Legislative Decree 81/08 and the plan for maintaining the fire safety level. As for active protection measures (Proa), only hydrants, both internal and external, and fire extinguishers were included. The security measures (Sec) and passive protection (Prop) remained identical to those analyzed in the previous scenario. For security (Sec), all provisions in the index method were adopted, including the perimeter fence, surveillance system, and access control. For passive protection (Prop), the only measure considered was the presence of water collection basins for firefighting. The analysis conducted with these configurations resulted in a new risk index of 1220, classifying the warehouse as a medium-high-risk level (Table 3). Below are the values of the parameters considered in the two case studies with complete and basic prevention and protection systems.

Table 2 - Parameters Obtained in the Two Case Studies.

Parameter	Case Study with Full Prevention and Protection Systems	Case Study with Basic Prevention and Protection Systems
q_f [MJ/m2]	12971.83	12971.83
Pr	1500	1500
Pt	0	0
FC	475	300
FD	20	20
IR	**1045**	**1220**
Risk level	**Medium**	**Medium-high**

b. Sensitivity Analysis

Since the initially calculated risk in the case study with complete prevention and protection systems was medium, it was deemed appropriate to further reduce it by focusing on the parameters that significantly influence the variation in the risk level. The main parameters for reducing risk include optimizing the prevention and protection measures. However, the only feasible intervention in this area would be the implementation of compartmentalization between indoor operational areas, which would help confine a potential fire, limit its consequences, and thus reduce the risk level. From the application of Formula (1), the introduction of compartmentalization would increase the passive protection value (Prop) by 100, leading to a reduction in the risk index. However, in none of the cases analyzed did this reduction prove sufficient to lower the risk index to a lower level. Therefore, an alternative was considered that focused on reducing the specific fire load (q_f), achieved by varying the mass of the stored combustible material. Initially, reductions of 10%, 20%, 30%, and 40% in mass were considered; however, even with these decreases, the specific fire load (q_f) remained within the high range (q_f> 1200 MJ/m²), keeping the risk at the medium level. For this reason, a targeted sensitivity analysis was conducted to identify a mass reduction that could bring the specific fire load value into a lower range. This analysis revealed that a mass reduction of up to 5184 kg, or 7.2% of the initial mass, was sufficient to achieve a specific fire load compatible with a medium-low risk level. Subsequently, the mass required to achieve a low risk level was found to be 2592 kg, corresponding to 3.6% of the initial mass.
The trend of the risk index, as a function of mass, was represented in the diagram below, illustrating the direct relationship between the mass reduction and the decrease in the risk index.
From Figure 4, it can be observed that the risk index (Pr) as a function of the mass of combustible material exhibits a stepwise behavior. This behavior is intrinsically linked to the calculation method of the Pr index, which is determined by the value of the specific fire load (q_f). The latter is classified into predefined intervals (q_f< 600, 600 < q_f< 1200, and q_f > 1200), within which the Pr value remains constant. When the q_f

value exceeds the threshold of one interval and enters the next, the Pr index increases by 500, resulting in a stepwise pattern in relation to the variation in the mass of combustible material.
In the case study using complete prevention and protection systems, two significant reductions in the fire risk index (IR) are observed. In the first phase, the index decreases from 1045 to 545, corresponding to a reduction in risk from medium to medium-low. Subsequently, the IR further decreases from 545 to 45, with a change in the risk level from medium-low to low (Table 4). In the case study with basic prevention and protection systems, the risk index follows a different trend. The risk index first decreases from 1220 to 720 and then more significantly from 720 to 220. These decreases correspond to a reduction in the risk index from high-medium to medium and then from medium to low (Table 5), while maintaining the same mass variation observed in the complete prevention and protection case. This three-level reduction in the risk index demonstrates that even with less advanced protection systems, it is possible to achieve a final risk level comparable to that achieved with complete prevention and protection systems. In fact, with the same mass of combustible material, the risk level is low in both case

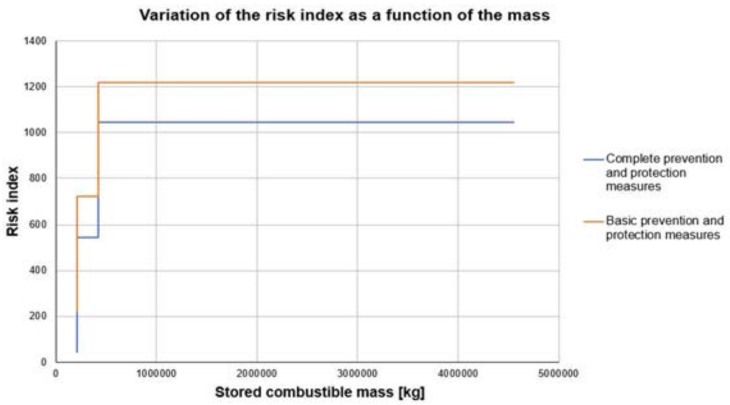

Fig. 4. Analysis of the variation in risk index relative to stored fuel mass.z

The analysis reveals that prevention and protection systems, even basic ones, are particularly effective in rapidly reducing the risk index, in contrast to the more gradual reduction observed with complete systems. However, this behavior does not meet initial expectations: it was anticipated that complete systems would result in a more significant reduction in risk. This discrepancy highlights a limitation of the adopted index-based method, which presents further critical issues, as discussed below. A first limitation concerns the warehouse structure: in the Guidelines for the External Emergency Plan, the risk index value remains unchanged regardless of whether the warehouse is open or closed, thus failing to account for different configurations that could influence fire propagation. Additionally, no distinction is made between the different types of active protection systems (Proa); for example, automatic extinguishing systems are considered generically, without distinguishing between water-based and foam-based systems, even though this difference is crucial for the effectiveness of fire control and suppression, depending on the nature of the stored materials. An additional issue has emerged in the determination of the FD index, which assesses the distance between the facility's boundary and the external sensitive target, as the method does not account for the internal distance between the warehouse (potential source of the fire) and the facility's boundaries. In the event of a fire, the internal distance could, in fact, lead to a reduction in the risk outside the facility's perimeter.

c. Project development

Future work is planned to further investigate fire characterization in warehouses and the analysis of the dispersion of toxic fumes generated by combustion, using advanced modeling software such as CFAST (Consolidated Fire and Smoke Transport) [9] and PHAST (Process Hazard Analysis Software Tool) [10]. The primary goal will be to compare the results obtained from modeling software with those of the preliminary analysis conducted so far using the index-based method, in order to improve the understanding of fire propagation dynamics and the environmental and health impacts resulting from the dispersion of contaminants. In this preliminary phase, a detailed analysis of the inputs and outputs required by both software programs was conducted. The choice to use these software tools was motivated by the simplicity of the required inputs and the specific features of each: CFAST is a simulation software developed by the National Institute of Standards and Technology (NIST) for fire analysis, smoke, and heat transport within buildings. The results provided by the simulation include the mass flow rate of smoke emitted during combustion, the amount of pyrolysis products (defined as the amount of fuel undergoing thermal degradation per unit of time), the heat release rate (HRR) curve, indicating the power developed by the fire over time, as well as the intensity and height of the flame. PHAST is an advanced software tool used to analyze the risks associated with incidents in industrial facilities, particularly those involving hazardous substances that can cause fires or explosions. The results obtained from the simulation include pollutant concentration curves over time and space, the chemical composition of combustion products, dose and lethality probability curves, and smoke fallout curves. These outputs allow for the evaluation of environmental impact and health risks resulting from the dispersion of toxic substances, as well as the estimation of potential damage to the near structures and people.

5 Conclusions

This study provided an evaluation of the risks associated with fires in waste storage warehouses, with a particular focus on a case study involving a warehouse for used tires. The analysis adopted the index-based method for fire risk assessment, comparing scenarios with complete and basic prevention and protection systems, highlighting the importance of protective measures in reducing the risk level. In both scenarios, reducing the mass of combustible material proved effective in decreasing the specific fire load, with significant impacts on the risk index. Despite the effectiveness of the method in providing a risk estimate and guiding the design of mitigation strategies, some critical issues emerged, including the failure to consider different warehouse configurations and the specifics of active protection systems. Furthermore, the risk index does not adequately account for internal distances, which may be relevant in case of fire, between the warehouse and the boundaries of the facility.

The index-based method, as described in the guidelines for the External Emergency Plan, has proven useful for a preliminary risk assessment with limitations. Comparing the results with field samples represents a goal for future studies, which could provide more concrete and verifiable data to optimize emergency management.

The historical analysis of fires in Piedmont revealed that industrial facilities and waste treatment and storage facilities are among the most affected activities, a trend that reflects the national situation. The results show that the provinces of Turin, Alessandria and Cuneo are the most affected, with materials most commonly involved, including waste and chemicals. This analysis allowed the identification of significant trends, highlighting the predominance of certain types of facilities and materials, as well as the concentration of fires in specific sectors and geographical areas.

Finally, the adoption of advanced modeling software appears to be a promising strategy for simulating fire scenarios and improving the prediction of toxic dispersion. Future work will aim to further investigate, through the use of advanced modeling software, the characterization of warehouse fires and the analysis of toxic smoke dispersion resulting from combustion. The goal is to compare the results obtained from modeling software with those from the preliminary analysis to improve the understanding of fire propagation dynamics and the environmental and public health effects arising from contaminant dispersion.

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