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Review Article

Industrial Disasters and Hazards: From Causes to Consequences—A Holistic Approach to Resilience

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Abstract

Starting from accelerated industrial development, industrial disasters (chemical spills, explosions, nuclear accidents, etc.), which fall under man-made (technological) disasters, increasingly threaten human lives, the environment, and property. Their complexity and far-reaching consequences, both at the local and global levels, require effective management of industrial risks and the disasters themselves (preparedness, mitigation, response, and recovery). For these reasons, the review paper aims to provide a holistic description of the diverse causes, dynamics, and multidimensional consequences of disasters. Additionally, it highlights and explains the key factors that directly or indirectly contribute to their occurrence. Furthermore, it could be said that the paper analyzes existing strategies for managing risks from industrial disasters and systematizes recommendations for improving preventive and reactive measures in high-risk industries. On the other side, the paper utilizes a comprehensive literature review, which involves the systematic identification, review, analysis, and critical evaluation of existing scientific papers, studies, reports, and regulatory documents on industrial disasters. Besides that, it also includes a detailed analysis of well-known industrial disaster cases such as Seveso (Italy, 1976), Bhopal (India, 1984), Chernobyl (Ukraine, then USSR, 1986), and Fukushima (Japan, 2011). The paper emphasizes that industrial disasters are often the result of the combined influence and interaction of technical failures, human errors, and inadequately developed safety procedures. Moreover, it can be highlighted that the design and implementation of preventive measures, such as regular maintenance of technical systems and systematic training and education of employees, are crucial for reducing the likelihood of such catastrophic events. The implications of this review paper are multifaceted and point to the following: the need to reassess current safety practices in industries; reconsider the potential for introducing innovations in preventive technical-technological solutions; examine the thorough implementation of innovative early warning systems, safety procedures, and modern equipment in facilities; improve cooperation between engineers, safety managers, and regulatory workers; reassess the need for additional updates and tightening of regulations regarding the storage, transport, and use of hazardous materials in industry; and improve the management of risks from industrial disasters.

Keywords

Hazards; disasters; resilience; industrial; definition; classification; consequences; human health; economic; environmental impact; causes; failures; human error; lessons.

1. Introduction

The rapid technological development has greatly improved the quality and way of life of modern people, but it has also contributed to the rise of various risks to their safety. In many sectors of production, processing, distribution, and storage, devastating negative events occur that have the potential to evolve into serious disasters. The dependency on chemical products is increasing, which leads to the growth in the number and size of petrochemical plants. These industries are required to meet the needs of mass production, which necessitates the storage of larger quantities of hazardous compounds in these facilities. If chemical leaks occur, they can have serious consequences for human health and the environment (Yet-Pole & Fu, 2021) .

Industrial hazards fall under the category of man-made (technological) hazards, which refer to dangers arising from technological or industrial conditions. These include accidents, hazardous processes, infrastructure failures, or specific human activities and can result in loss of life, injuries, illnesses, or other health effects, property damage, loss of livelihoods and services, social and economic disruption, or environmental harm (UNISDR, 2009). Given their complex nature, the potential for severe and serious consequences, conflicting interests, and incomplete knowledge of mitigation measures, it can be freely said that industrial disasters represent a malignant problem of modern society (De Abreu & De Andrade, 2019).

The analysis of industrial disasters shows that their specifics are directly related to the following characteristics: a) raw materials used in the production process; b) method and technology of production; c) the level of technical-technological development and innovation in the production process; d) preventive and protective measures implemented; e) characteristics related to geographical location, natural resources, workforce, transportation links, etc.; f) the degree of implementation of information systems and automation; g) collective awareness of employees, etc. (Cvetković, 2024).

What is often emphasized in the literature is that the incubation period is crucial for the occurrence of technological disasters. It represents the imperceptible accumulation of small events that directly or indirectly lead to such a disaster (Shaluf, 2007). If the factors contributing to such events were summarized, they could be grouped into three categories: a) human errors; b) organizational errors; and c) technological errors. The combination of these errors, as well as their other interactions, creates the conditions for the manifestation of harmful effects of technological hazards. The most well-known technological disasters are the Chernobyl disaster in 1986, the Bhopal disaster in 1984, the coal mine explosion in France in 1906, etc.

Considering all the circumstances, it can be stated that the stability and safety of industrial facilities depend on: a) the reliability and safety of production management systems; b) the capacity and ability of industrial facilities to withstand the effects of various harmful factors; c) protective measures taken to safeguard workers and other personnel from the negative consequences of various hazards; d) measures to protect facilities from damage caused by secondary hazards; e) the capacity of facilities to recover and restore production to its previous state (Мастрюков, 2011).

Certain technological disasters, such as incidents in Bhopal, Mexico City, Basel, Seveso, Exxon Valdez, and Chernobyl, have attracted serious international attention. Such attention led to the engagement of various expert groups, institutions, and organizations in addressing issues of prevention and remediation at the local, regional, national, and international levels. Furthermore, it is important to emphasize that the Chernobyl disaster directly led to the International Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. Additionally, the release of chemicals into the Rhine River was the starting point for bilateral and multilateral agreements regarding early warning systems for accidental discharges of hazardous substances into rivers (Krejsa, 1997).

1.1. Definition of Industrial Hazards and Disasters

In the literature, there are various definitions of industrial hazards used by authors to describe the basic elements and consequences of such events. It is important to note that there is no universally accepted definition for industrial disasters, and the criteria (number of victims, costs, damages) used in their definition vary and are not universally accepted (Ibrahim, Fakharu'l-razi, & Aini, 2003). The term technical-technological (anthropogenic) disaster is most commonly used to describe events caused by intentional or unintentional actions and activities undertaken by humans (Cvetković, 2019; El-Mougher, Abu Sharekh, Abu Ali, & Zuhud, 2023; Mohammed Mohammed El-Mougher & Mahfuth, 2021; Kachanov, 2021; Mohammed & Maysaa, 2022). According to Richardson, a socio-technical disaster occurs in four types of organizational situations: a) failures in plants and factories (major accident); b) failures in transportation; c) accidents at stadiums and other "public places"; and d) failures in the production process (Richardson, 1994).

Industrial disasters can be defined as specific events caused by human activity, involving hazardous substances, and capable of causing severe consequences to health and the environment (Lillibridge & Brennan, 2005). According to authors (Cole & Wicks, 1994), major industrial hazards are dangerous events that arise from the use of industrial technology and have the potential to cause serious injuries or inflict significant damage outside of working hours (Cole & Wicks, 1994). In contrast to this definition, industrial hazards can also be interpreted as high-risk events with potentially harmful effects on people and the environment, including fires, explosions, and the spread of toxic materials (Pasman, 2015). Akbar (2006) defines industrial hazards as all possible dangers, losses, and risks present in the industry, which may be caused by human error or other physical or mechanical failures.

According to the Serbian Law on Disaster Risk Reduction and Emergency Management (Official Gazette RS, No. 87/18), a technical-technological accident is defined as a sudden and uncontrolled event or series of events that have escaped control during the management of certain work tools and while handling hazardous substances in production, use, transportation, trade, processing, storage, and disposal. Such hazards, according to the mentioned law, include: fire, explosion, breakdown, traffic accidents in road, river, rail, and air transport, accidents in mines and tunnels, stoppages of cable cars for human transport, dam failures, breakdowns in power, oil, and gas plants, accidents involving handling radioactive and nuclear materials, severe pollution of land, water, and air, consequences of war destruction and terrorism, whose consequences can endanger the safety, life, and health of a large number of people, material and cultural goods, or the environment on a larger scale.

1.2.Classification of Industrial Risk, Hazards and Disasters

In the literature, there are various criteria for classifying industrial hazards and disasters, as well as different types of such events. Technological disasters include: a) industrial (related to production, processing, distribution, storage, usage); b) structural (various forms of collapse); c) nuclear; d) computer-related; e) transportation (transport) (Cvetković, 2019, pp. 104-105). Generally speaking, all industrial disasters can be classified based on: a) the type of incident; b) the cause; and c) the materials involved. Each type of industrial disaster carries specific risks and consequences for people, the environment, and material assets. Considering that industrial disasters fall under the category of technological disasters, it is important to note that technological disasters are divided into (Cvetković, 2024ab): transport-related (disasters involving transportation infrastructure, aviation, maritime, rail, and road); infrastructural (failures of telecommunication systems, computer network crashes, critical levels of water supply, main pipeline failures); industrial (disasters caused by improper handling and storage of hazardous substances); and international, civil, and political disasters – terrorism, crime, and war.

Additionally, industrial disasters can also be distinguished by certain criteria (Cvetković, 2024): development phases (the accumulation stage, initiation of the emergency event, culmination, and resolution); the speed of spread (sudden, rapid, moderate, and gradual); scale (local, municipal, regional, national, international, and global); nature of the cause (natural, technological, ecological, and social); frequency (rare, occasional, and frequent).

Industrial disasters generally include: explosions caused by gas leaks or pressure buildup in enclosed spaces; fires, as uncontrolled combustion processes, that occur due to faulty electrical installations, machinery, devices, or flammable materials; chemical spills, involving numerous hazardous substances that can pollute the environment and threaten human health; gas leaks, such as the release of toxic gases like ammonia or chlorine; collapses, typically of industrial facilities like mines or buildings; radiation incidents, involving the release of radioactive materials; and poisonings, often caused by improper handling or storage of toxic chemicals.

It is important to emphasize that industrial disasters differ depending on the type of industry in which they may occur. Thus, industrial disasters can arise in the following sectors (Cvetković, 2024): heavy industry (mining, energy, metallurgy, construction industry, chemical industry); light industry (food, textile, wood, tobacco, printing, construction materials, and leather and footwear industries); extractive and processing industries, etc.

The specifics of such disasters are directly related to the following characteristics of the industry: a) the raw materials used in the production process; b) the production method and technology; c) the level of technical-technological development and innovations in the production process; d) the preventive and protective measures implemented; e) characteristics related to geographical location, natural resources, workforce, transportation, connections, etc.; f) the level of information system utilization and automation; g) the collective awareness of employees, etc. (Cvetković, 2024).

In the process of providing technical and organizational tools for the prevention, mitigation, and remediation of disasters, the International Working Group (UN) has created an indicative list of different types of actions that may represent technological hazards (Krejsa, 1997; Silei, 2014): chemical releases into the atmosphere due to explosions, and fires; chemical releases into water (groundwater, rivers, etc.) due to tank ruptures, pipeline breaks, chemicals dissolved in water (fire); oil spills into marine ecosystems; satellite crashes (radionuclides); radioactive sources in metallurgical processes; other sources of radionuclide release into the environment; contamination from waste management activities; soil contamination; accidents with groundwater contamination (road, railway); groundwater contamination due to waste dumps (slow-moving contamination); airplane crashes; releases and contamination as a result of military actions (e.g., depleted uranium) or the destruction of facilities; releases as a result of industrial use of biological material (e.g., viruses, bacteria, fungi).

A comprehensive analysis of the significant characteristics of natural and technological (industrial) hazards highlights that the following differences can be identified: a) destructive power; b) predictability and mitigation potential; c) suddenness of occurrence; d) speed of harmful impact dissemination; e) prevention and response methods, etc. On the other hand, according to Coppola (2006, p. 35) the fundamental difference between natural and technological disasters stems from the fact that natural disasters are acts of higher power, beyond human control or cause. In contrast, in technological disasters, humans are the most critical factor participating in the interaction that leads to negative outcomes.

2. Etiological Factors of Industrial Disasters

Industrial disasters can be triggered by numerous individual and interconnected factors originating from anthropogenic or technological spheres. It can be said that they have their roots in deeper systemic contradictions that include (Shrivastava, 1994): a) human; b) organizational; and c) technological factors. These contradictions are based on poor and underdeveloped communication, inadequate safety procedures and protocols, the use of outdated and faulty technology, as well as poor strategic and tactical risk management for such events. Over time, in line with the mentioned phases of industrial disaster development, these problems grow, become more complex, and accumulate, which collectively leads to a systematic increase in vulnerability and a weakening of resilience across all lines and sectors.

Certain studies (Ale et al., 2014) show that disasters in high-risk industries, such as oil and gas exploration (Deepwater Horizon) and petrochemical production (Texas City), reveal that the causes of such events vary significantly, ranging from direct technical failures to organizational shortcomings, insufficiently developed regulations, and inadequately developed corporate cultures. A further complication is that risk management processes are often based on risk models focused on technical failures, while the primary causes are rooted in the organization's culture itself (Ale et al., 2014).

2.1. Technical Causes of Industrial Disasters

Industrial facilities are composed of complex technical, technological, informational, mechanical, and other processes that can be threatened in various ways. A disruption or inadequate functioning of these systems, if preventive safety measures are not taken, can lead to different types of industrial disasters. For example, in the case of earthquakes, floods, or lightning strikes, pipes and storage tanks may be the most vulnerable equipment (Krausmann, Renni, Campedel, & Cozzani, 2011). It is important to note that such critical infrastructure and equipment are vulnerable due to the transport of hazardous materials that may be highly flammable, toxic, corrosive, poisonous, etc. Minor to major tremors caused by earthquakes can lead to small and large cracks, resulting in leaks due to such damage. Additionally, floods can cause equipment submersion, leading to corrosion or hazardous material spills. All of this, following the principle of interconnected vessels, can trigger chain reactions that may be difficult to stop.

Certainly, the technical causes of industrial disasters vary depending on the type of industry, as each industry has specific technologies, processes, and materials that carry certain risks:

a) Heavy industry (production of large and heavy materials and equipment, involving energy-intensive processes and the use of large machinery, mining industry): primary metallurgy (steel, aluminium, copper production); machinery industry (production of large machines, vehicles, ships); construction industry (production of concrete, cement, building materials);

b) Light industry (production of smaller, consumer goods, with less need for raw materials and energy): textile industry (production of clothing, fabrics); pharmaceutical industry (production of medicines); consumer electronics industry (production of electronic devices); food industry (production of food and beverages);

c) Chemical industry (production of chemical products from raw materials such as oil, natural gas, ore, and minerals): petrochemical industry (production of plastics, rubber, synthetic fibres); fertilizer and pesticide industry; pharmaceutical chemistry (production of active substances for medicines); paint and coatings industry;

d) Manufacturing industry (transformation of raw materials into finished products, which can be used as final products or components in other industries): automotive industry; electronics and electrical industry; wood and paper industry;

e) Energy industry (production and distribution of energy, including renewable and non-renewable sources): oil and gas industry; coal industry; nuclear industry; renewable energy sources (wind farms, solar power plants, hydroelectric power plants);

f) Agricultural industry (activities related to food production, industrial raw materials, and fibers, including crop production, livestock, and aquaculture): agribusiness (agricultural production, plant and animal husbandry); food and beverage industry (food processing, packaging);

g) Service industry (not producing physical products, the service industry provides support and services to other industries and end consumers);

h) Financial industry (banking, insurance): IT industry (information technologies, software services); transportation industry (transport of goods and passengers); healthcare industry (hospitals, clinics, pharmaceutical services);

i) Extractive industry (extraction of natural resources from the earth and their transportation to processing plants or directly to the market): mining industry (extraction of coal, metals, minerals);

oil and gas industry (exploration and extraction of oil and natural gas); forestry (logging and wood processing); fisheries (catching and processing fish);

j) Renewable resource industry (production and management of renewable resources): renewable energy (solar, wind, hydro); recycling industry (processing waste into useful materials).

Fires can threaten all types of industrial facilities, especially those that produce or use hazardous materials in the production process. Regarding specific industries, equipment failures and process breakdowns are typical for heavy industry. In primary metallurgy, industrial disasters can occur due to furnace failures, inadequate temperature control, molten metal leaks, or gas explosions. In the machinery industry, which can be highly diverse, failures may occur in the production of vehicles or ships, leading to collapses, fires, or explosions. In the construction industry, improper application of safety procedures during the production of cement and concrete, structural weaknesses, explosions, or chemical leaks can result in catastrophic events.

In contrast to heavy industry, industrial disasters in light industry can be caused by: machine malfunctions in weaving or dyeing, which may lead to fires due to high temperatures (textile industry); technical problems that could cause product contamination, faulty medicines, or chemical reactions in laboratories (pharmaceutical industry); overheating, malfunctions, or other damage that can cause fires or explosions (electronics industry); food contamination or failures in cooling systems, which can lead to serious health risks (food industry).

In the chemical industry, the technical causes of such disasters are often related to faulty facilities for storing or processing chemicals. In the petrochemical industry, fires or explosions can occur due to chemical leaks. Equipment failures in chemical synthesis can lead to disasters caused by contamination or the release of toxic gases.

In the manufacturing industry, which relies on the proper transformation of raw materials into finished products, various breakdowns or damage can occur. For instance, in the automotive industry, failures frequently occur on assembly lines, in electrical systems, or in fuel storage components. Electrical components can overheat, leading to melting and sparks that cause fires. On the other hand, sawdust or dryer malfunctions can result in serious fumes.

On the other hand, the energy industry carries many risks of industrial disasters. Explosions at drilling sites, oil spills, or pipeline failures are the most common causes of oil and gas industrial disasters. Gas explosions (methane), various collapses in mines, radiation leaks, reactor failures in nuclear plants, or malfunctions in wind turbines or hydroelectric power plants can lead to various disasters.

In the agricultural industry, equipment failures for processing and storage, harvest machinery failures, irrigation system malfunctions, food processing equipment breakdowns, natural hazards (droughts, floods, strong winds, hail, etc.), biological hazards (pests, livestock diseases, invasive species), land degradation, and water and air pollution can be direct causes of various disasters. Conversely, typical causes of disasters in the service industry include software system failures, interruptions in banking or insurance institutions, vehicle breakdowns or logistical system failures, technical problems with medical devices or software, etc.

In the extractive industry, the causes of disasters are mainly related to equipment malfunctions for resource extraction, as well as other equipment for ensuring worker safety in such processes. Also, these may include explosions in mines, tunnel collapses, accidents caused by various mining machines, drilling platform failures, gas leaks, improper handling of cutting machines, or ship malfunctions. Finally, in the renewable resource industry, there may be various accidents associated with technology failures for energy production, such as wind turbine or solar panel failures, explosions in recycling facilities, etc.

2.1.1. Failures in Design and Engineering

In theory, but also in practice, industrial disasters cannot occur unless certain human or technical errors take place. However, considering that absolute safety is difficult to achieve, certain systemic failures in design and engineering can create critical vulnerabilities that contribute to the conditions necessary for disasters to occur. When focusing on design errors, it is often highlighted that certain devices, equipment, or facilities are not adequately designed to withstand all external pressures (e.g., the manifestation of harmful effects of shock waves), which can lead to the collapse of the structure itself. For example, in architecture, the lack of detailed drawings and poor coordination between disciplines lead to the necessity of performing additional work and delays in construction processes (Ayalp & Metinal, 2023). Therefore, if all external and internal factors that could affect the collapse of a structure are not considered through design processes, analytical methods, and very detailed analyses, it is very likely that some type of incident or accident will occur. For instance, improper installation of inverters and the configuration of the system itself can lead to significant energy losses, requiring detailed on-site corrections, all due to inadequate design (Bakır & Merabet, 2023).

Incorrect engineering assumptions, which may be based on imprecise data or inaccurate calculations, can lead to catastrophic outcomes. Additionally, if materials that do not meet the required standards of resistance, durability, and elasticity are chosen during the design process, the likelihood of an accident increases. One particularly important precondition is improving the level of redundancy, meaning that failures in one part of the components do not cause cascading failures throughout the entire facility.

To mitigate poor levels of redundancy, backup systems need to be designed to support the key operations of the industrial process, particularly in high-risk industries such as nuclear, chemical, or energy industries (Samson, Michael, Akanni, Pelumi, & Avidime, 2023). Moreover, it is important to have basic and advanced safety systems, such as fire prevention systems, automated control systems, emergency shutdown systems, and systems for halting certain industrial operations. Their design, implementation, and functioning reduce the levels of risk, i.e., the likelihood of the initial event occurring, and if it does occur, the consequences are minimized (DeMott, 2018).

One of the prevalent problems and causes of industrial disasters relates to numerous deficiencies in the processes of short-term and long-term maintenance of technical components and the systems themselves (Silvestri, McVee, Shanahan, & English, 2023). Prolonged wear, the formation of micro-damage, corrosion, etc., first leads to a reduction in functionality and later to complete failure. On the other hand, it is very important to continuously improve employee training, through which workers would be familiarized with all present direct and indirect risks and ways to eliminate them. Furthermore, in all situations, it is important that everyone adheres to certain safety protocols.

2.1.2. Human Error and Its Role in Technical Failures

In industrial systems and facilities, although the level of automation in work processes and safety control has been elevated, human errors still remain an unavoidable factor in causing serious consequences. Human errors are understood as all unintended or inappropriate decisions made at different levels of the organization that are unsuitable for the given situation (Vondráčková, Voštová, & Nývlt, 2017).

Numerous studies (Rasmussen, 1990; D. Smith, 2000; Williamson, Webb, Sellen, Runciman, & Van der Walt, 1993) show that human errors play a key role in the occurrence of technical failures across various industries. Such errors create far-reaching consequences for safety, operational efficiency, and reliability in industrial processes. For this reason, various methodologies for assessing human factor reliability have been developed, aimed at evaluating the frequency and impact of human errors in industrial environments such as production or engineering processes (González-Prida, Parra, Crespo, Kristjanpoller, & Gunckel, 2022). By using the Cognitive Reliability and Error Analysis Method (CREAM) in the maritime industry, human errors in the auxiliary systems of ship diesel engines were systematically analyzed, revealing that such errors could critically endanger engine safety (Demirel, 2021). In construction, directly or indirectly, human errors can significantly contribute to structural failures. These errors can occur due to inadequate decision-making at various management levels under the influence of disruptive factors such as fatigue, stress, the quality of education, working hours, and organizational climate (Vondráčková et al., 2017).

In the prevention of technical failures, through the realization of potential human error analyses in complex systems, various methods are applied (Human Error Probability HEP assessment, CREAM cognitive reliability error analysis methods). These methods are based on identifying the probability of errors during operations and analyzing factors such as operator fatigue levels, the adequacy of training, and decision-making processes, allowing risk managers to predict potential errors. Based on these analyses, corrective measures are designed and implemented later (e.g., ergonomic adjustments, process automation) (González-Prida et al., 2022).

2.2. Organizational Causes of Industrial Disasters

Organizational factors, in addition to technical factors, can be among the most significant contributors to the occurrence and further development of industrial disasters. It can be assumed that even if a technical cause arises if all preventive and organizational planning measures are in place, the consequences can be mitigated or prevented. On the other hand, certain studies (Schmitz, Reniers, Swuste, & van Nunen, 2021) emphasize that organizational factors can indirectly influence the occurrence of certain disasters caused by ammonia leaks by affecting the quality or reliability of barrier systems.

In general, if an organization does not pay sufficient attention to safety requirements and prioritizes production over the development and implementation of safety measures, an incident, or disaster will likely occur. Furthermore, a weak safety culture among employees and managers can result in non-compliance with prescribed safety procedures and protocols. Safety culture addresses the subtle difference between formal regulations and the practised and collectively accepted way of acting, which is based on shared assumptions, values and norms (Hopkins, 2018). Thus, a weak safety culture can lead to delayed identification of potential hazards and improper use of safety equipment.

When it comes to the policy of maintenance and the implementation of regular, extraordinary, and inspection controls, it should be noted that poor planning of technical system maintenance and safety equipment upgrades can lead to the degradation of protective barriers. This, in turn, increases the risks of various mechanical failures or leaks, which can result in more serious safety threats. Additionally, if well-developed communication channels and procedures for reporting minor structural and non-structural deficiencies are lacking, this can lead to further negative developments.

The safety management of companies plays a decisive role in establishing and improving safety procedures. Maturity models can help to assess and develop a safety culture - from compliance to commitment, where safety is proactively managed (Cooper, 2018). If there are no assessments and sanctions for bypassing the implementation of key protective and preventive measures, a more serious safety threat scenario will likely occur in the future. Developing a culture of punishment can also have the opposite effect, where mistakes and near misses are not reported out of fear (Marx, 2018). Organizational structures reflect top leader's priorities, and addressing organizational factors can strengthen the reliability of preventive and protective systems within companies.

2.3. Environmental and External Causes of Industrial Disasters

The safe operation of various industries is conditioned by numerous external and internal risks and threats. Such external and internal events can seriously affect the occurrence and development of industrial disasters. Various natural hazards, which can originate from the lithosphere, hydrosphere, atmosphere, biosphere, or extraterrestrial sources, may lead to the most likely and severe scenarios of industrial safety threats.

Disasters caused by natural hazards, such as earthquakes (e.g., the Fukushima earthquake), floods (e.g., in 2011 at a toxic chemical plant in Thailand, and in 2002 in the industrial zone in Dresden, Germany), hurricanes (e.g., in 2017, Hurricane Harvey caused massive flooding across Texas, particularly in the industrial belt around Houston), and extreme temperatures (e.g., excessive cold causing pipeline ruptures in Siberia) can create both direct and indirect causes of industrial disasters. The direct impact of such natural events involves their harmful effects (shock waves, thermal, radiation, etc.) on the technical and non-technical aspects of the functioning of various industries. The indirect impact of disasters on industrial operations can be seen in the disruption of supply chains due to destroyed or damaged critical infrastructure (e.g., collapsed bridges, flooded roads, power outages, etc.), the interruption of telecommunications, the absence of labour, the generation of socio-economic consequences, and changes in regulations and insurance. Additionally, the influence of climate change, which increases the frequency and intensity of various natural hazards, cannot be overlooked.

In addition to the mentioned disasters, negative social phenomena, such as sabotage and terrorist attacks, can lead to disasters in various industrial sectors. Sabotage, which involves deliberate damage or disruption of the functioning of industrial facilities, equipment, and processes, can result in serious industrial damage (Taylor & Walton, 2020).

In acts of sabotage, various physical attacks, cyberattacks, equipment manipulation, or intentional shutdowns of key technical and other systems can be executed. There are numerous examples of such sabotage: sabotage at oil facilities in Nigeria, where armed groups carry out numerous sabotage attacks on oil platforms, pipelines, and refineries; the cyberattack on facilities in Saudi Arabia in 2017, where security systems (compromising the automatic shutdown of facilities) at a Saudi oil and gas processing plant were attacked; drone and missile attacks on refinery facilities in Saudi Arabia in 2019; the explosion caused inside the Iranian uranium enrichment plant in Natanz; in the USA, an unknown individual added cyanide to Tylenol capsule bottles; and Volkswagen engineers deliberately installed emissions manipulation software in diesel vehicles in 2015.

Besides sabotage, other economic and political factors and conflicts can contribute to the occurrence of industrial disasters. For example, cost-cutting in the maintenance of the "Deepwater Horizon" oil platform in the Gulf of Mexico in 2010 led to a serious incident resulting in a massive oil spill in the gulf. Dangers arising from armed conflicts can also pose a massive threat to safety. The fighting around the Zaporizhzhya nuclear power plant during the war in Ukraine could have caused a reactor accident with far-reaching consequences for Europe.

3. Nature, Dynamics and Unpredictability of Industrial Disasters

Accelerated industrial development worldwide is characterized by chaotic systems, which are largely marked by their unpredictable nature, complexity, and sensitivity to numerous factors (Ndofor, Fabian, & Michel, 2018). The unpredictability refers to its likelihood of occurrence, the extent of damage, and how that damage may be distributed or manifested. This is especially true for technological innovations and related emerging risks. In difference, large industrial facilities harbour a complex risk: if an incident happens, its consequences can be immense because of complex interrelations and cascading effects (Renn, 2017).

In chemical or nuclear facilities, operations are conducted under specific and extreme conditions. Minor deviations in temperature, pressure, or system integrity can quickly escalate and lead to very dangerous consequences. Human errors can creep in every day during the production process because the employees themselves represent a source of danger. Stress or time pressure can affect their attention and diligence; inadequate training or familiarization, as well as a lack of physical or mental ability, can be the cause of incidents. Although innovative technologies are used to reduce the likelihood of human error, such as various alarm and sensor systems, both minor and major incidents still occur frequently.

Analyses show that current methods for managing human factors and risks are insufficiently effective in identifying and addressing the challenges arising from complex interactions between humans, technology, and organizational structures in industrial environments. It is thus very difficult to understand the complex interplay between human errors, technological failures, and deficiencies in organizational processes (Hassall, 2015). A deeper examination of the interconnectedness within industrial systems reveals that their elements are interdependent, meaning that a minor failure in one area can lead to catastrophic consequences in another sector (Silei, 2014). This can be described as a domino effect, which explains the interaction of interconnected components. The inherent uncertainty in industrial processes and the impact of human errors on all process levels from design, construction, and operation to maintenance show the importance of precaution, precisely because incidents can have massive consequences (Mannan, 2005).

4. Consequences of Industrial Disasters

Industrial hazards and disasters possess an immense energy potential to cause serious material and immaterial consequences. Analyses show that the scope and magnitude of the consequences of industrial disasters depend on the physical characteristics of the events themselves (size, scale, duration, frequency), as well as on the demographic, socio-economic, and psychological predispositions of the affected population in the impacted area (Hofer & Messerli, 2006). Similarly, Paul (2011) emphasizes that the consequences of disasters also depend on complex social, economic, demographic, political, and cultural factors. K. Smith and Ward (1998, p. 35) advocate a classification into direct and indirect consequences, which can be both material and immaterial. According to them, direct material consequences arise from the damage to buildings, structures, and infrastructure, while indirect consequences include lost production, income, and work absences (Cvetković, 2024).

Overall, it can be stated that industrial disasters can cause both direct and indirect damage and losses. Direct consequences typically refer to material (buildings, artefacts, work equipment) and immaterial damage, while indirect damage can be material (malfunctions in strategic services, decreased production levels) or immaterial (psychological and physiological impacts, abandonment of cultural assets, etc.). Thus, the consequences of industrial disasters are often multidimensional and multisectoral, which can significantly complicate the efforts of responsible government authorities to prevent them.

In an interesting study, the authors (Cvetković, Renner, Aleksova, & Lukić, 2024) analyzed the geospatial and temporal distribution of natural and technological disasters that occurred between 1900 and 2024. The study found that 25,836 disasters occurred worldwide, of which 69.41% were of natural origin (16,567), while 30.59% were of technological origin (9,269). The study also highlighted that technological disasters were most frequent in Africa, accounting for 43.79% of all disasters on the continent. Asia followed with 38.11%, while Europe and South America reported 35.46% and 33.44%, respectively. Oceania had the lowest percentage of technological disasters, with only 8.49%. Although Asia had the highest total number of disasters, it also had a significant share of technological disasters (38.11%), indicating the presence of technological accidents in the region. The high percentage of technological disasters in Africa (43.79%) may reflect various socio-economic factors and levels of infrastructural development (Cvetković et al., 2024).

4.1. Impact on Human Health

Industrial disasters produce multiple consequences for human health, and their specifics depend on the type of industrial hazard involved. Chemical industrial disasters can have widespread effects on public health in the immediate vicinity and the broader area surrounding the facility where the incident occurred. Such consequences require urgent and immediate medical measures to provide first aid and medical assistance to contaminated individuals (Clements & Casani, 2016). In such chemical disasters, it is crucial to quickly identify the hazardous or toxic substances involved. For these reasons, numerous technical systems are available to facilitate the identification of hazardous materials during disasters. Additionally, emergency and rescue personnel are equipped with mobile technical devices (pagers) that allow them to continuously monitor the presence and quantity of hazardous substances.

In addition to identifying the hazardous material, it is important to know the length of exposure to understand the safe levels and the potential courses of action in such situations. After chemical industrial disasters, the responsible authorities must establish a registry of individuals, documenting who has been exposed to certain chemicals and for how long. To promptly implement all operational, tactical, and technical protective measures for safeguarding human life and health during chemical industrial disasters, close cooperation is crucial between the industrial complex where the disaster occurred and the authorities and citizens before, during, and after the disaster. The exchange of information, timely notifications, and preventive public education on potential hazards and how to respond during such disasters are of utmost importance for preventing or mitigating the consequences of such events.

Industrial disasters bring serious and unique challenges in providing an adequate and timely response, particularly for medical services, considering the many gaps in scientific knowledge and the insufficient training of citizens and service personnel (Keim, 2011).

According to some research, such disasters have the potential to seriously affect the quality of life of employees, causing industrial pathology, occupational diseases, and cases of poisoning (Каширина, Салмина, & Каширина МВ, 2020). Of course, it is also important to note that when it comes to industrial disasters, there are double standards in health protection, where underdeveloped technologies are exploited in developing countries rather than in the countries of origin, exposing entire communities, societies, and workers to a wide range of health consequences.

Globally, the development of science and technology has contributed to the rapid emergence and proliferation of numerous hazardous materials that can endanger people and their health. These materials are often called "silent killers," and it is not uncommon for households to possess various chemicals that can directly or indirectly cause harm. For this reason, a prerequisite for the preventive protection of people is knowledge about the basic characteristics of how these hazardous materials react and behave. Certainly, there are different ways hazardous materials can enter the body: a) inhalation; b) absorption through the skin or eyes; c) ingestion; or d) injection. Depending on the specific material and the method of contamination, the entire response strategy of emergency and rescue services will be determined (Cvetković, 2022).

4.2. Economic Impacts of Industrial Disasters

The inevitable consequences of industrial disasters include serious economic damages both within and outside industrial complexes. These damages can have short-term or long-term economic effects and often depend on the type of industrial disaster. It is an undisputed fact that they lead to significant financial and social costs, which can also affect entire local communities where industrial complexes are located.

One study shows that industrial accidents causing offsite injuries, property damage, and requiring immediate evacuations can lead to a decrease in local property values by 5 to 8%, translating into an average financial loss of $12,000 to $20,000 per household within a five-kilometre radius (Guignet, Jenkins, Belke, & Mason, 2023). Additionally, industrial disasters can cause serious environmental consequences, as well as production losses. The dam failures in Brumadinho and Mariana in Brazil resulted in losses of approximately $13.48 billion (Gonzalez, da Silveira Rossi, & Vieira, 2022).

In terms of financial losses for the companies themselves, in the short term, such accidents can lead to numerous financial losses due to cleanup costs, decontamination, remediation, regulatory fines, business interruptions, hiring additional labour, etc. Conversely, in the long term, industrial disasters can also lead to financial crises in the market, especially within related industrial sectors. This occurs due to investors' predictions that, following previous industrial disasters, there will be higher regulatory costs and stricter safety procedures (Corbet, Larkin, & McMullan, 2018). In addition to the direct financial impacts, it should be noted that such accidents also have significant socio-economic implications for the labor market, where affected individuals may face prolonged periods of unemployment and reduced income (Parro Greco, 2023).

4.3. Environmental Impacts and Long-term Effects

The environmental consequences of industrial disasters can pose a significant challenge for disaster risk management professionals. The specific characteristics and extent of such environmental impacts depend on the type of disaster. Due to their diverse nature, these consequences can cause harmful effects on the soil, water, and air. Industrial accidents could have harmful effects on the environment, the health of a community, and ecosystems (Cvetković, 2024; Parro Greco, 2023; Poortinga, Pidgeon, Capstick, & Aoyagi, 2014; Schmitz et al., 2021). Also, industrial disasters have both immediate effects (injuries and fatalities), as well as long-term health impacts in the form of chronic diseases or disabilities. For instance, it can be said that many years after the Bhopal gas tragedy, people who were not even born at that time still had higher rates of cancer and several disabilities while in their mother's womb (McCord, Bharadwaj, McDougal, Kaushik, & Raj, 2023). On the other side, it can be mentioned that the economic implications are also significant, especially for global mega-corporations that potentially cause existential environmental crises. Markets reveal this year after year by continuing to price out risks from environmental damage, with financial losses extending far into the future. Investors react similarly, showing concern about potential future liabilities (Carpentier & Suret, 2013).

Additionally, industrial disasters are often associated with long-term transgenerational consequences. Also, they are more pronounced and prevalent in susceptible subpopulations such as neonates. We saw that the mining dam collapse in Brazil led to heightened infant mortality rates coupled with lower birth weights, signifying devastating health implications (Carrillo, Da Mata, Emanuel, Lopes, & Sampaio, 2020). This is why remnants of chemical spills can linger in the environment for years to decades. For instance, residents of Seveso, who developed chloracne, had increased long-term concerns about cancer risks even 20 years after the dioxin release (P. A. Bertazzi, 1991). These industrial disasters deliver not only physical harm but also an emotional toll — the latter can be just as devastating in communities already burdened with social and environmental challenges. For example, uranium mining in the Navajo community resulted in high levels of mental health issues such as anxiety and depression (Markstrom & Charley, 2003). Industrial accidents cause massive and enduring harm — ecologically, as well as to public health and economies, both immediate and intergenerational. Effectively responding to these effects and assisting recovery, while hastening the adoption of strategies that build resilience, requires a focus on prevention, regulation, and an effective response system.

5. Historical Overview of Industrial Disasters

5.1. Major Industrial Disasters: Case Analysis

In 1600, Bernardino documented the first recorded industrial chemical disaster. In his report, more than three centuries old, he noted that the toxic effects of industrial activities could affect not only workers but also the general population. This report was triggered by a citizen filing a complaint against the owner of a chemical laboratory (P.-A. Bertazzi, 1989).

In Seveso (with 17,000 residents), a commune in Lombardy, Italy, an industrial disaster occurred in 1976 at a chemical production plant, about 20 km from Milan. The disaster was caused by the interruption of a process that involved removing ethylene glycol from the reaction mixture by distillation. There was a serious drop in the load on the turbine, leading to an increase in the temperature of the released steam to around 300 degrees. The operators did not notice these changes in time, which resulted in the activation of a safety valve, releasing around 6,000 liters of chemicals within an 18 km radius. Immediately after, the affected area was divided into three zones: A (greater than 50 micrograms), B (between 5 and 50 micrograms), and R (negligible concentration less than 5 micrograms), based on the declining values of TCDD concentrations in the soil. Numerous preventive measures were taken, one of the most significant being the immediate euthanasia of over 80,000 animals to prevent them from entering the food chain. Zones A and B were fully evacuated, and all individuals underwent rigorous health examinations. Extensive decontamination and cleaning of the affected areas were carried out. The chemical leak led to an increased mortality rate due to cardiovascular and respiratory diseases (Cvetković, 2022).

Shortly after, in 1982, the Seveso Directive was introduced, strengthening preventive measures in industries. Updates to the Seveso III Directive followed in 1996, 2008, and 2012, prompted by various disasters. In 1987, after the Bhopal disaster and again after the fire at the Sandoz agrochemical warehouse near Basel, where chemicals, mainly organophosphate pesticides, spilled into the Rhine River, causing severe pollution and the death of nearly the entire European eel population spawning downstream of the spill (Güttinger & Stumm, 1992).

Another major industrial disaster occurred in India on December 3, 1984, in the city of Bhopal. A technical malfunction at the plant owned by the American chemical company Union Carbide caused a leak of 45 tons of toxic gas, methyl isocyanate, into the atmosphere, with devastating consequences for the environment and human health (Cvetković, 2024). Although this substance is often used in the industrial production of pesticides, it possesses dangerous properties, making it extremely hazardous (it is highly unstable, volatile, reacts violently with water, a hundred times more lethal than cyanide, and more dangerous than phosgene, a chemical weapon) (Lewis, 1992).

According to official reports, the disaster was caused by inadequate maintenance of safety devices, and no warning systems were in place (Peterson, 2009). A dense gas cloud covered an area of about seven kilometres, and according to the official report of the Indian government, 15,000 people died, and about 60,000 were injured. The poorest areas of the city were the most affected due to the high population density. There were no well-developed evacuation plans, and people inhaled the gas; local knowledge was poor, no proper evacuation was conducted, and there were no decontamination recommendations. The American legal system opposed compensation, and the Indian government paid damages totalling $470 million (Keith Smith & Petley, 2009, pp. 292-293). This event is recorded in history as the deadliest industrial disaster ever (Cvetković, 2024).

Furthermore, in Ukraine, near the city of Pripyat, a nuclear disaster occurred in 1986. At the Lenin Nuclear Power Plant near Pripyat, an experiment was conducted to test whether the electrical generator could provide sufficient power to cool the reactor while the diesel generator was activated. During the test, the routine steam supply from the reactor was cut off, and the power level dropped below 20 percent. The reactor was not shut down, and enormous amounts of steam and chemical reactions created pressure that caused an explosion. Pieces of radioactive material were ejected from the reactor and deposited about 1 km away from the plant, igniting other fires. The main component of the radioactive dust and gas released into the atmosphere contained iodine-131 and cesium-137, both of which can easily be absorbed by living tissue. The consequences of the event were catastrophic: about 30 people died while trying to extinguish the fires, and another 200 people sustained serious injuries due to exposure to radiation doses 2,000 times higher than normal. More than 130,000 people were evacuated from a 30-kilometer radius of the radioactive zone, and the city of Pripyat was abandoned (Cvetković, 2024; Keith Smith & Petley, 2009).

Another significant example of this type of disaster occurred in 2011 when Japan was struck by a powerful earthquake that triggered a tsunami, leading to a series of nuclear accidents in Fukushima. Before the earthquake, six nuclear reactors were operational, three of which were shut down during the earthquake, while the other three were automatically shut down. The tremor did not cause the disaster, but the tsunami waves flooded the entire area, causing water infiltration that left the remaining diesel generators without power. As a result, the necessary cooling of reactors 1, 2, and 3 could not be maintained, leading to partial core meltdowns and hydrogen explosions. Acting according to the disaster plan, the population within a 20 km radius of the nuclear plant was evacuated in a short period (Cvetković, 2024; Cvetković & Martinović, 2021).

5.2. Lessons Learned from Past Events of Industrial Disasters

Every industrial disaster carries numerous causes and consequences, and analyzing these can provide valuable lessons for improving conditions in this field. Such analyses can offer important insights regarding safety management in the industry, regulatory policies and practices, as well as the level of preparedness for future challenges, risks, and security threats. The analysis of the Fukushima Daiichi nuclear disaster revealed significant shortcomings in safety protocols concerning workers, particularly regarding the prevention of heatstroke and the long-term health effects of radiation exposure. The lessons learned from this event highlight the importance of continuous health monitoring for workers directly involved in the remediation of nuclear incidents (Mori et al., 2024).

Moreover, the Fukushima disaster also pointed to broader global health issues that such a catastrophe can cause (Said, Ahmadun, Kadir, & Daud, 2009). Also, an analysis of several industrial disasters was conducted, resulting in recommendations grouped into the following categories (Said et al., 2009):

a) Technical recommendations (improving specific technical specifications such as design parameters, implementing additional physical safety measures, enhancing the physical condition of the facility or demolishing and rebuilding it, conducting specific technical tests);

b) Recommendations regarding authority (improving the implementation of existing laws and regulations, introducing additional appropriate measures by the government, taking legal actions against those who do not comply with regulations, increasing penalties, revoking licenses or registrations);

c) Recommendations regarding existing laws and regulations (formulating more effective laws, regulations, and guidelines, amending existing laws, adding additional clauses, introducing new registration systems, and changing jurisdictions);

d) Recommendations regarding the revision of current work procedures (improving the appropriate monitoring and control systems, enhancing supervision, establishing and further strengthening comprehensive security procedures, improving horizontal and vertical coordination, developing proper documentation procedures, establishing financial management and quality resource allocation);

e) Recommendations regarding professional engagement (improving the hiring process of highly qualified and skilled workers, ensuring an adequate number of expert staff, ensuring that only qualified workers perform tasks related to safety);

f) Recommendations regarding education and training (increasing the current level of public awareness about safety, establishing adequate training for employees and emergency response personnel);

g) Recommendations regarding the formation and maintenance of specialized bodies or agencies (mandatory establishment of a national body for coordinating and overseeing issues related to the construction industry, mandatory introduction of specialized firefighting units within facilities handling hazardous materials).

6. Conslusion

A pace of technological advance means the opportunity for industrial disasters is never far away, and safety challenges continue to exist in various industries. It can be said that this multifaceted context of human errors, organizational weaknesses, and sometimes poor system performance underscores the importance of taking a holistic approach as part of comprehensive disaster risk management efforts. This fragility analysis reveals that addressing these risks cannot be limited to responses and defence mechanisms which are end-of-the-pipe but must include the design of systemic preventive strategies from an upstream perspective. The other significant aspect of this study suggests that safety measurements need an upgrade along with strict regulations to prevent low-frequency, high-severity events (i.e. disasters such as Chernobyl or Bhopal) and high-frequency, lower-impact events (i.e. personal injuries). Installing sophisticated early warning systems and scheduling equipment maintenance to avoid incidents are some of the measures that must be followed by industrial plants. Furthermore, Safety Culture is encouraged within organizations by consistent training and education to reduce human factors; an important cause of disaster.

The implications of this study stress the importance of interdisciplinary industrial disaster prevention involving engineers, safety training managers, and inspection authorities. International cooperation constitutes one of the key softer levers, in which best practices and lenses are shared to develop unified frameworks that can be taken up or adapted globally. Countries also need to ensure that there are stricter rules in place regarding the proper use of dangerous substances, and industries should be made accountable for their work by adhering further to safety regulations as well. The rapid technological development, industrial disasters become an important challenge to safety in different sectors. The lack of a consistent definition underlines the need for an all-encompassing model that enables sectors and decision-makers to prevent and mitigate these events. When it comes to creating a safety strategy, increased awareness of industrial hazards can go far. Also, the classification of industrial risks into type, cause, and materials streamlines risk management for an industry. Each sector can only collapse in a specific way, and by understanding the risks that are unique to each industry industries can take any number of precautions which when implemented prevent systemic collapses from occurring again.

This is because industrial disasters have complex effects, ranging from immediate physical destruction to long-term economic and ecological disasters with enormous social and health consequences. To mitigate the far-reaching impacts of this disruption, industries must work together with governments and other stakeholders on complete recovery plans that address their immediate needs at once while planning to restore regions in a resilient manner for years. Industrial disasters, typically but not solely chemical and nuclear accidents, have also had health consequences that demand urgent medical attention. This entails timely detection of toxic agents and long-term health surveillance of populations exposed. In minimizing health impacts, collaboration between industrial facilities that may be sources of contamination and other stakeholders, like emergency services and public health bodies is crucial.

The consequences of industrial disasters go beyond the short run and can have long-lasting economic impacts. Supplies and facilities do not exist that we can use to return habitat conditions, including these fish populations. The financial losses initially involve the clean-up and restoration attempts but extend on into property values, production abilities of all sorts, as well as economy-wide consequences. It is economically risky for the industries if they do not invest in mitigation methods and plans to make sure recovery will leave as little damage as possible on their financials, while governments should help with relief efforts within impacted communities.

Certainly, industrial disasters can generate horrendous damage to surrounding ecosystems and biodiversity. It underscores the crucial role that environmental regulations play in internalizing these externalities, as well as ensuring the industries put into place strict containment measures. Developing the capacity to address long-term environmental recovery is central to any disaster management response. Risk management for industrial disasters is highly challenging due to its unpredictable nature. Because the events are complex, so must the safety solutions — they need to accommodate future dynamic industrial process situations. Industries are capable of meeting the unknown nature of these disasters by integrating cutting-edge technologies and enhancing organizational oversight.

A lot of things are needed to occur in an industrial disaster, also there is a human role to take its part and organize as well other than the technical faults. These factors must be addressed together as part of any efforts to prevent tragedies like this in the future. Smarter, safer technologies along with heightened workforce training are necessary to protect every part of industrial operations. This includes the continuous development of competencies: a) consciously acquired skills and b) specifically deployed employees, considering their personality traits and attitudes towards safety and risk.

Many industrial disasters are the result of failures in design and engineering (for example, if a dam is built too weakly or from substandard materials), which can make what would otherwise be normal operation dangerous due to vulnerabilities. Working to improve procedures around design, and installing state-of-the-art safety equipment should also play a role in addressing these risks. Preventing minor residual designs from turning into full-scale disasters.

The fact that human error is a major cause of industrial disasters still holds in environments with advanced automation. Improving human reliability with training is needed to reduce technical failures as the latter commence from poor decision-making processes. Eliminating preventable disasters, the emphasis on human factors in industry. A safety culture, incompetence in maintenance, etc. -- are organizational failures that can cause industrial disasters. Preventing such incidents will require better corporate practices, from enforcing safety protocols to regular maintenance. Good organization will help prevent disasters from striking too often.

In the same way, industrial risk management needs to incorporate external factors such as natural disasters and sabotage. Industries need to have some concrete solutions that can help them in dealing with these external threats, which cause a huge loss of life and property. These strategies should also be able to focus on what the internal risk factors are (usually have greater controllability), as well they must examine how to take into account the risks occurring externally while drawing up disaster recovery management. This encompasses the range of hazards that need to be protected in industrial facilities.

Studying industrial disasters of the past provides critical lessons for doing better in managing future calamities. Industries can use the knowledge of what led to and followed these cases. The general idea is that from the study industries should learn lessons so as not to fall into a similar trap. Key takeaway: Lessons learned from previous incidents, improved regulatory frameworks, and safety protocols are to ensure that the risk of future industrial disasters is reduced. To prevent industrial disasters, it is amenable to multi-disciplinary and proactive risk management efforts. While the elimination of technology from its operations is an impossibility, the industry can reduce exposure to these hazards by implementing state-of-the-art engineering solutions, building stronger organizations, and tightening regulatory systems in managing risks associated with technological threats. Expanded prevention readiness capacity is essential to learn continually about previous disasters and international cooperation in industrial systems safer, and more resilient.

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