PREVENTION OF EMISSIONS AND ENVIRONMENTAL POLLUTION IN HIGH-RISK FACILITIES BY INCREASING SUPPLY CHAIN RESILIENCE

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Abstract
NaTech (Natural Hazard Triggering Technological Disasters) refers to events where natural disasters—such as floods, earthquakes, hurricanes, or landslides—trigger technological failures, leading to the release of hazardous substances, fires, or explosions. These compound events reflect the intersection between natural and technological hazards and represent an increasingly relevant risk in the context of accelerating climate change. Even more severe are the consequences related to NaTech events in SEVESO sites. Slovenia is exposed to multiple types of natural hazards, including floods, landslides, earthquakes, wildfires, and extreme weather events. In particular, the frequency and intensity of floods and landslides are increasing as a result of climate change, elevating the risk of NaTech incidents. Strengthening the climate resilience of industrial and critical infrastructure is therefore essential.
Keywords: *NaTech (Natural Hazards Causing Technological Disasters), natural hazards, technological disasters, floods, climate change*
JEL classification: Q50, Q56, P58, L52, M11, M14

INTRODUCTION

Natural disasters are increasingly revealing the vulnerabilities of technological systems, leading to the occurrence of NaTech events. These events, in which natural hazards cause technological failures, represent complex risk scenarios that require comprehensive understanding and strategic management. With the acceleration of climate change, an increase in the frequency and intensity of natural disasters is expected, which in turn heightens the potential for NaTech incidents. This theoretical framework delves into the dynamics of NaTech disasters, regulatory frameworks, and the critical importance of protecting such facilities while also strengthening supply chain resilience (Necci et al., 2018; European Commission, 2020; UNECE, 2023).

NaTech accidents occur when natural hazards such as floods, earthquakes, hurricanes, or landslides cause technological failures, leading to the release of hazardous substances, fires, explosions, or other catastrophic events. These incidents present considerable challenges, as they require simultaneous response to both natural and technological disasters. For instance, the 2002 summer floods in Europe and hurricanes Catrina and Rita in 2005 highlighted the severity of such combined events, where the interaction between natural and technological hazards led to serious consequences far beyond the immediate site of the accident (Necci et al., 2018).

In managing risks associated with hazardous facilities, the European regulatory framework plays a crucial role. The Seveso III Directive (European Commission, 2012) and the Industrial Emissions Directive (European Commission, 2020) provide strict guidelines for managing industrial activities involving dangerous substances. These directives emphasize the need for robust risk assessment methodologies and emergency preparedness plans to effectively manage NaTech-related risks.

Despite progress in regulation and risk governance, significant challenges remain in addressing NaTech risks. A major issue is the lack of comprehensive data and dedicated tools for assessing NaTech-specific scenarios (Necci & Krausmann, 2022). Furthermore, the simultaneous occurrence of natural and technological disasters places an additional burden on emergency response resources, complicating mitigation efforts. This dual impact requires an integrated approach to disaster management that considers the interdependence between natural and technological systems (Girgin et al., 2019).

Effective protection of NaTech-prone facilities requires a clear understanding of the complex interactions between natural and technological systems, as well as the development of integrated risk assessment methodologies and emergency response planning. The eNATECH database, developed by the European Commission's Joint Research Centre (JRC), systematically collects NaTech accident data worldwide, providing a valuable platform for accident analysis and learning (European Commission JRC, 2023). This tool offers in-depth insights into the causes and consequences of NaTech events, supporting improved risk assessment and the development of preventive measures. Key strategies for protecting NaTech-sensitive sites include the use of Best Available Techniques (BAT) to reduce emissions and reinforce structural resilience against natural hazards. Examples include elevating critical infrastructure above potential flood levels, reinforcing buildings against seismic activity, and ensuring robust containment systems for hazardous substances (European Commission, 2020). Krausmann, Girgin, and Necci (2019) emphasize the importance of using performance indicators for risk management, which enable the monitoring and improvement of preparedness for NaTech accidents.

Climate change has a significant impact on the frequency and severity of natural disasters, thereby increasing the risk of NaTech events. The rise in extreme weather events such as storms and heatwaves is directly correlated with higher probabilities of NaTech incidents (Necci et al., 2023).

Addressing these risks requires a proactive climate adaptation approach, including the incorporation of climate resilience into the design and operation of industrial facilities. This involves adopting climate-adaptive infrastructure, enhancing monitoring and early warning systems, and integrating climate risk assessments into regulatory frameworks (UNECE, 2023). Pilone et al. (2021) stress the importance of local-level awareness and preparedness for effectively managing climate-driven NaTech risks.

NaTech events also critically impact supply chain resilience. Disruptions to industrial operations caused by natural disasters can result in cascading effects across global supply chains. Strengthening supply chain resilience requires not only mitigating the direct impacts of natural disasters but also addressing the technological vulnerabilities that can exacerbate those impacts (Holgado & Niess, 2023; Jiang et al., 2023). Strategic measures such as supplier diversification, infrastructure robustness, and the development of emergency response plans are essential for building supply chain resilience to NaTech risks. Moreover, integrating knowledge management with supply chain resilience strategies can enhance overall performance and recovery capacity (Mukherjee et al., 2024).

In their study, Navaratnam et al. (2022) identify and develop measurement frameworks that allow for accurate assessment of critical infrastructure resilience. Their findings emphasize the need for multidimensional approaches that integrate technical, organizational, and social aspects to improve the overall resilience of such systems to both natural and technological hazards.

To improve the understanding and management of NaTech risks, continued research is essential. Studies focusing on the root causes and evolution of NaTech disasters can provide valuable insights for developing preventive measures (Cruz, 2012). In addition, advancements in risk assessment methodologies and the creation of comprehensive databases such as eNATECH will improve the ability to anticipate and respond to such events effectively. The adoption of guidelines and frameworks provided by agencies such as the Cybersecurity and Infrastructure Security Agency (CISA) is also crucial for maintaining the safety and resilience of critical infrastructure (CISA, 2019).

1. KEY FINDINGS OF THE RESEARCH

As part of this research, the project addressed the interaction between climate change, environmental risk facilities (SEVESO sites), and technological vulnerability. The project focused on:

- **Identifying facilities at risk:** In Slovenia, 60 Seveso-type facilities operate with various hazardous substances. Their vulnerability to NaTech events depends on the type and handling of these substances, and on location-specific natural hazard exposure (flood zones, landslide areas, etc.).
- **Characterizing NaTech risk pathways:**
    - **Extreme weather events** (floods, storms, heatwaves, droughts) are becoming more frequent and severe, directly threatening technological infrastructure.
    - **Sea-level rise** increases the risk for coastal industrial zones.
    - **Compound and cumulative effects** of climate-related disasters (e.g. simultaneous heat and drought events) increase system stress and failure likelihood.

- **Repetitive natural disasters** can degrade infrastructure over time, heightening the risk of future technological accidents.

- **Assessing impacts on supply chains:** NaTech events may severely disrupt supply chains by damaging critical facilities and infrastructure. Increased resilience is necessary to prevent cascading effects across economic and logistical systems.

Within the systematic literature review and review of lessons learned from specific databases (e-NaTech and E-MARS covering all NaTech and SEVESO disasters) adaptation and mitigations strategies were identified and directions for more resilient operations of SEVESO sites were proposed. Among them we would like to expose:

1) Adaptation and Risk Reduction Strategies

The project identified and proposed several adaptation pathways:

- **Climate-resilient infrastructure**:
  - Elevating facilities above projected flood levels
  - Reinforcing structures against landslides and storms
  - Implementing flood protection barriers
  - Updating construction standards to incorporate climate adaptation in vulnerable regions
- **Nature-based solutions and green infrastructure**:
  - Green roofs, bioretention systems, and preserved natural ecosystems help absorb stormwater and reduce urban heat
  - These also improve operational continuity and emergency access during extreme events
- **Advanced early warning systems and contingency planning**:
  - Climate-integrated risk scenarios
  - Updated emergency response plans incorporating NaTech-specific threats
  - Real-time monitoring and predictive warning tools
- **Awareness, training, and governance**:
  - Education and training for operators of high-risk facilities
  - Public awareness campaigns about NaTech and climate change
  - Cross-sectoral collaboration between industry, academia, public authorities, and civil society

b) Policy and Research Implications

The research emphasizes the need for:

- **Integration of climate change adaptation into environmental and industrial risk management** (e.g., Seveso III and IED directives)
- **Enhanced data collection and vulnerability mapping**, including the use of global databases such as eNATECH (JRC)

- **Development of robust, locally relevant performance indicators** for risk reduction
- **Comprehensive supply chain resilience planning**, including diversification, critical node protection, and emergency logistics

CONCLUSION

In conclusion, NaTech disasters represent a multi-layered risk scenario, intertwining natural and technological domains. As climate change continues to increase the frequency of natural hazards, the potential for NaTech incidents grows, highlighting the need for robust regulatory frameworks, integrated risk management strategies, and resilient supply chains. By systematically addressing these challenges through coordinated approaches and ongoing research and integrating adaptation strategies, the research contributes to improving industrial safety, environmental protection, and the resilience of supply systems with which the societies can become more resilient and better prepared to mitigate the impacts of future NaTech events.

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