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Modelling Industrial Vulnerabilities to NaTech: Methodological Contributions from Historical Lightning Triggered Analysis

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The Sendai Framework addresses the need to strengthen resilience and adaptive capacity against natural hazards and disasters while considering traditional approaches to reduce losses in lives, livelihoods, health, and the environment. The process industry, which owns several industrial macro-sectors (Ricci et al., 2021), provides essential services to society that can be harmed by the impact of natural hazards on critical industrial infrastructure. In this line, the natural hazards triggered by technological accidents (NaTech), have been generating recently large interest for research on the safety of critical industrial assets, facilities, equipment, or systems. Historical record analysis is essential for evaluating the likelihood of such events, determining the conditional probabilities of natural impact damage to industrial structures, and determining their final scenarios (Cozzani et al., 2010; Krausmann et al., 2011). Modelling is difficult since disaster intensity, frequency, and extension are hard to forecast, and their effects on facilities are often unknown. (Reniers et al., 2018). Although lightning constitutes only 11.3 % of NaTech events in the process industry (Ricci et al., 2021), the registered events hold significant consequences (Renni et al., 2010). The purpose of this work was to explore the modelling of industrial critical infrastructure vulnerabilities to NaTech events, implementing advanced methods to cope with the lack of or incomplete information available (Moriguchi et al., 2023). A historical analysis of events triggered by lightning strikes in the process industry was used as a pilot case study.

The approach sketched in Figure 1 consists of two phases: data collection and data analysis, with five steps each. Phase 1 involves source selection, retrieval assumptions, dataset setting, technical criteria definition, and data quality considerations. Phase 2 involves an overall analysis which encompasses events characterization, from diverse perspectives such as, source of data and geographic information, type of industrial event, frequency of functional attributes, consequences of technological scenarios analysis, and modelling techniques introduction.

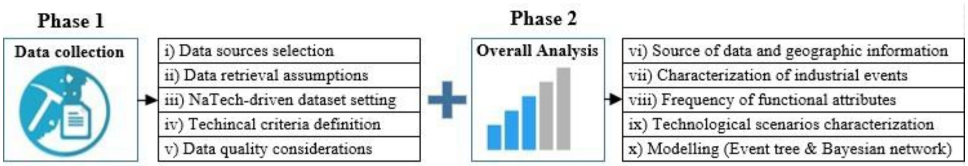

Fig. 1. Methodological approach to model the industrial vulnerabilities facing NaTech events.

The main result of phase 1 was a new dataset of 689 records, saved in a public repository (Castro Rodriguez et al., 2023). It includes information updates that span events until 2022. To this end, the open-source databases on industrial accidents ARIA, eMARS, TAD IChemE, eNATECH, and NRC/CSB were consulted for Europe and the US. Then the necessary inclusion criteria were rigorously defined (i.e. NaTech events triggered by lightning in the process industry). All the categories and criteria (i.e. scenarios, damage state, industrial macro-sectors, equipment, etc.) should be compatible with the background of NaTech research (Renni et al., 2010; Ricci et al., 2021) and comply with international standards (British Standards Institution, 2017). The categories “others” and “unknown” were added in case insufficient information for further statistical treatment during data analysis. Moving to phase 2, the data analysis revealed that over 80% of the instances resulted in significant incidents that injured people or caused loss of containment, mostly in the Chemical and Petrochemical sectors during regular plant operations. A strong seasonal pattern was detected with implications in preemptive lightning protection system planning. “Storage equipment”, and “electrical equipment and electronics devices” were the most damaged categories. Moreover, fire (F) was the predominant final scenario, particularly present in events involving hazardous substances classified as physical hazards (70% of cases) using a refined subset of 127 observations. Event tree analysis identified the frequency of direct and indirect paths of these events regarding the source of damages, while Bayesian network algorithms addressed incomplete information identifying signals and learning from refined datasets, which were generalized to the extended dataset with missing values. It allowed modelling conditional relationships between lightning damage sources and states, infrastructure with industrial macro-sectors and critical equipment and ultimately triggered scenarios. The conditional probability tables (CPTs) connecting Bayesian variables used to describe vulnerabilities are the main output of phase 2. Figure 2 offers the CPTs as heatmaps to assist the results visualization.

a) b)

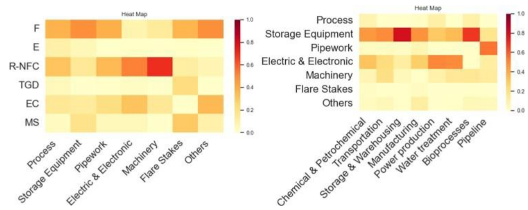

Fig. 2. Heatmaps for CPTs: a) Final scenario/Equipment involved, b) Equipment involved/Macro-sector.

The obtained vulnerability of industrial infrastructure to lightning strikes is a key component in modelling the impact of natural hazards on critical industries. This data should be coupled with other functional vulnerabilities of industrial entities (for example, hazardous substance storage) and territorial and weather-related information on natural disaster intensity relative to the plant location. For instance, the annual grounding lightning rate per square kilometer of surface (Ng). This research aids engineers in designing and assessing lightning protection systems, assists inspections, and contributes to enhanced industrial and territorial resilience to lightning strikes. This method needs more investigation to be applied to other natural hazards impacting industrial infrastructure.

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