DOTTORATO DI RICERCA IN INGEGNERIA CHIMICA
PhD PROGRAM IN CHEMICAL ENGINEERING
THESIS SUMMARY

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Titolo della tesi – Thesis title: "Modelling Industrial Vulnerabilities within a Multi-hazard Framework for the Resilience of the Territories."

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Sommario della tesi e descrizione dei principali risultati ottenuti-Summary and brief description of the obtained results:

A lamentable record of catastrophic events involving hazardous materials has resulted from the process industry historical development and evolution in Europe. The lessons learnt from these events are considered milestones in the evolution of process safety and show that accidents were not merely the result of technical failures, but also of complex nonlinear interactions among human, organizational, and/or external elements, such as natural hazards. These interactions represent unique risks to both the environment and neighboring communities, that should be addressed from a holistic perspective.

Nevertheless, substantial conceptual advancements in the fields of sustainable development, process safety, loss prevention, and disaster management (including the influence of climate change), coupled with the long break since the last publication in 2012 of the Seveso III Directive –current European framework for controlling major accident hazards involving hazardous substances–, established the necessity for revisions. The insights gained from Member State experience and some shortcomings identified by the scientific community, aim to address resilience as an emerging concept able to fill the gaps.

In this context, expected scenarios in Europe for the annual damage to critical infrastructure due to the impact of natural hazards, highlight the industrial sector among the ones with higher potential losses. Consequently, the European Commission has issued Directive (EU) 2022/2557 to strengthen the resilience of critical entities, where is explicit, that integrated risk assessment should be done in adherence to the sector-specific stipulated legislation of the European Union, with specific mention of the 2012/18/EU (Seveso III Directive), concerning process plants identified as critical infrastructure.

Pursuing the above-mentioned integration for risk evaluation between the current and future transposed directives, each Member State should adopt relevant organizational, methodological, and technological steps to guarantee the resilience of critical industries that are threatened by multiple hazards present in their surrounding territories. It should include steps to identify the vulnerabilities not well addressed due to the identified shortcomings of Seveso III. However, neither explicit instructions nor methodologies are included in the referred European directive about how vulnerabilities should be handled, or the resilience be enhanced.

As a result of the previous situation and focus on the Italian context as a representative Member State used as a case study, the following research questions (**RQ**) have been raised:

- **RQ1**) How effectively does the transposed legal framework for the Seveso III Directive address the resilience approach for Industrial Critical Infrastructures (ICIs) within multi-hazard contexts?

- **RQ2**) Can the implementation of modelling advanced methods, contribute to the identification of hidden signals that might trigger complex scenarios connecting the function of ICIs and the threats inherent to their multi-hazard surrounding territories?

- **RQ3**) Can the implementation of spatial advanced methods for vulnerability characterization reduce the gap regarding the disconnection between ICIs and external factors inherent to their multi-hazard surrounding territories?

- **RQ4**) How can the vulnerability signals coming from complex technological attributes against multiple hazards in industrial contexts be effectively addressed to enhance awareness from a multi-risk perspective?

From these controversies is generated the following hypothesis: "*The implementation of advanced methods to address the shortcomings in the Seveso III legal framework will increase the vulnerability awareness of ICIs threatened by multiple hazards in their surrounding territories, contributing to strengthening their resilience*."

Hence, the purpose of this research is to establish theoretical and methodological contributions for modelling and assessing the vulnerabilities of ICIs exposed to multiple hazards belonging to their surrounding territories, addressing detected gaps in the transposed legal framework for Seveso III Directive. Therefore, four specific scientific goals (**Sg**) are respectively associated with each one of the research questions previously stated:

- **Sg1**) Propose a novel approach to supplement the resilience of ICIs under a transposed Seveso III legal framework, addressing its exposition to multi-hazard contexts.

- **Sg2**) Design a procedure for modelling industrial vulnerabilities to NaTech events, implementing advanced mathematical methods to learn from past events in the presence of hidden uncertainties.

- **Sg3**) Design a placed-based procedure for the systematic vulnerability characterization of multiple attributes at a multi-level scale and within the multi-hazard relationship between ICIs and their surrounding territories, using real-world and hypothesized scenarios.

- **Sg4**) Integrate the functional and territorial vulnerabilities inherent to the ICIs within multi-hazard contexts in a comprehensive way that helps figure out how much NaTech potential a specific industrial plant has.

In a nutshell, this Ph.D. thesis presents theoretical and methodological contributions aiming to increase the vulnerability awareness of ICIs facing their multi-hazards contexts. The principal research outcomes are in line with the scientific objectives and were developed in four independent chapters after an initial theoretical background, these outputs represent a first methodological step that contributes to strengthening the resilience of ICIs.

The principal results obtained can be summarized as follows: i) Opportunities to enhance resilience within the anticipated integration framework between Directives 2012/18/EU and (EU) 2022/2557 were identified through the state-of-the-art analysis. ii) The Italian legal framework for transposing the Seveso III Directive was characterized using the process-based approach and a supplement was designed to strengthen the resilience, aiming to overcome the detected flaws. iii) A procedure to model historical vulnerabilities against NaTech was designed, including advanced modelling techniques to estimate the functional industrial vulnerabilities facing the data uncertainty present in the available industrial databases. This methodology was based on a historical examination of lightning-triggered NaTech events within the process industry, contributing novel insights and methodological generalizations. In addition, a lightning-triggered NaTech-driven dataset of 689 records was published. iv) A dynamic multi-hazards spatial approach was used to comprehensively characterize the territorial vulnerability across multiple geographical scales. v) At last, a multi-risk approach was developed by combining probabilistic and phenomenological functional data with territorial one to identify the NaTech potential of critical industries and focus on the principal hazards that correspond to their geographic locations. In addition, a factor to assess the potential of dangerous substances to cause major accidents was integrated into a decisional matrix for the comprehensive evaluation of NaTech potential.

So, the research was structured into 5 scientific chapters with balanced extensions and similar structures. Each chapter starts with a roadmap of the contents discussed and ends with partial conclusions and a references section. The partial conclusions were integrated and further discussed in the general conclusions chapter. Finally, recommendations and implications for ongoing works are summarized. A few annexes can be found at the end of the thesis which pretend to clear some specific passages.

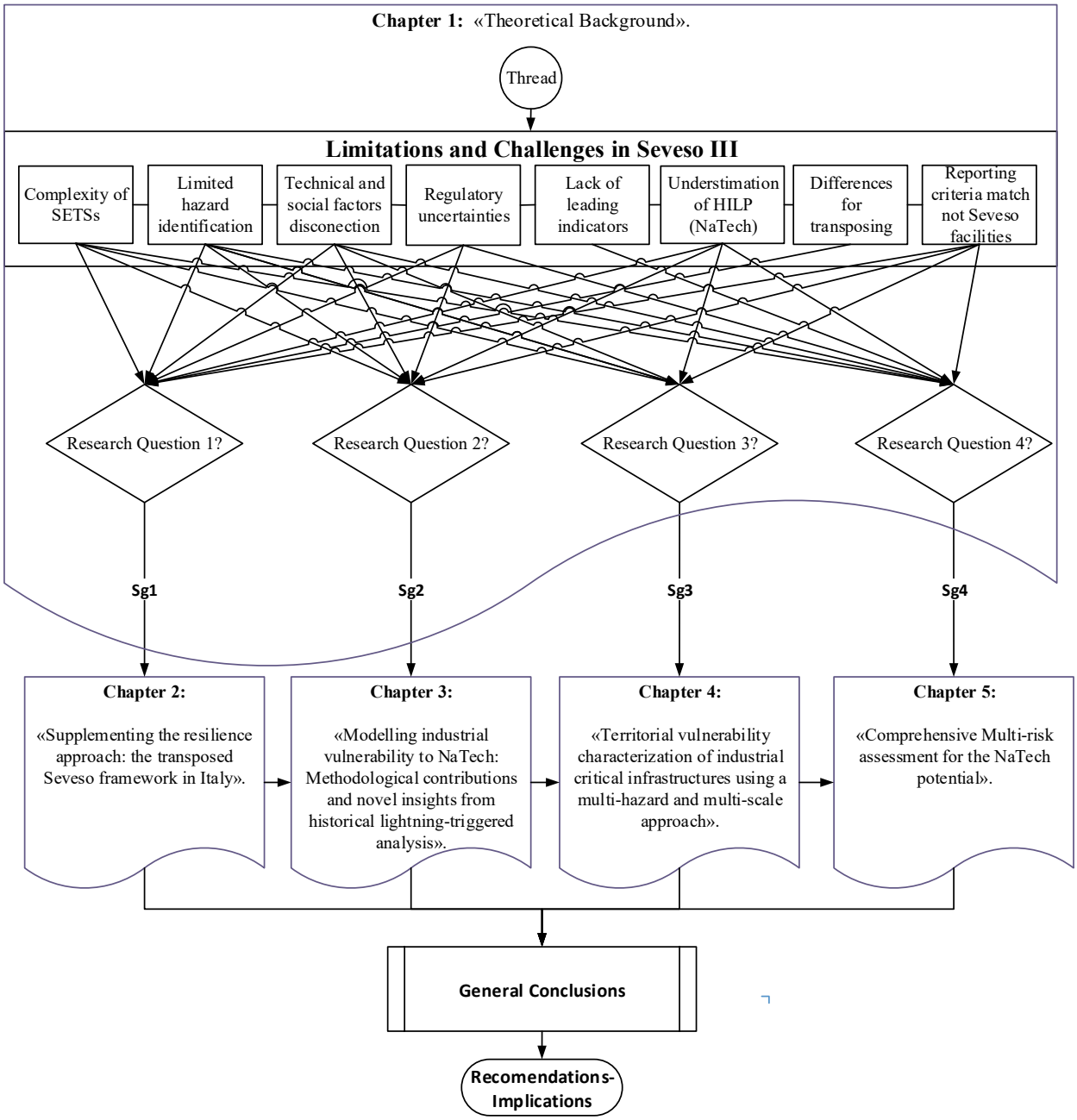

Figure 1. Thesis structure.