Learning from the past to enhance the resilience of nuclear power plants against natural disasters.

Leveraging Digital Technologies within the learning process to enhance resilience.
A Socio-Technical Systems Theory perspective.

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Master Thesis submitted to TU Delft

in partial fulfilment of the requirements for the degree of

Master of Science

In Management of Technology

Faculty of Technology, Policy and Management
at Delft University of Technology,

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to be defended publicly on
03-03-2025

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Acknowledgements

My academic journey at TU Delft began many years ago. Starting with a bachelor's in Mechanical Engineering, after which I moved onto the Management of Technology master's program. For my thesis is sought to combine organizational process management with technical systems. With this thesis project providing an excellent opportunity to explore these further. After months of research, writing and reflection I am proud to present the results of my work in this thesis report. The success and completion of this research would not have been possible without the guidance from various individuals whom I would like to thank.

I would like to express my sincere gratitude to my primary supervisor, Dr. Ming Yang. For his invaluable input, support and dedication. Answering my many questions and engaging with me in our discussion sessions throughout this entire thesis project. His insights were essential to the completion of this research. I would also like to thank Dr. Geerten van de Kaa, as chair and second supervisor. For his input and guidance during this process. His sharp analyses and feedback have helped elevate my research and ensured I remained critical of my own work as a researcher.

Additionally, I would like to express my appreciation to all my other professors and the staff I came across during my time at TU Delft. Their time and efforts have contributed to my academic development and growth as a person and a professional.

I would also like to thank friends and family, who have been there for me unconditionally throughout my academic journey. Your support and encouragement have made me pull through difficult times and motivated me to pursue my goals. Especially my girlfriend Cecile, for her love and patience. I am proud to share this success with you. Lastly, a thank you to my fellow student Kasana. Who guided and supported me throughout this academic journey. You have encouraged me to be the best version of myself and I am proud to call you a friend.

Thank you.

Maarten J.P. Hoogstad
Delft, February 2025

Executive Summary

As natural hazards and their impacts on critical infrastructures pose a significant threat to the stability and safety of society. Due to its' reliance on these critical infrastructures for providing valuable services such as telecommunication, transport or energy. A natural disaster impacting the operations of a critical infrastructure can have a far reaching and long-lasting impact on society. Particularly nuclear power plants, due to the potential consequences of a disruption in these systems. Therefore, enhancing resilience, meaning the ability to prepare for, adapt to, withstand and recover from a disaster, is imperative.

The research conducted in this thesis is focused on strengthening the learning from past incidents process, within nuclear power plants. To enhance their resilience in the face of natural hazards. And is aimed at laying the groundwork for an enhanced learning mechanism incorporated into a technical guideline document. The research involved a comprehensive review of relevant literature, which identified several knowledge gaps in existing practices. Current resilience strategies largely focus a reactive approach rather than a pro-active learning one. Furthermore, the lack of structured learning mechanisms within policy and regulatory document of the industry. And even though digital technologies offer advanced data processing, simulation and data-driven decision-making, their potential remains largely underutilized within resilience learning practices. Highlighting a gap, which this research aims to address. Through the introduction of the Enhanced Learning Process-model, which leverages digital technologies within a structured learning approach from a socio-technical perspective. Thus, supporting the resilience enhancement of nuclear power plants.

The methodology employed in this research, involves a comprehensive literature review, results obtained revolved around current resilience practices, social and organizational dimensions influencing the learning process and digital technologies that show potential to enhance resilience learning. Taking a Socio-Technical Systems approach to help structure the learning process, helped align technology adoption with identified actors and organizational factors. The model practicality was validated through expert consultation and case-based evaluation. As well as its' feasibility to lay the groundwork for a learning process guideline.

This research contributes to the field of resilience engineering and organizational learning by addressing resilience learning, incorporating digital technologies in a unique manner. Namely through the lens of Socio-Technical Systems theory. Providing a holistic view of the literature and the resilience learning process.

Additionally, this research provides insights for policymakers, industry experts and nuclear power plants operators. Who aim to enhance the resilience learning processes of nuclear power plants. With a structured learning enhancement approach. Integrating

digital tools, having the possibility to enhance learning capabilities. Leading to enhanced preparedness, adaptability and continuous learning in the face of natural hazards. Further avenues of research were also identified, spanning research on the influence of digital technologies on learning capabilities, and moderating effects within. Together with recommendations for further development of the ELP-model, including extending case studies, running a pilot and collaborating with industry regulatory experts on an international level to ensure the models feasibility to serve as the foundation for a learning process guideline.

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List of abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
ANVS	Autoriteit Nucleaire Veiligheid en Stralingsbescherming
AR	Augmented Reality
ASN	Nuclear Safety Authority
CI	Critical Infrastructure
DRM	Disaster Risk Management
DT	Digital Technology
ELP	Enhance Learning Process
EDF	Électricité de France
ENSREG	European Nuclear Safety Regulators Group
EPZ	Elektriciteits-Produktiemaatschappy Zuid-Nederland
ESA	Euratom Supply Agency
EU	European Union
Euratom	European Atomic Energy Community
GIS	Geographic Information System
IAEA	International Atomic Energy Agency
IoT	Internet of Things
ML	Machine Learning
MOT	Management of Technology
NATECH	Natural Hazard-Triggered Technological Accident
NEA	Nuclear Energy Agency
NGO	Non-governmental organization
NPP	Nuclear Power Plant
PRA	Probabilistic Risk Assessment
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
READ	Resilience Capacities Assessment for Critical Infrastructures Disruptions
RQ	Research Question
SLR	Systematic Literature Review
SRQ	Sub Research Question
STS	Socio-Technical Systems
UNDRR	United Nations Office for Disaster Risk Reduction
VR	Virtual Reality
WNA	World Nuclear Association

Glossary

Concept	Definition
Absorptive Capacity	The ability of an organization to recognize, assimilate and apply new knowledge to strengthen its' operations
Artificial Intelligence	The study and development of computer systems able to mimic intelligent human behaviors. Enabling them to learn, reason and make decisions autonomously
Cascading Effects	A chain reaction of failures in interconnected systems, where an initial disruption in one system leads to additional failures in others, compounding the impact of a disaster.
Critical Infrastructure	Systems that are vital for the functioning and welfare of society. Including, energy, water, telecommunication, transport.
Digital Technology	Advanced tools, systems or devices that can generate, create, store or process data.
Digital Twins	Virtual replicas of physical systems that use real-time data to simulate, analyze, and predict system behavior under various scenarios.
Disruptive Event	An unexpected event or hazard which impacts the performance of critical infrastructures.
Enhanced Learning Process Model	A structured approach to integrate lessons from past disasters into resilience strategies, leveraging digital technologies.
Fukushima Daiichi Disaster	A NATECH event in 2011 caused by an earthquake and tsunami, which led to a nuclear disaster.
Internet of Things	A network of interconnected devices and sensors that collect and share data to improve monitoring, decision-making, and operational efficiency.
Learning Process Guideline	A technical document containing a structured framework for systematically capturing, analyzing, and applying lessons from past disasters to improve resilience strategies.
Machine Learning	A subset of AI that enables systems to learn from data and improve performance over time without explicit programming.
NATECH Events	Natural-Hazard Triggered Technological Accidents, where natural hazards lead to technological accidents/disruptions.
Organizational Learning	The process by which an organization gathers, interprets, and integrates knowledge to improve its operations, enhance resilience, and adapt to changing conditions.
Resilience Engineering	Strategies used by systems to prepare for, absorb, recover and adapt to natural disasters and disruptions
Sendai Framework	A framework promoting resilience through learning from past disasters and fostering proactive strategies.

Socio-Technical Systems Theory	A framework analyzing the interplay between social (human, organizational) and technical (digital tools) components in complex systems.
Stakeholder Engagement	Active collaboration and communication with all relevant parties (e.g., regulators, operators, emergency services, and the public) to ensure the success of resilience and learning practices.
System Resilience	The capacity of a system to prepare for, absorb, recover from, and adapt to disruptive events, ensuring continuity of critical functions.
Systematic Literature Review	A methodical approach used to analyze and synthesize existing research on resilience, learning, and digital technology integration.

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Chapter 1: Introduction

1.1 Safeguarding nuclear power plants and society

Critical infrastructures (CIs) are essential for societal stability, providing vital services, such as energy, telecommunication or transport, that underpin daily life and economic prosperity. Their resilience, meaning the ability of these critical infrastructures to withstand and recover in the face of natural disasters such as earthquakes, tsunamis, and hurricanes, is crucial. Especially nuclear power plants (NPPs) where disruptions affecting these systems have far reaching consequences (IAEA, 2015). These disastrous events pose significant risks to the physical integrity of NPPs and the broader energy grid, emphasizing the need for resilience-enhancement strategies to mitigate their impact and ensure continuity of essential services.

Nuclear power plants sit in the energy sector and are classified as critical infrastructures (Labaka et al., 2015). “A Critical infrastructure is defined as a system that is essential for maintaining the vital functions of society, and the health, safety, security and economic wellbeing of the community, whose cessation or destruction would have a significant impact” - (European Commission, 2008 as cited in Curt & Tacnet, 2018). This notion of resilience is supported by (Labaka et al., 2015). Safety and risk management are paramount for NPP operations as is underlined by multiple studies. Kim et al. (2017) highlights the lack of a systematic risk management method and try to address this with a risk classification system. Similarly, Kim et al. (2018), aim to enhance the resilience literature by developing a quantitative resilience model. Providing new methods for safety assessment in NPPs.

There is a significant and growing call for resilient critical infrastructures, especially nuclear power plants, due to their potential for long-lasting consequences if they fail (UNDRR, 2015), (Krausmann et al., 2016). Resilience in this context means not just being prepared for disasters but having the ability to absorb shocks, adapt to new conditions, and recover swiftly. The aim is to build systems that can cope with these disruptions, minimizing their impact and ensuring continuity of essential services.

1.1.1 Natural Disasters

Natural disasters are characterized by their unpredictable nature and potentially have severe consequences for critical infrastructures. Under preparedness or lack of awareness aggravates the risks they pose. Enhancing the resilience of NPPs requires a proactive approach that includes learning from past disasters, improving risk management and resilience practices. Leveraging digital technology capabilities for better data processing and decision-making. Improving resilience through systematic learning and continuous adaptation.

1.1.2 NATECH events

Natural-Hazard Triggered Technological Accidents (NATECH) refers to technological accidents that are directly caused by natural hazards such as earthquakes, floods, tsunamis, hurricanes, or other natural events (eNATECH, n.d), (Misuri & Cozzani, 2024), (Krausmann et al., 2016). Where these phenomena lead to failures of industrial facilities, its' infrastructures or other technological systems. These incidents highlight the intersection of natural and technological risks and the unique challenges they present for prevention, preparedness, response, and recovery. The Fukushima Daiichi nuclear disaster in 2011 (IAEA, 2015), triggered by a magnitude 9.0 earthquake and subsequent tsunami, is a clear example of a NATECH event, where natural hazards caused major technological incidents leading to severe environmental and societal consequences. NATECH events highlight the interconnectedness of nature and human-made systems. As societies become more industrialized, complex and CI dependent, the potential for such events increases. Understanding and mitigating NATECH risks are important for reducing the overall impact of natural disasters and ensuring societies resilience (Mesa-Gómez et al., 2020).

By addressing NATECH risks, plant operators, policymakers, governmental bodies and emergency responders can better prepare for and manage the cascading effects of natural hazards, ultimately safeguarding human lives, the environment, and economic stability.

Characteristics of NATECH

NATECH events are characterized by their dual impact nature. Which means, natural hazards that cause cascading effects, leading to technological disruptions. Indirectly, these hazards can lead to secondary technological accidents, compounding the overall impact (Misuri & Cozzani, 2024).

Furthermore, the complexity of the response to such events need not be forgotten since emergency response efforts must address both the natural disaster and the technological accident simultaneously. Resources are often strained, and coordination becomes more challenging. Risk assessment and safety management go hand in hand with NATECH events (Krausmann et al., 2016). Assessing NATECH risks involves understanding both natural hazard vulnerabilities and the resilience of technological systems. Requiring integration of natural disaster preparedness with industrial safety protocols (Misuri & Cozzani, 2024).

NATECH resilience requires understanding how natural forces impact technological infrastructures. The concept focuses on identifying and evaluating the vulnerabilities of technological systems to natural hazards and assessing the potential cascading effects of natural events on industrial infrastructure and operations. Emphasizing the need for NPPs to reflect on the past and be aware of their situational surroundings. Several studies underline that the concept of NATECH warrants the development of strategies to enhance the resilience of critical infrastructure systems against natural hazards, therefore integrating natural hazard preparedness with technological risk management practices (Krausmann et al., 2016), (Misuri & Cozzani, 2024), (Mesa-Gómez et al., 2020).

1.2 Considering resilience engineering

Resilience engineering is a multifaceted concept with various interpretations. It generally involves stages such as planning, absorption, recovery, and adaptability. However, traditional definitions often overlook the aspect of learning. According to Holling (1973), resilience in engineering terms is the speed of return to equilibrium, whereas ecological resilience focuses more on adaptability of the systems. Given that post-disaster equilibrium often shifts, resilience must incorporate flexibility and the capacity for learning and adaptation. Whereas Holling (1973) mentions learning as a part of resilience, but more modern interpretations of resilience generally overlook this.

The resilience of critical infrastructure systems, as stated by Mottahedi et al. (2021) is the capacity of these systems to predict, adapt to, protect against, absorb, and recover from disruptive events. Setola et al. (2016) endorse this. Similarly, Möhrle et al. (2021) describe infrastructure resilience as three stages: probability reduction capabilities, shock absorption, and re-establishing normal operating conditions. This is supported by Kim et al. (2021). Moreover, resilience encompasses four pillars: robustness, redundancy, resourcefulness, and rapidity (Bruneau et al., 2003), (Sambowo & Hidayatno, 2021). Curt & Tacnet, (2018) propose the addition of a fifth element to this list, 'Protectiveness'. This refers to the ability of external mechanisms or tools to safeguard the system. However, specifics on these externalities are not mentioned.

Moreover, Möhrle et al. (2021) argue that one way to enhance resilience is to strengthen risk management. By improving awareness of the current situation and forecasting future events. Effective resilience in part is mitigation of the probability of possible events, and reduction of consequences using preventive and protective programs (Mottahedi et al., 2021). Identification of preventive and protective programs within the study is absent.

Curt & Tacnet, (2018) underline that the conceptualization of resilience has been extensively discussed throughout the literature. However, calling for the development of a structured framework to obtain an overview of this concept. And providing argumentation for limitations in the resilience of CIs literature. Building upon this, Petrenj et al. (2018) propose the READ framework, with a capabilities-based approach, to enhance resilience. Yet, learning capabilities are not included within this framework.

Furthermore, Curt & Tacnet, (2018) emphasize the need for taking into account different scenarios and metrics in resilience tool design in light of data analysis deficiencies. Highlighting the lack of enhanced data processing and analysis techniques within resilience strategies against disruptive events.

Risk Management and Resilience Engineering

"Resilience management goes beyond risk management and is a complementary set of activities that uses strategies of service restoration and adaptation to improve traditional risk management" - (Petrenj et al., 2018, p. 2). Resilience has been an emerging topic within risk management, it is needed to manage the uncertainties associated with disruptive events (Bruneau et al., 2003). As stated by multiple studies; (Mottahedi et al., 2021; Curt & Tacnet, 2018; Möhrle et al., 2021) limitations exist within risk management, recognizing the necessity for strengthened understanding of resilience to withstand and recover from disruptive events. Risk management has a primarily preventive focus (Mottahedi et al., 2021). Whereas resilience employs more adaptive and recovery strategies, utilizing a more holistic approach (Petrenj et al., 2018).

Risk management and resilience engineering are interconnected yet distinct concepts. Traditional risk management focuses on identifying, assessing, and mitigating risks before they materialize, primarily through preventive measures. Both concepts are essential for managing the uncertainties associated with natural disasters, but resilience engineering goes beyond risk management by incorporating adaptive and recovery strategies (Petrenj et al., 2018). Emphasizing the ability to withstand, adapt to, and recover from adverse events. This encompassing approach is crucial for managing the unknowns within natural disasters.

Current practices and challenges in the face of disruptive events

Current resilience practices in NPPs often focus on reactive and predictive measures, neglecting the importance of systematic learning from past events. This oversight hinders the ability to effectively prepare for and mitigate the effects of future disasters. Key challenges in current risk management practices include the complexity of managing risks, restricted access to information, procedural errors, and the need for more comprehensive frameworks that integrate learning and adaptive strategies. As stated by (Mottahedi et al., 2021), CIs are of vital importance to society. To create organizational resilience and safeguard CIs, all stakeholders need to be involved. To accomplish this, managers employ risk management practices as the core method to enhance CI safety.

Risk management is important for CIs and their operations. Consisting of different practices and strategies to prepare and adapt for disruptive events and support resilience (Mottahedi et al., 2021; Möhrle et al., 2021). However, risk management practices do have its limitations. Current risk management practices fall short in their effectiveness in rare or unforeseen events, natural hazards and NATECH events are part of such disruptive events. Moreover, an effective approach for managing pre- and post-disruption activities (Mottahedi et al., 2021), is lacking. Furthermore, Curt & Tacnet (2018) show there are some challenges regarding risk management, most notably, the inherent complexity of risk management as a whole. Issues such as restricted access to information, lead to merely an approximation of reality. Making it difficult for systems to identify root-causes of disruptions. Moreover, the incompleteness of resilience strategies, the aggregation of various human factors and errors in procedures. These points underscore the notion, within CI risk management and resilience literature, that risk management practices and strategies need to be further expanded.

1.3 Learning from the past to inform resilience strategies

Organizational learning, as the process of gathering new or existing knowledge in organizations, as well as how past events are analyzed as part of the resilience of NPPs is mentioned in (Kim et al., 2018). Learning as part of NATECH event management has also been touched upon by Krausmann et al., (2016). Within NATECH literature, Misuri & Cozzani (2024), provide a roadmap for the quantitative assessment and prevention of NATECH events, however digital technology utilization is not mentioned. Further development by Kim et al. (2021) of the resilience model introduced by Kim et al. (2018) utilizes past event data to enhance the model. Establishing the concept of organizational learning as an aspect of NPPs resilience practices. However, the study does not consider organizational learning in its event analysis due to the lack of correlation found between resilience and organizational learning identified in Kim et al. (2018). Important to note that the impact of digital technology adoption within resilience learning processes, from past events, within NPPs have not been fully utilized. Contrary to this, Labaka et al. (2015) highlight the importance of absorptive capacity as part of resilience engineering, concerning NPPs. Furthermore, several studies have shown the usefulness of digital technologies in resilience enhancement of other CIs as evidenced in the following sections. Historical catastrophes, such as the Chernobyl disaster (Aitsi-Selmi & Murray, 2016) and the Fukushima Daiichi accident (IAEA, 2015), have fundamentally changed the approach to disaster risk reduction. Frameworks like the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015), emphasize the importance of resilience on a global scale. Highlighting the need for learning mechanisms to prevent similar disasters in the future. Incorporating systematic learning from the past into resilience strategies, however, involves capturing and analyzing historical data to inform future practices, thereby enhancing the absorptive capacity and overall resilience of NPPs. And utilizing digital technologies to increase learning from historical data, to be better prepared and more resilient against natural disasters.

1.4 Digital technology integration to support resilience learning

Digital technologies, such as machine learning (ML) models, Digital Twins or Internet of Things devices (IoT), have the potential to enhance the resilience of NPPs (Argyroudis et al. 2022). These technologies can improve data collection, analysis, and predictive capabilities, enabling better decision-making during and after natural disasters. However, the practical application of these technologies in resilience practices remains limited, indicating a need for further research and development of integrated frameworks that leverage these tools (Argyroudis et al. 2022), (Möhrle et al. 2021).

Digital technologies, as external tools to strengthen climate resilience of CIs, show promise, as stated by Argyroudis et al. (2022). Furthermore, the study underlines a lack of consensus and integrated approach in the literature and challenges still exist. Similarly, Möhrle et al. (2021) highlight the potential of DTs, specifically deep learning practices to enhance CI resilience, by analyzing complex environments and large datasets. Internet of Things (IoT) devices can play a large role in the predictive capabilities of a system, as stated by Abreu et al. (2016). Gohel et al. (2020), propose a machine-learning algorithm to perform predictive measures in NPPs. Showcasing the potential of DTs, such as machine learning and AI to enhance data analysis, regarding CI resilience enhancement.

Within the literature the relationship between utilizing enhanced data analysis of disaster data to learn from past events and learning capabilities, as part of absorptive capacities of resilience enhancement practices of CIs has not been fully addressed. Opportunities exist regarding CI resilience enhancement, by integrating available practices and current technologies that can aid the resilience and risk management of CIs, within the realm of this study, NPP systems in particular. Laying the foundation for an effective learning process guideline, integrated with digital technologies for enhanced disaster data analysis to strengthen the absorptive capacity of systems and resilience practices and would provide a valuable effort to fill this gap.

1.5 STS theory and the Enhanced Learning Process (ELP) model

The Enhanced Learning Process (ELP) model, developed in this study, attempts to address the need for a structured approach to learning from past disasters to enhance the resilience of NPPs against natural hazards. By building upon the gaps and insights identified in the literature surrounding resilience engineering, organizational learning and digital technology utilization. Namely, the lack of systematic and structured learning from the past mechanisms. Underutilization of the potentials of digital technologies within NPP resilience and integration into structured protocols.

Taking a Socio-Technical Systems theory (Ottens et al., 2006) perspective on the learning from the past process to structure the model. The Socio-Technical Systems (STS) framework is an often-used framework in organizational management. STS theory allows organizations to comprehend and address the multifaceted nature of the challenges associated with modern organizational and engineering management. The STS framework has been used within the realm of NPP systems and CI resilience engineering (Dainoff et al 2023), (Thomas, 2017), (Reiman, 2007). Labaka et al. (2015), has touched upon the interconnectedness of socio-technical systems within their proposed framework. This STS framework will be utilized to analyse the interaction between the social and technical elements in the context of the learning process resulting in enhanced NPP resilience. Helping to identify how organizational, human and technological factors influence each other as well as resilience strategies and their implementation.

Providing a rounded perspective on the learning process. And how digital technologies present opportunities to strengthen it. Through the interconnectedness of social and technical dimensions in an organizational context. STS theory emphasizes that alignment of human actors, social organizational dimensions and technical systems, results in organizational performance (Ottens et al., 2006). This study recognizes that enhancement of the learning process and resilience is achieved through alignment and strengthening of these interconnected components (Dainoff et al., 2023), (Thomas, 2017), (ESReDa, 2015).

The learning process proposed in this research, detailed further in Chapter 4, is visualized through various stage in the ELP-model. Focussed on systematically extracting and integrating lessons from past disasters to enhance resilience. Promoting the use of digital technologies to enhance learning in various stages of the process. The integration of these technologies, such as IoT devices, ML-models, Digital Twins or governance and collaboration platforms into the ELP-model. Enables comprehensive data collection and analysis for extracting actionable insights from historical disaster data. And ensures data-driven resilience strategies. Prepare from potential natural hazards and assess operational performance through simulated scenario-based learning. And support feedback mechanisms to improve decision-making and iterate on learning outcomes and resilience strategies. Facilitating a structured continuous learning approach to data-driven resilience enhancement. And attempts to lay the foundations for a learning process guideline. Guiding NPPs in systematically extracting and incorporating lessons from the past into their resilience strategies.

1.6 Research Objectives

This research seeks to build a foundation onto which an effective learning process guideline to enhance the resilience of nuclear power plants against natural disasters can be developed. Specific objectives include:

1. *Context comprehension:* Understanding the context of Nuclear Power Plant systems. Including regulations and stakeholder identification to ensure the guideline's applicability and effectiveness.
2. *Explore current practices:* And evaluate existing resilience and risk management practices to identify gaps and barriers.
3. *What does it take to learn:* Highlighting what factors influence learning capabilities. To develop a practical guideline that integrates digital technologies to improve the absorptive capacity and resilience of nuclear power plants.
4. *Establish the role of digital technologies in enhancing learning for resilience:* Investigate what and how digital technologies can improve disaster data collection and analysis to enhance learning outcomes in resilience engineering.
5. *Develop a socio-technical learning process approach*: Structure a theoretical potential enhanced learning process. Based on literature synthesis and insights. Using STS theory, to align technological integration, with social dimensions.
6. *Validation and verification of results:* Demonstrate the practical application of the devised learning process using a relevant historical event. To evaluate points of improvement for the resilience learning process within NPPs and assess its' value in improving learning from past disasters. Further verify and validate the outcomes of the research and underscore the model's practical value. Through expert consultation feedback, from a professional in the industry.

Research Questions

"How can a structured learning mechanism, using digital technologies, be developed and implemented in nuclear power plants to enhance their resilience against natural disasters?"

The main question is focused on the structuring and implementation of a structured learning mechanism for NPPs. Leveraging digital technologies to enhance their resilience against natural disasters. Laying the foundation for the development of a learning process guideline.

Sub-questions:

1. What challenges exist in current resilience engineering learning processes for NPPs?
2. Which digital technologies can be utilized to address these challenges and enhance historical disaster data processing and improve resilience strategies?
3. How can digital technologies be integrated into a learning mechanism to strengthen learning capabilities through enhanced historical data-driven decision-making, and inform resilience strategies?

The sub-questions follow a chronological order for the research to be conducted and aid in answering the main research question. Which highlights the importance of resilience engineering, systematic organizational learning and digital tool integration. Sub-question 1, helps to understand the problem, identifying challenges and gaps in current resilience and learning practices. The next sub-question explores the technical solutions available to address the gaps and points of improvement within the learning processes. Helping to build a theoretical foundation and comprehension of the literature to develop the theoretical learning process model. Sub-question 3 is aimed at developing a structured learning mechanism that integrates digital technologies. And assess its' practical feasibility in enhancing the learning processes.

1.7 Relevance

1.7.1 Society

This research holds relevance to society by addressing the need for enhancing the resilience of nuclear power plants, which are important components of our energy infrastructure. Natural disasters can have severe impacts on these facilities, leading to disruptions in energy supply, economic losses, and potential safety hazards. By synthesising literature and laying the foundation for a protocol that incorporates advanced digital technologies, this research aims to improve the ability of nuclear power plants to prepare for, adapt to, withstand and recover from such events. This enhancement not only ensures a more reliable and secure energy supply but also safeguards public health and safety, thereby contributing to the overall stability and resilience of society.

1.7.2 Scientific/scholarly community

From a scholarly perspective, this research contributes to the field of disaster resilience engineering and risk management. It addresses existing gaps in the literature by focusing on the integration of digital technologies to enhance learning from past natural disasters. By highlighting the elements needed enhance resilience that includes socio and technical dimensions to learning and resilience, this study aims to advance the theoretical understanding of resilience learning in nuclear power plants. Furthermore, the interdisciplinary approach, combining elements of engineering, technology management, and organizational learning, provides a comprehensive model that can be developed and applied to suit other critical infrastructures beyond nuclear power plants. This research not only expands the academic discourse but also offers practical insights and mechanisms that can be utilized by researchers and practitioners in developing more resilient infrastructure systems globally.

1.7.3 Management of Technology

This research aims to enhance the resilience of nuclear power plants in the face of natural disasters by way of learning from the past. Laying the foundation for the development of a learning process guideline. To do this the challenges and barriers of the process of learning need to be identified on a human-level and organizational scale, in the form of the absorptive capacity of an organization. Utilizing digital technologies as tools to enhance (historical) data collection and integrating them into the protocol. These elements that make up a protocol will lay foundation for further research and will aid nuclear power plants to be more prepared and build resilience against future natural disasters.

The way this study has been set up, together with the accompanying objectives, utilizing the knowledge that is taught within the Management of Technology (MOT) masters. Sitting at the intersection of multiple disciplines, underlines the interdisciplinary nature of the Management of Technology program. Investigating the cross-roads of risk and resilience management, together with technological innovation and organizational learning capacities. One of the core objectives of MOT is to equip students and future leaders with the skill to address technological advancements, on a global-scale, and navigate in fast-changing environments with complex socio-technical systems. The emphasis on utilizing the available digital technologies to further learning and enhance resilience strategies within this research, further underline objective of the program to leverage technological innovations for the benefit of society. During the class of Technology, Strategy & Entrepreneurship, students are introduced into various business strategies surrounding new projects to make them successful. Risk management is introduced as a key part in business and product development processes. Utilized as a tool to improve performance of the project, product or organization.

As this study focusses on nuclear power plants, it is important to understand the environment surrounding such organizations, stakeholders within the organization and on the outside in adjacent organizations. To stay in line with policies and regulations concerning processes and safety as this is of key importance within this sector. The understanding of the importance of the environment surrounding an organization or sector is a topic that is discussed throughout the curriculum, with the course of Inter- and Intra-organization decision emphasizing the importance. Students are given multiple examples of organizational surroundings and how to approach stakeholders, inside and outside of an organization. Furthermore, to cross-validate findings, information collected from different sources will be analyzed and compared. Ensuring a level of internal assessment to this study.

1.8 Aim of research

The aim of this thesis project research is to strengthen NPP resilience learning processes. Informed by investigation of literature surrounding resilience engineering, organizational learning and digital technology utilization. To conceptualize a theoretical enhanced learning process in the form of the ELP-model. Recognizing limitations in current resilience learning processes within NPPs. This study emphasizes the importance of adopting a systematic learning from past disasters approach to improve preparedness, adaptability and recovery of NPPs in the face of natural hazards.

By integrating digital technologies into a structured learning approach, this research seeks to enhance data collection, analysis and decision-making within NPP resilience learning. Existing practices often overlook the importance of systematic, pro-active learning mechanisms where digital technology advantages are not fully utilized. This study aims to bridge the gap by exploring what and how digital tools can facilitate a more comprehensive and pro-active learning approach. This study employs Socio-Technical Systems theory to develop the model. Regarding the interconnectedness of humans, social and organizational learning dynamics and digital tools. And appreciates that technology adoption within resilience enhancement learning needs alignment of both human and organizational factors.

Through the conceptualization and validation of the ELP-model. This study aims to lay the groundwork for a learning process guideline. That can be implemented within NPPs to systematically extract, process data and integrate lessons from past disasters.

Supported by digital technology utilization. By doing so, contributing to strengthening the absorptive capacity of NPPs, facilitating that reflection on the past is transformed into actionable resilience strategies, resulting in a more safeguarded NPP, industry and society in the face of natural hazards.

1.9 Research Outline

This thesis research and its' report cover several components. The structure of the report is as follows. Chapter 1 has served as the gateway into the research, introducing the need for research and the various topics, together with the research objectives, introducing the research questions and the research relevance. Chapter 2 details the research design and the methodology and theory applied to address the objectives and research questions. Chapter 3 contains an in-depth review and synthesis of the literature exploring the topics surrounding resilience engineering, organizational learning and digital technology utilization. Gathered through the SLR. The literature synthesis serves to create a deeper comprehension of the context of this research topic and identify knowledge gaps, combining various areas of literature to bridge these gaps consolidate into a knowledge base to develop a theoretical potential enhanced learning process within NPPs. Which is developed, illustrated and described in Chapter 4. For this study to validate and verify its' findings and outcomes the validation process is delineated in Chapter 5. Which contains a case-based evaluation of the model, to demonstrate the practical application of the model, and identify points of improvements for the learning processes within NPPs based on the application of the model onto the studied case. Additionally, an expert in the field was consulted. To cross-validate the insights and findings gathered from the literature as well as assess the practical feasibility of the model in the context of the study. On enhancing the resilience learning process. Chapter 6 discusses key insights and research outcomes in regard to the research questions. Furthermore, discussing limitations of the methodology employed. The theoretical and practical implications of this work. And highlight areas that warrant further research, which includes propositions for further exploration. Finally, Chapter 7 holds the conclusion of this thesis research project. Appendix A presents the reviewed literature in a systematic way, showcasing important characteristics of the sources and relevance to the research conducted in this thesis. As well as the search strategy. Appendix B serves as an addition to Chapter 3, exploring the physical infrastructure of the NPP, providing an overview of the discussed digital technologies and discussing their potential benefit when integrated into a learning process guideline. Appendix C holds the transcript of the expert consultation session. Appendix D provides an addition to the discussion through synergy of the topics and a composition of an adjusted STS framework.

Chapter 2: Research Design and Methodology

This chapter outlines the research design, the methods and frameworks used in this study to lay the foundation for the development of a learning process guideline aimed at enhancing the resilience of NNPs against natural disasters. This study illustrates a theoretical enhanced learning process approach, in the form of the ELP-model. Which integrates digital technologies to support systematic learning from past disasters. To gain a deeper understanding of the context and generate a solid knowledge foundation for development of the ELP-model. A Systematic Literature Review (SLR) was conducted. The SLR was performed by adopting the PRISMA framework (PRISMA, 2020) guidelines. Ensuring a rigorous and transparent selection and synthesis of the relevant literature. The methodology has been established and adapted to suit the specific context and objectives of this study. And builds on the gathered information within the literature of resilience engineering, organizational learning, digital technology utilization and STS theory. Which collectively informed the conceptualization of an enhanced learning approach for NPPs. Using STS theory to provide structure to the model. To ensure that both social and technical dimensions are effectively aligned. The data analysis and literature synthesis has been organized into thematic clusters, relevant to the context. Which flows from the data source matrix, outlined in Appendix A, created during the Systematic Literature Review. The subsequent sections describe the research design, outlining steps taken. Detailing the frameworks employed and validation process to ensure validity of the outcomes and applicability of the model.

2.1 Preparation and Research Design

The research flow diagram is shown in Figure 1 below. The research set-up involved an initial exploration of the research subject and its' context through online data sources. Scoping the problem and initial identification of knowledge gaps, creating a theoretical background. This led to the development of the research objectives and subsequent research questions. And the designing of this study's methodology.

A major part of this research consists of the collection, analysis and synthesis of the literature data, in the form of a SLR. Conducted to consolidate relevant insights from resilience engineering, organizational learning, digital technologies and STS theory. The next phase consists of the development of a procedural model. Which conceptualized the ELP-model. Visualizing a structured learning approach, to enhance NPP resilience, integrating digital technologies into the learning process. Validation of the developed model and the insights on the NPP learning process commenced through demonstration of the applicability of the model, a case-based evaluation was conducted. Applying the model to a real-world disaster event, the Fukushima Daiichi nuclear disaster. Additionally, the report contains the development of several propositions based on the findings, gaps and insights on the outcomes of this research. Lastly, an expert consultation session was conducted with a professional in the field of nuclear safety. To further verify the findings and validate the outcomes of the research, including the propositions. And asses the practical feasibility of the proposed learning approach.

To conclude a discussion is held on the research performed and its' outcomes. Ending with drawing appropriate conclusions and recommendations as well as limitations of this work. This research design is specifically tailored to address the research questions and objectives. Aimed at addressing the call for research as outlined in Chapter 1. The separate stages of this research are further elaborated on in this section.

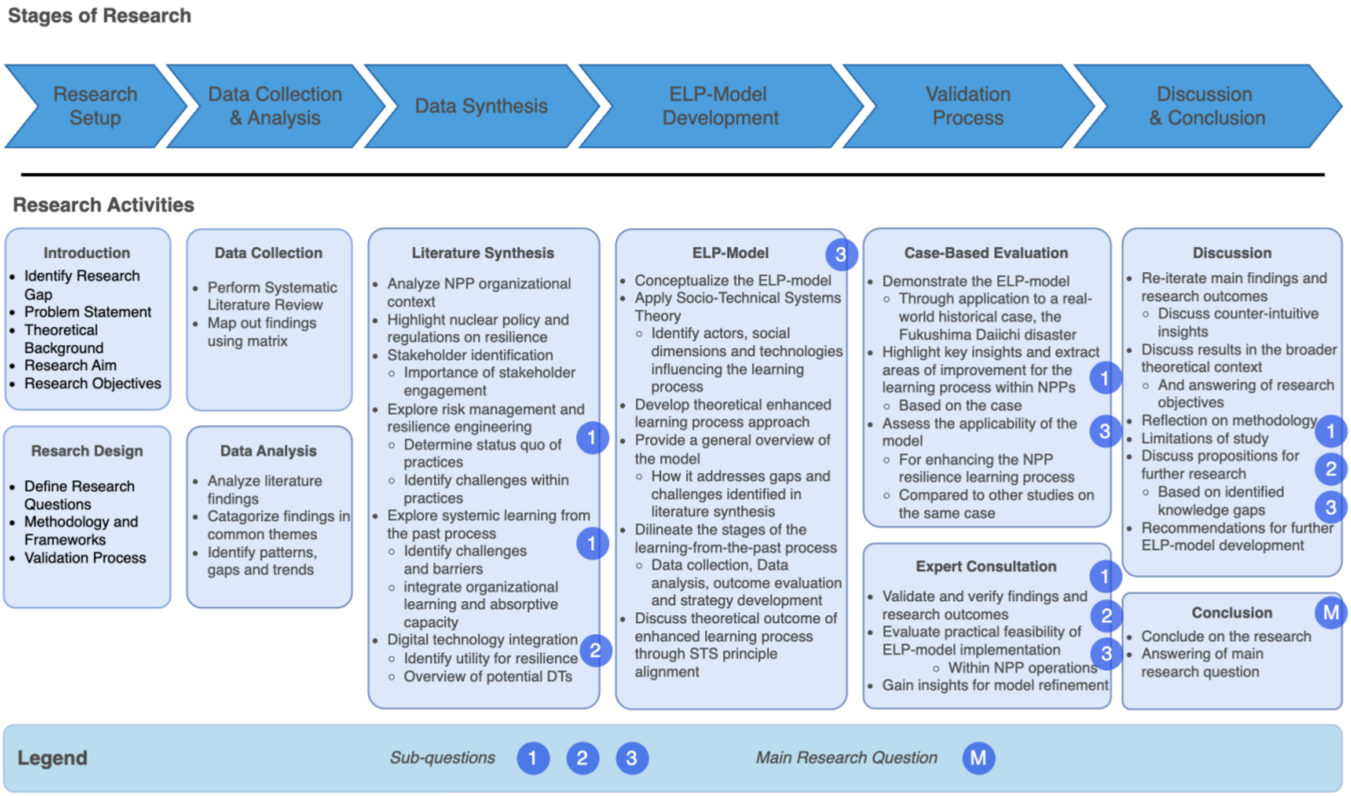

Figure 1: Research Flow Diagram

Data collection

The main data collection method for this research consists of a systematic literature review. The data collection process for this research was designed to ensure comprehensive coverage and relevance of the literature related to the resilience of nuclear power plants against natural disasters. Aiding in creating an in-depth understanding of resilience engineering and learning from the past practices, leveraging digital technologies in the context of nuclear power plants. As well as the policy and regulatory landscape surrounding these critical infrastructures. Gathering data on the potentials of digital technology integration, to enhance resilience through learning from the past. For this study to lay a foundation for guideline development. As well as creating an understanding of seeing the learning process within NPPs as a Socio-Technical System. Supporting a culture of learning and strengthening absorptive capacity to be able to process historical data surrounding NATECH events, generate lessons and build resilience. Through the utilization of digital technologies. By synthesizing the collected data from the literature considering the concepts revolving around the research objectives to ensure appropriate coverage.

In the SLR a broad search was conducted across academic databases (Web of Science and Scopus) using specific keywords related to resilience engineering, NATECH events, socio-technical systems, organizational learning, and digital technology utilization. In the context of NPPs. The specific steps taken in the SLR will be discussed later in this chapter. This search method yielded a substantial number of data sources, which were then subjected to inclusion and exclusion criteria to ensure the selection of relevant literature. The selected documents were systematically reviewed, and their key characteristics and findings were documented in a matrix. This matrix facilitated the identification of patterns and trends, which were critical for the subsequent stages of data analysis and synthesis. To further compliment the findings derived from the literature review, feedback on the research outcomes was gathered in relation to resilience learning practices within the nuclear industry from expert consultation, ensuring that theoretical insights were aligned with practical perspectives from the industry.

Data analysis process

The data analysis stage of this research involves a thorough examination of the literature collected during the systematic literature review (SLR). Each data source was carefully reviewed and mapped into the literature matrix. By reviewing the literature, certain patterns and trends emerged, providing insights into common challenges and best practices within the literature and in enhancing NPP resilience against natural disasters. The details of the matrix and the analysis process will be expanded on later in sub-chapter 2.2. The paper matrix and subsequent mapping served as a foundational tool for visualizing and categorizing the data sources and identifying recurring themes, key topics, and notable gaps. This structured approach enabled a comprehensive analysis of the collected data, ensuring that all relevant aspects were considered and integrated into the overall research findings.

Synthesis of literature

In the data synthesis stage, the findings and insights from the systematic literature review and the subsequent data analysis are integrated into a comprehensive overview of the literature research performed, allowing for a synthesis of the findings and discussion of the outcomes of the SLR, outlined in Chapter 3. This research consolidates existing perspectives, knowledge, practices and concepts from the literature to establish a foundation onto which an enhanced learning-from-the-past process could be extracted. Through the identification of gaps in practices, barriers to learning and digital technology integration. As well as what is part of scope of the learning process from an STS perspective. The synthesis is structured into several distinct sections, each addressing critical aspects of this study and NPP resilience enhancement. Each building on the previous one to provide a clear narrative. This ensures alignment with the objectives of the study.

Model development approach

The development of the Enhanced Learning Process (ELP) model adopts a conceptual model development approach as discussed by Delcambre et al., (2018). Integrating theoretical insights from resilience engineering, organizational learning and digital tool utilization. The model is developed to address gaps in systematic learning from past disasters within NPPs. By providing a structured learning mechanism, aimed at supporting data-driven decision-making and resilience engineering learning processes. he work done up to this point, extracting literature, processing and synthesizing findings. Laid the basis for the visualization of an enhanced learning process, leveraging digital technologies to support this. In the form of the ELP-model.

The rationale behind the development of the ELP-model is to address gaps in resilience engineering learning practices, incorporating a systematic and continuous learning mechanism, leveraging the capabilities of digital technologies. Thereby laying the groundwork for a strengthened learning process within NPPs. To be able to turn historical data into actionable lessons integrated to inform resilience strategy development. The theoretical foundation is based on the synthesis from the SLR, coupled with own researcher insights to develop the model. And allowed for key social and technical factors to be identified, influencing the learning from the past process. The integration of STS theory was essential to the model's structure and perspective on the learning process. Providing a systems-level perspective of the dynamic between human actors, social and technological factors in resilience learning processes. The alignment of social goals (e.g., transparency, communication, feedback and compliance) with digital technologies (e.g., Data analytics tools, Digital Twins, governance/compliance platforms) was central to its approach to visualize an enhanced learning process. The model is structured as a theoretical representation of a potential enhanced learning process. And was conceptualized as a continuously iterative and cyclical model, with stages covering historical data collection, data analysis, outcome evaluation and strategy development. And was validated through expert consultation.

The specific steps taken, to outline the various stages of a potential enhanced learning process, and a visual diagram of the model are demonstrated in Chapter 4. Figure 2 below shows how the combining of various areas of literature (resilience engineering, organizational learning from the past and digital technology utilization), and the use of STS theory. Have led to the development of the model.

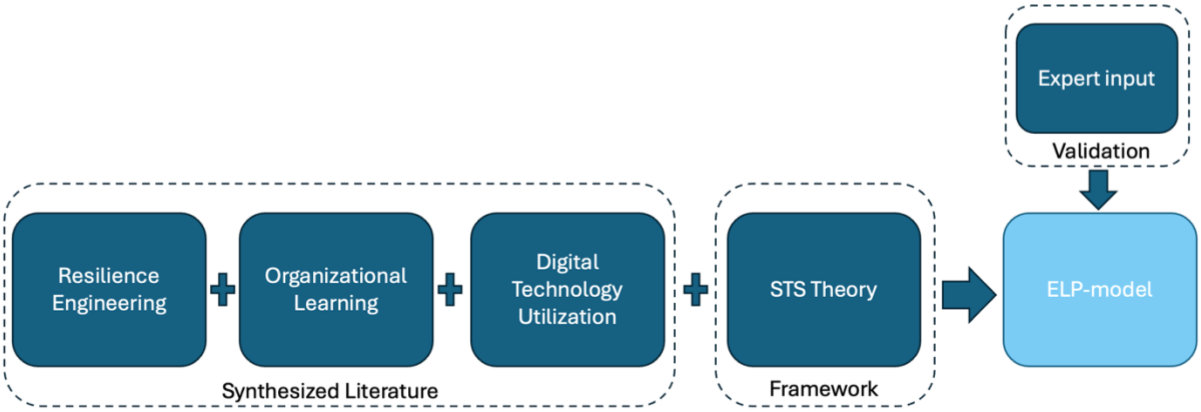

Figure 2: Building blocks of the ELP-model

Validation process

To validate the ELP-model and its' contents, demonstrating its' applicability and theoretical value. A case-based evaluation and expert consultation were conducted. The case study method was employed due to the possibility to provide demonstration of the application of the model in a real-world disaster event. Additionally, to further verify the outcomes of this research and validate the practical feasibility of the model. Key take-aways from the literature synthesis were incorporated into the consultation session to cross-validate findings and insight. As well as to discuss the practical value of the model and evaluate the propositions.

Case-based evaluation

This case-based evaluation adopts an illustrative case study approach, where the events that unfolded during the Fukushima disaster serves as a descriptive historical event to demonstrate the application of the ELP-model. The Fukushima Daiichi nuclear disaster was selected for an ex-post analysis. Due to its high relevance and coverage within the literature. Giving an in-depth overview of the disaster scenario. And help underline the complexity of NATECH events, vulnerabilities in NPP operations and the danger of unforeseen cascading failures in such events. The case study approach employed in this research is aimed at validating and illustrating the model's value (Grima-Farrell, 2016), encompasses retrospective exploration and illustration of a real-world event. To gain practical insights into the application of the proposed learning process approach in Chapter 4. It involved the review of reports and policy documents related to the Fukushima Daiichi disaster to gain a deeper understanding of the scenario and events that led to the disaster. Giving a concrete example to demonstrate the application of the model. With more in-depth discussion of the application of the ELP-model to the case in Chapter 5.1.3. Using the Fukushima disaster case to demonstrate how NPPs can extract insights to better understand vulnerabilities within their plant and anticipate risks.

The application demonstration of the ELP-model to this disaster scenario helps to visualize how digital technology utilization integrated into a theoretical learning process through STS principles can support the resilience learning processes within NPPs. And can go beyond contemporary resilience learning processes. Guiding future researchers and practitioners through step-by-step demonstration of the model in a real-world context, seeking to develop the model by applying it in their own environments and showcase areas of improvement for their learning processes. Additionally, the review and analysis of existing studies on the case was included comparatively. To assess how the ELP-model adds theoretical value in identifying lessons and addresses points of improvement within resilience learning processes. And can enhance current learning processes. Where the feedback from the expert has verified the insights surrounding the areas of improvement within resilience learning processes of NPPs. The comparison serves to illustrate how the ELP-model uniquely attempts to address the resilience learning process within NPPs and how it can help generate lessons compared to other approaches. Thereby allowing the ELP-model, (i.e. the proposed learning process) to serve as the foundation for a guideline against existing resilience practices. Strengthening the theoretical validity of the ELP-model by demonstrating how it adds a unique value to resilience learning process that go beyond existing practices, by taking a holistic approach, adopting digital technologies in socio-technical alignment.

Nevertheless, it is important to acknowledge some limitations in this approach. While the examination of the scenario provides depth, the scope is limited to a single disaster. Every disaster presents unique circumstances and challenges. Thus, generalizability issues may arise, where broader validation would require additional case studies or practical application of the model in longitudinal studies within existing NPPs. Despite these limitations, this approach still offers the opportunity to explore the theoretical application of the ELP-model. Allowing this study to highlight the potential of the model to lay the groundwork for the improvement of learning processes within NPPs and resilience enhancement practices. Adopting digital technologies in socio-technical alignment.

Expert consultation

The expert consultation involved a semi-structured feedback session, with an expert in nuclear safety and experience with nuclear industry learning processes. The consultation was aimed at verifying the findings extracted and insights generated from the literature synthesis and validation of the proposed model and its' practical feasibility to serve as the foundation for a learning process guideline document. The preparation of the session involved sending ahead a summary of the study. Together with a detailed description of the generated insights and findings, on the resilience learning process within NPPs from the literature synthesis as summarized in Appendix A.3. And the ELP-model, detailing each of the steps and its' contents, combined with the diagram in Figure 7. Together with the developed propositions, highlighted in Chapter 6. Lastly, as part of the preparation. Questions were sent ahead regarding the resilience engineering and learning from the past practices, as well as digital technology utilization within the industry. To help verify the insights from the literature synthesis. And questions directed at the validity of the model itself and how it represents and builds upon the existing practices as found from the literature review. These questions were then revisited during the actual session and are directly related to the objective of this session. The full transcript of the consultation session can be found in Appendix C.

The session involved discussion on resilience engineering and learning from the past processes and challenges within digital technology utilization in the context of NPPs and the nuclear industry. Additionally involving the assessment of the model's feasibility and relevance to practical applications. And to evaluate the propositions developed based on the research findings. Which helped to address the verification of the findings, and validity of the model. By showcasing that the findings indeed are a realistic representation of the current resilience learning landscape within the industry. As well as the model, at its' basis contains the adequate factors at play within the learning process, the actors within, and does indeed touch upon the areas of improvement for the resilience learning process, from the experts' point of view.

Adopting a semi-structured format allowed the consultation session to maintain flexibility in its questioning process. Enabling the expert to give nuanced and comprehensive insights. The consultation involved an in-person, one hour session. The responses were transcribed during the consultation session and processed afterwards. To prevent researcher interpretation bias, the transcript of the consultation was sent to the expert for review and agreement. A limitation of the method of expert consultation for the validation of the outcomes of the research is the small sample size. Which leaves the possibility of personal bias in the feedback given by the expert. Important to note this limitation arises due to limited availability of experts in the field regarding the context of this research. It was a challenge to find relevant experts willing to provide feedback. Nevertheless, despite these limitations, the insights gathered from the expert consultation were invaluable and provided practical validation and verification of the results of the literature synthesis, case study and the propositions for future research. And provided this research with a recognition of the feasibility and applicability of the devised ELP-model.

Propositions

A separate section of the reports has been devoted to the development of several propositions. And can be found in Chapter 6. Derived from the results of this study, including the outcomes of the SLR and its' literature synthesis. These propositions aim to address and bridge several gaps within resilience engineering, organizational learning and digital technology utilization, as identified in this study. They aim to provide the call to action for further research on the context of this study and the practical implementation of the contents of the ELP-model. Outlining relationships between factors that influence learning processes in NPPs. The propositions are outlined and devised in such a way to explore the relationship between digital technology utilization and enhanced organizational learning capabilities. Emphasizing how digital technologies can enhance the collection, processing and integration of historical disaster data to strengthen the absorptive capacity of NPPs. And following with the exploration and investigation of several moderating factors that influence the effectiveness of digital tool utilization for enhanced resilience learning.

The theoretical contribution of investigating these propositions on the literature on resilience engineering and organizational learning involves the following. It explores the interplay between digital technologies, data quality, learning culture and organizational absorptive capacity. Underlines the use of taking an STS perspective to learning enhancement and resilience engineering. And provides a foundation for future research in understanding how to implement and maximalize the influence of digital technologies on resilience enhancement.

Discussion and Conclusion

The discussion re-iterates the main findings of the research and consolidates the research outcomes regarding the research questions and objectives. And how they were individually answered. The evolution of the existing learning process from DT utilization towards an STS structured resilience learning process (i.e. the ELP-model) is discussed. Through a comparative summary of the traditional learning process, a DT-supported learning process and the ELP-model. Furthermore, reflecting on the methodology employed in this study, discussing strengths and limitations of the research methods. Furthermore, discussing the theoretical and practical implications of this work. Which include the application of STS in resilience learning, proposition of theoretical DT-supported resilience learning process for resilience engineering by bridging the gap between organizational resilience learning and digital technology utilization. Which through further development, can serve as the basis for a learning process guideline to be adopted by the nuclear industry. To roll up the proposed ELP-model, a comparison is laid out, based on the findings of the literature synthesis and the research outcomes. To show how the ELP-model with its' STS perspective on resilience learning and DT-integration goes beyond the existing learning processes. Driving home the theoretical and practical implications of this study. Lastly discussing recommendations for further research and ELP-model development into a learning process guideline. Highlighting areas warranting further exploration which are encompassed by the propositions developed. The conclusion of this research serves as a round-up of this thesis. And contains the discussion on the answering of the main research question. And a summarization of the relation and implication of this thesis to the broader context of this study.

2.2 Systematic Literature Review (SLR)

A systematic literature review (SLR) is a structured and methodical approach to identifying, assessing and synthesizing existing research on a specific topic, as stated by Khan et al. (2003). The primary objective of the SLR is to provide a comprehensive overview of the current state of knowledge, identify gaps in the literature, and inform following steps of this research. A SLR was chosen to review the literature to ensure a comprehensive and replicable synthesis of existing studies. The enhancement of resilience engineering through a DT-supported learning process. Whilst integrating the socio-technical systems perspective, remains underrepresented in previous literature. This SLR systematically evaluates and synthesizes literature surrounding resilience engineering, organizational learning, digital technology utilization and STS theory to identify key gaps in practices, ensuring that the proposed enhanced learning process is developed on a solid theoretical foundation.

This study has adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to guide the SLR (PRISMA, 2020). This systematic approach ensures that the review process is transparent, replicable, and minimizes bias. This sub-section details the framework utilized and approach taken within this literature review. Further details on the SLR search and selection process can be found in Appendix A.2.

Scope and Boundaries

The scope of the SLR revolved around the main focus of this study, the enhancement of system resilience in nuclear power plants, against natural disasters. The review considered only literature related to the following key concepts:

- Resilience engineering and risk management practices in critical Infrastructures
- Learning from past natural disasters and NATECH events and the accompanying challenges and barriers
- Organizational learning in nuclear power plants.
- Digital Technology utilization for enhanced disaster resilience

Identifying relevant work

To identify relevant scholarly literature, search queries were developed using keywords and phrases related to the scope and research questions. These queries were tailored to ensure comprehensive coverage of relevant studies. The list of queries can be found in Appendix A.2 Revolving resilience engineering and risk management practices in critical infrastructures. Organizational learning and learning from past natural disasters and

NATECH events, and the accompanying challenges. Digital technology utilization for enhanced (disaster) data management. The search queries were designed to capture a wide range of relevant literature. To understand the environment this research sits in and provide a comprehensive view of the field and its' current literature. The databases used were Web of Science and Scopus.

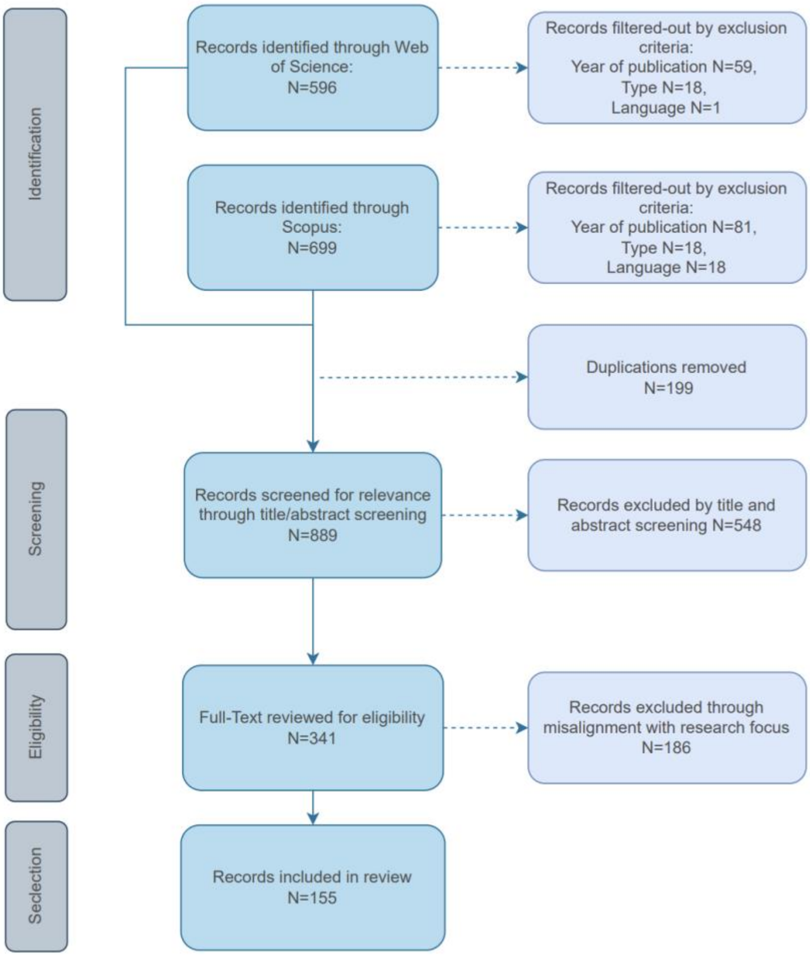

Figure 3: Literature research strategy flow diagram, adapted from (PRISMA, 2020)

Screening and selection process

To ensure a broad overview of the relevant literature the screening process involved multiple stages. Initial screening involved the filtering out of results including papers older than 15 years, due to their perceived irrelevance in the ever-changing environment critical infrastructures exist and operate in. As well as alignment with the Fukushima Daiichi nuclear disaster as major event that caused adjustments within the nuclear industry on resilience and policy. And the emergence of industry 4.0, influencing technological innovation and adoption. To minimize misinterpretation, studies not published in the English language were excluded. The total records from both databases were first combined and then duplicates were removed using Endnote (EndNote, 2024). Important to note is that both databases have unique contributions to offer, despite large overlap. They differ in coverage, indexing policies and focus areas. Meaning each database contributes unique records to a literature review. Hence the number of screened documents is able to exceed either record counts of both databases, since they are combined. Furthermore, as can be seen from the detailed description of the literature identification process, outlined in Appendix A.2. Sometimes records from Web of Science exceeds the records from Scopus and vice versa. This pattern is not uncommon in systematic reviews that use multiple databases, and this consistent with existing literature. For example, the PRISMA search strategy in Rahim et al. (2024) similarly screened 601 records, which also exceeds its Scopus record count (N=431), due to additional contributions from Web of Science.

The full list of inclusion and exclusion criteria for the screening and eligibility selection process of the scholarly literature are listed in Appendix A.2. After initial filtering. The titles and abstracts of the results were reviewed to exclude irrelevant studies. Full-text review commenced for eligibility. To select the studies based on their focus relevance to the context of the research and its' objectives. Therefore, the review focuses on the most applicable and relevant literature for this research. Providing a solid basis for the subsequent analysis, synthesis. Providing a strong theoretical foundation for the conceptualization of the enhanced learning process.

Data extraction and analysis

Data extraction focused on capturing key information from each study, including:

- The scope and objective of the study.
- Methodologies used.
- Key findings and conclusions.
- Relevance to this study
- Identified gaps within existing literature and calls for further research.

The extracted data sources were organized into a synthesis matrix to facilitate comparative analysis and identification of patterns and trends. Through a comprehensive overview of the literature. This matrix includes columns for characteristics of the source, methodologies, findings, and relevance to the research questions and study. Furthermore, categorization of the data sources per concept in the context of this research, ensured clear distinctions where these papers and articles fit within the study and during the analysis and synthesis of the data. Providing efficiency and clarity during information extraction of all the data throughout every stage of the study. The reviewed literature can be found in Appendix A.2

After the screening and selection process, data collection, filing and categorization of the sources was performed. Highlighting trends and connections within the literature and clarifying any common practices, challenges and/or gaps. Allowing for clear and comprehensive understanding of the context surrounding this study and covering all facets. From NPPs and their surroundings to learning with digital technology integration and resilience engineering enhancement. The SLR and the analysis of the data following from that, paved the way for an exhaustive synthesis of all the collected data, which will be extensively discussed within Chapter 3 of this report. The synthesis process involves interpreting the extracted data to identify common themes, trends, and gaps in the literature. Such as resilience engineering frameworks, challenges within resilience enhancement. Digital technology utilization within the context of learning from the past and resilience. Factors influencing organizational learning capabilities. This analysis provides a comprehensive understanding of the current state of research on resilience and risk management in NPPs, highlighting areas where further research is needed.

Combined with the analysis of additional data on the nuclear industry. Such as nuclear organization reports, policy documents and regulatory frameworks. Providing essential insights into how policies and regulations provide a foundational framework for resilience strategies within NPPs. Gaining practical insights into how policy directives and regulatory frameworks illustrate the challenges and gaps in best practices and resilience engineering within the nuclear industry. Through the synthesis and consolidation of the various areas of literature, building a foundation for comprehension and an overview of the literature. Serving as the building blocks to devise a theoretical potential enhanced learning process, outlined in Chapter 4. A consolidation of the key findings and implications for this study from the SLR can be found in Appendix A.3.

Literature synthesis

The extracted literature was divided into the following sub-sections. Giving structure to the synthesis of the outcomes of the SLR, outlined in Chapter 3:

Nuclear power plant context (Chapter 3.1): This section provides a detailed overview of the operational environment of NPPs**.** And their role as critical infrastructures. It discusses existing policies and regulatory frameworks that shape resilience and safety practices. Highlighting gaps in DT-integrated structured learning mechanisms.

Stakeholder engagement (Chapter 3.2): Highlighting the importance of stakeholder engagement within resilience learning. Bringing forth an overview of the stakeholders present within the NPP system and its' environment. Exploring their roles and influence.

Risk Management and Resilience Engineering (Chapter 3.3): This section discusses the concepts of risk management and resilience engineering. Exploring their roles within the nuclear industry. Discussing their differences and interrelations. And identifies existing challenges and explores considerations for improving resilience strategies. Highlighting the absence of systematic frameworks for integrating historical reflection in resilience practices.

Learning from the past (Chapter 3.4): Focusing on the importance of integrating historical lessons into resilience learning. Discussing organizational learning from an STS perspective and the concept of absorptive capacity and how or organizational learning can be enhanced. Addressing barriers such as poor data management, organizational inertia, NATECH event complexity and the lack of structured approaches to systematically utilize historical data.

Leveraging digital technologies (Chapter 3.5): This section explores the potentials of digital technologies within critical infrastructure resilience. However, also the challenges in integrating these technologies within learning processes. And reviews the utility of digital technology integration, such as advanced data analytics, digital twins and digital platforms, in improving the learning process.

2.3 Socio-Technical Systems Theory

Socio-Technical Systems (STS) theory highlights the interconnectedness between social and technical elements within a given system. Emphasizing on the importance of the alignment and strengthening of this relationship for achieving organizational performance. Although a lack of consensus exits within the literature on the definition of an STS and a clear method for analysis is absent. However, as consistently considered by Reiman, (2007), Thomas, (2017) and Dainoff et al., (2023), STS theory underscores the need for a holistic view of a system to achieve successful operations. And at its' basis appreciates the interplay between human, organizational and technological factors, in a complex context such as the NPPs resilience learning process. Taking a socio-technical approach provides a framework for understanding how different sub-systems influence each other within a given system. Taking the STS perspective, enables this study to explore how technical innovations (i.e. digital technologies) can efficiently be integrated within an organizational process through alignment with human and social contexts, to improve learning from the past to enhance resilience. As Dainoff et al., (2023) discusses, the effectiveness of technical subsystems often hinges on the integration with organizational structures and social processes, underlining the need for a joint optimization approach.

In the context of NPP resilience learning, the analysis according to STS principles helps understand how the workforce dynamics, organizational management and culture, and technological tools and work processes interact. Thus, strengthening the learning process. And affecting the plant's ability to adapt to natural hazards through learning from the past. This analysis helps in identifying potential areas of improvement and ensuring that both social and technical aspects are considered in the resilience engineering strategies, as Labaka et al., (2015) and Azadeh et al., (2015). have done. This perspective helps this study to create a foundation for the development of resilience learning enhancing process guideline.

2.3.1 Core Principles of Socio-Technical Systems

As several studies have highlighted, the STS framework at its' core is based on the understanding that optimal system performance, regarding this study strengthened learning capabilities for resilience enhancement, are achieved when social and technical elements are aligned. This alignment necessitates a joint optimization approach where both human and technological factors are considered as interconnected and are mutually influential. In the context of this study, it involves a comprehensive examination of how organizational culture, human aspects, stakeholder dynamics, technological tools and organizational processes interact to influence a nuclear power plants' ability to respond to and recover from natural disasters in a resilient manner.

Following the STS principles, helps to create a comprehensive overview of a system for analysis. Where improvement in one area, can enhance or hinder performance in another. So that systems remain adaptable, allowing for adjustment and iteration to achieve alignment between sub-systems. Lastly, understanding that effective system operations require stakeholder engagement, accounting for the influence of human actors.

The rationale for integrating Ottens et al., (2006) interpretation of STS theory and system analysis into this study. Hinges on the perspective of system analysis taken within their research. Considering not only technical elements and social elements, but also actors that influence the system. Where technical elements encompass infrastructure, hardware or software, in the case of this study digital technologies. Understanding that actors and social elements are two distinct concepts. However, that these social elements are highly influenced by actors within the system. Through dynamics and behavioral components. Such as the interaction between the plant and regulators. Which again strongly aligns with the environment of NPPs and context of this study. Figure 4 below shows the elements and their relations in a social-technical system, according to the work by Ottens et al., (2006).

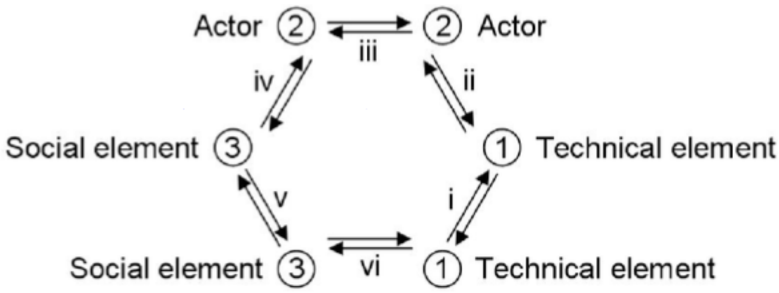

Figure 4: Diagram of the elements and relations in an STS (Ottens et al., 2006)

2.3.2 Adoption of Socio-Technical Systems theory in this study

This study applies STS theory to analyse the literature through the perspective of STS theory. Where the STS theory framework acts as a building block for the ELP-model, outlined in Chapter 4. Extending the usage of STS theory within resilience enhancement engineering literature, by applying STS theory in a unique manner by regarding the resilience learning process itself as a socio-technical system. By applying STS theory to structure the ELP-model, it is important to define the system and its boundaries clearly. Based on the work of Reiman, (2007), Labaka et al., (2015) and Ottens et al., (2006). This study delineates its' boundaries based on the interaction of human, social and organizational, and technical elements, relevant to NPPs resilience enhancement learning processes. The organizational boundary refers to the strategic management of the NPP system. In the case of this study, regarding resilience engineering management. Where NPP management and leadership has the responsibility to support a culture that integrates resilience learning into its' operations and collaborative efforts, ensuring regulatory compliance on safety standards and policies. Moreover, this boundary covers the capabilities of the NPP system regarding resilience enhancement, such as learning, awareness and responsiveness. The social sub-system integrates key actors and encompasses processes directly involved in resilience enhancement learning, such as collaborative knowledge-sharing, performance or organizational processes and stakeholder dynamics influencing learning and decision-making processes. The technical sub-system is defined as digital technologies that have the capability to support these social and organizational facets and can support data collection, analysis, processing and learning. The visualized theoretical learning process brought forth in this study is based in this STS boundary. Focussing on the dynamics between these identified sub-systems. How they interact and can support each other, along the principles of STS theory. Setting these boundaries help this study in taking an encompassing approach to the literature and model development. Ensuring that both social and technical factors are identified and considered in a comprehensive manner.

By viewing the learning process, highlighted in this study, as a socio-technical system. This study and the model developed within, is ensured to consider the adoption and leveraging of digital technologies not in isolation. But understands that these need to be integrated into organizational process, and not unimportantly, be informed by these social dimensions. Considering both human behaviour and organizational dynamics. To support the efficient adoption and successful integration of these technologies. Aids to address potential misalignments and pave the way for targeted adjustments to improve technical and organizational performance, leading to a strengthened learning process. For example, if certain digital technologies used for historical data processing, do not address social or organizational challenges (e.g., transparency, compliance or communication), their effectiveness may be diminished. The nature of the model, and inherent iterative and continuously adaptive approach, supports that the utility of technical tools are tailored to the social context of the learning process.

In summary, STS theory is applied as a framework for analysing the literature through an STS lens. Reviewing the existent literature, generating knowledge and insights as a foundation for developing the theoretical enhanced learning process within NPPs. This helps the model to be grounded from a socio-technical relationship alignment perspective. Where technology adoption is aligned with and informed by social dimension of the resilience learning process.

Chapter 3: Synthesis of the literature

This chapter captures the synthesis of the literature by discussing the outcomes from the SLR and the findings and insights extracted from the literary data. Based on the analysis of the data collected in the SLR. The literature that was reviewed has been branched in five main sub-chapters. Firstly, the NPP context is investigated, information on the physical infrastructure is added in Appendix B.1. Discussion is held on the policies and regulations that govern the nuclear industry and dictate industry-wide resilience practices. Laying the groundwork to understand how the industry currently learns from the past. Secondly, the importance of stakeholder engagement is explored, coupled with an overview of the various stakeholders present in the NPPs environment. Creating a basis for understanding the actors present, influencing the learning process, in line with STS principles. Thirdly, the current status of resilience engineering and risk management within the literature is discussed, together with the distinction between these concepts. Furthermore, the importance of learning from the past as an organizational practice is brought to light, together with the challenges within learning from the past and historical disaster data management. Lastly, the evolution of industry 4.0 capabilities within CIs is discussed. Leading up to a consolidation of the advantages that DTs have to offer regarding resilience learning enhancement. Gaining an understanding of how DTs can improve the existing learning processes. And illustrate in what way their capabilities can enhance resilience learning. Building upon that an overview is made of the DTs integrated into the ELP-model, the overview itself can be found in Appendix B.2. The literature synthesized helps to create a knowledge basis onto which a theoretical potential enhanced learning process is formed, laid out in the ELP-model and further elaborated on in Chapter 4. And helps to build the comparison between current resilience learning practices, and in what way the model developed in this study extends beyond current practices. Additionally, the synthesis of the literature has helped develop several propositions for further, shown in Chapter 6.2. Representing several key relationships, gaps and challenges within the literature surrounding resilience engineering, organizational learning and digital technology utilization. In the context of this study. And forms the basis for recommended next steps building upon this study to bridge these knowledge gaps.

3.1 Nuclear Power Plant Systems

This section will synthesize and discuss all the findings and insights, taken from the data collection and analysis on the environment surrounding NPPs. Firstly, an introduction to NPPs and their position, as a critical infrastructure within the energy sector. Then an exploration of the regulatory and policy landscape surrounding NPPs on a national and international level. Elaborating on the various organizational bodies present. As well as frameworks and directives related to the resilience of NPPs.

3.1.1 Introduction to Nuclear Power Plants

Nuclear power plants are complex facilities designed to generate electricity through nuclear reactions, primarily the fission of uranium-235 or plutonium-239 (EPZ, 2024). Where the heat produced in this reaction is used to make steam that spins a turbine, producing electricity. The operation of NPPs involves three stages: startup, steady-state operation, and shutdown. During startup, the reactor is brought to criticality, and power output is gradually increased to the desired level. Steady-state operation involves maintaining a stable power output while continuously monitoring and adjusting reactor parameters. Shutdown procedures are used to gradually reduce reactor power and bring the reactor to a sub-critical state, ensuring safety and readiness for maintenance or refuelling. (EPZ, 2024), (Muellner et al., 2021)

The surrounding environment of NPPs is shaped by a network of institutions, policies, and regulatory frameworks designed to ensure their safe and efficient operation (Nukusheva et al., 2021). International bodies such as the International Atomic Energy Agency (IAEA, 2024) provide guidelines and standards for nuclear safety, which are adopted and enforced by national regulatory agencies. In Europe, the European Atomic Energy Community, Euratom for short, promotes research, establishing safety standards, and ensuring the secure supply of nuclear materials (Euratom, 2024), (European Parliamentary Research Service, 2017). The regulatory landscape is further complemented by national bodies, such as the Autoriteit Nucleaire Veiligheid en Stralingsbescherming (ANVS, 2024) or the Nuclear Safety Authority (ASN, 2024) in France, which oversee compliance and operational standards of NPPs within their jurisdictions.

In Europe, numerous nuclear power plants contribute to the energy grid. France's energy production group, EDF operates the largest fleet of nuclear reactors in Europe, with 56 reactors that provide approximately 70% of the country's electricity (WNA, 2024), (The EDF Group, 2024). Germany, on the other hand, has initiated a significant policy shift phasing out nuclear power, reflecting a broader energy transition towards renewable sources (Nukusheva et al., 2021). The Netherlands currently operates one nuclear power plant, the Borssele plant (Borssele, 2024).

The European Union (EU) members have a mixed stance on nuclear energy. Some member states, like France, Belgium and Netherlands, are for extending the potential of nuclear projects, others, such as Germany and Austria, are against this. The EU's overarching energy policy emphasizes a transition towards a low-carbon economy, with nuclear power being seen by some as a vital component due to its low greenhouse gas emissions during operation. (EU Commission, 2024), (Frost, 2024)

Globally, nuclear power contributes about 10% of the world's electricity (WNA, 2024). In the Netherlands, this share is smaller, with nuclear power accounting for approximately 3% of the total electricity generation. In contrast, the EU's average is higher, with nuclear energy providing around 25% of the electricity, driven largely by France's significant reliance on nuclear power (Eurostat, 2022). The nuclear energy production in the EU, and the members relative contribution is visualized in Figure 5. The benefits of nuclear power over other forms of electricity generation include its ability to provide a stable, continuous supply of electricity, unlike intermittent renewable sources such as wind and solar, which are depended on weather conditions. Additionally, nuclear power produces very low levels of carbon emissions compared to fossil fuels, making it a component of strategies aimed at reducing global greenhouse gas emissions. (IAEA, 2024), (WNA, 2024)

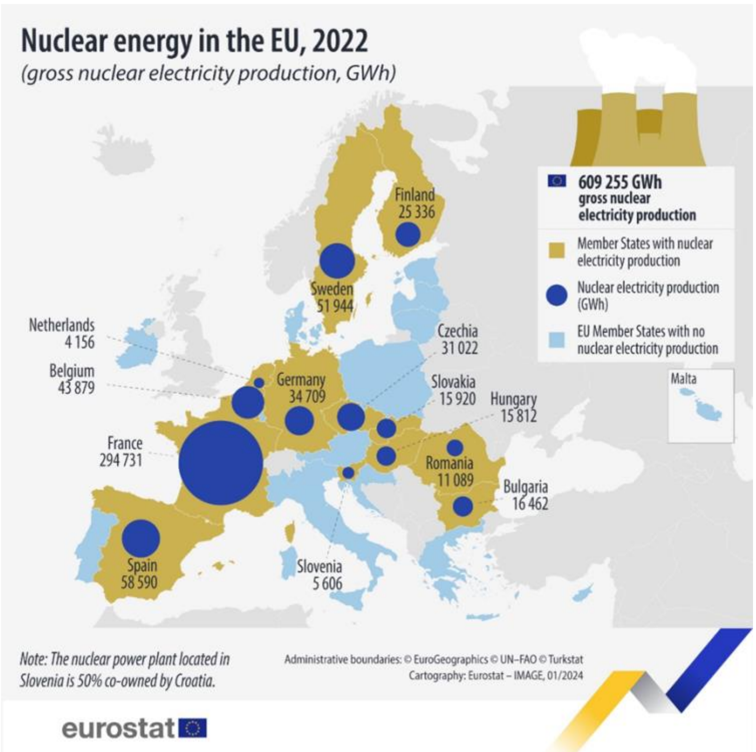

Figure 5: Nuclear energy production in the EU (Eurostat, 2022)

Within the EU, discussions are held to expand the nuclear power grid (Frost, 2024). The EU's sustainable energy policies recognize the role of nuclear power in achieving climate goals, and several member states are in support of this directive. For instance, The Netherlands has been considering the construction of new reactors to complement its renewable energy efforts and enhance energy security. These future expansions are seen as necessary to meet increasing energy demands while adhering to climate commitments. (Rijksoverheid, 2024)

In summary, NPPs play a significant role in the global and European energy landscape. They provide a stable and low-carbon source of electricity, which is needed for meeting current and future energy needs. The operation of NPPs is surrounded by institutions and policies that ensure their safety and efficiency, which will be discussed in the coming sections. As the world seeks more sustainable energy systems, nuclear power remains a viable option, particularly in Europe, where it contributes to electricity generation and helps achieve environmental goals. Further elaboration on the physical infrastructure facilities of NPPs are shown in Appendix B.1.

3.1.2 Organizational context of NPPs

The next step in the analysis of the context of NPPs, regards the organizational context of NPPs. Considering the principles of STS theory, outlined in Chapter 2.4. Primarily the social (organizational) dimensions are investigated in this section. Including the human, organizational, and regulatory elements that collectively ensure the plant's safe, efficient and resilient operation. At the core, human factors fulfil several roles; these include the competencies, training, and behaviours of the plant operators, engineers, and support staff (Reiman, 2007). Continuous professional development and training programs are needed to maintain a certain level of expertise and preparedness, particularly in emergency scenarios (Yamashita & Takamura, 2015), (Franchina et al., 2021), (Rehak et al., 2018). Organizational dynamics are equally significant, involving the establishment of a safety-centric culture that promotes pro-active resilience learning (Bucovetchi et al., 2024), (Lundberg & Johansson, 2015), open communication (Gualandris et al., 2015), (Farrell, 2016), , and accountability (Pearson & Sutherland, 2017). This culture must be supported by policies and procedures that govern operational practices and emergency responses (Tamasiga et al., 2024), (Ilseven & Puranam, 2021). Regulatory compliance forms a vital component, as NPPs are subject to stringent oversight by national and international bodies such as the International Atomic Energy Agency (IAEA) and local nuclear regulatory authorities (IAEA, 2024), (ANVS, 2024). These regulations mandate regular safety drills, inspections, and audits to ensure adherence to the highest safety standards. Furthermore, effective stakeholder engagement is crucial (Nguyen & Mohamed, 2018). Where organizational culture influences the level of engagement with stakeholders (Boesso & Kumar, 2016), (Osobajo et al., 2023).

Encompassing transparent communication (Eggers et al., 2021), (Parris et al. 2016) within the sector, the public as well as collaboration with regulatory agencies and coordination with local emergency services for support. This engagement fosters public trust and ensures that all stakeholders are informed and prepared to respond in the event of an incident and support newly implemented measures (Murakami et al., 2021), (Bronfman et al., 2016). Overall, the social facets of an NPP system integrate human expertise, organizational culture, regulatory compliance, and stakeholder interactions to support safe operations and resilience enhancement engineering (Florez-Jimenez et al., 2024).

3.1.3 Institutions and policy

The operations of nuclear power plant systems are surrounded by institutions, organizations, and policies at both national and international levels, establishing safe and efficient functioning of NPP systems (IAEA, 2024), (ANVS, 2024), (EU Commission, 2024). These regulatory bodies ensure that NPPs adhere to stringent safety standards, regulatory requirements, and best practices in operational and emergency management. This section discusses the key entities and current policies that shape the landscape of nuclear energy, in the context of The Netherlands and the European Union (EU). With a particular focus on policies addressing NATECH events.

National regulatory bodies in the Netherlands

In the Netherlands, the primary regulatory authority overseeing nuclear power is the Authority for Nuclear Safety and Radiation Protection (ANVS, 2024). Established in 2015, The ANVS is responsible for licensing, regulating, and inspecting all nuclear installations within the country. This includes the operation of the Borssele (Borssele, 2024) nuclear power plant, the only commercial reactor currently active in the Netherlands. The ANVS integrates several organizations responsible for nuclear regulation, creating a consolidated approach to nuclear safety and radiation protection. This ensures compliance with national and international safety standards, conducts regular safety inspections, and oversees emergency preparedness and response planning (ANVS, 2024).

Responsibilities of the ANVS

The ANVS grants licenses for the construction, operation, and decommissioning of nuclear facilities. This includes ensuring that all applications meet rigorous safety and environmental standards. The ANVS develops and enforces regulations that govern nuclear safety, security, and radiation protection. These regulations align with international standards and best practices. Regular inspections are conducted by the ANVS to ensure compliance with safety regulations and to identify areas for improvement. The ANVS oversees the development and implementation of emergency preparedness plans, ensuring that NPPs are equipped to respond effectively to potential incidents. (ANVS, 2024)

Policies in the Netherlands

The Dutch government's policy on nuclear energy is outlined in various strategic documents and legislative guidelines (Rijksoverheid, 2024). The Netherlands adheres to the Nuclear Energy Act, which governs the use of nuclear energy and radioactive materials. This act prioritizes safety, security, and environmental protection. Additionally, the Dutch government has expressed interest in expanding its nuclear capacity as part of its broader energy transition strategy. In alignment with the EU's broader energy transition goals. Aimed at reducing greenhouse gas emissions and enhancing energy security. This includes potential plans for commissioning new nuclear reactors to complement renewable energy sources, reflecting on the Netherlands' commitment to responsible nuclear energy use. (Rijksoverheid, 2024), (Ministry of economics and climate, 2024)

European Union regulatory bodies

At the EU level, the regulation of nuclear power is coordinated by several key institutions and policies. The Euratom for example, promotes nuclear research, establishing safety standards, and ensuring the secure supply of nuclear materials across member states. Euratom's regulatory framework includes directives and regulations that member states must transpose into their national legislation. These directives cover areas such as nuclear safety, radioactive waste management, and radiation protection. (ESA, 2024), (European Parliamentary Research Service, 2017) The responsibilities of the ESA revolve around the mission for equal supply of nuclear materials for all users in the European Atomic Energy Community and the strategic objective to maintain the security of supply of these materials via common supply policies. Furthermore, the ESA funds and coordinates nuclear research projects. Moreover, the ESA establishes and oversees regulations on safety standards to be implemented by its' members. Covering nuclear safety, such as reactor safety, radiation protection and waste management. With the task to foster progress of the peaceful supply and use of nuclear energy (European Parliamentary Research Service, 2017).

The European Nuclear Safety Regulators Group (ENSREG) is another body that facilitates cooperation and coordination among national nuclear safety authorities across the EU (ENSREG, 2024). ENSREG operates as an independent authoritative expert body. Aimed at improving collaboration and transparency between member states. Furthermore, when appropriate, advise the European Commission on rules and regulations on safe nuclear management. Furthermore, issuing directives of safe practices, management and the incorporation of lessons learned from the Fukushima Daiichi nuclear plant accident. (Directive 2014/87/EURATOM), (ENSREG, 2024)

EU Policies

The EU's approach to nuclear safety contains several main directives. The nuclear safety directive (Directive (2009/71/Euratom)), establishes a community-based approach for the nuclear safety of nuclear installations, requiring member states to ensure that their regulatory strategies and safety standards are secure and effective. The directive emphasizes the responsibility of its' license holders to maintain and enhance safety measures throughout the lifecycle of Nuclear Power Plant Systems.

The Radioactive Waste and Spent Fuel Management Directive, (Directive (2011/70/Euratom)) mandates that member states develop programs on a national level for the safe management of radioactive waste and spent fuel, from generation to disposal. Covering the lifecycle of waste management, from power generation to waste disposal, guarding long-term safety and ensuring that environmental protection is prioritized.

Comparing with other EU countries

France and Germany provide contrasting examples of nuclear energy policies within the EU. France, with its reliance on nuclear power for approximately 70% of its electricity, is a strong proponent of nuclear energy. The French Nuclear Safety Authority (ANS, 2024) oversees a vast network of reactors, ensuring stringent safety and operational standards. In contrast, Germany has embarked on a nuclear phase-out policy, shutting down all nuclear reactors in April of 2023 (*The Nuclear Phase-out in Germany*, 2024).

Policies on NATECH Events

NATECH events, referring to natural disasters that trigger technological accidents. Recognizing the potential severity of such events, both the EU and national governments have implemented policies to enhance the resilience of NPPs against NATECH events.

In the Netherlands, the ANVS incorporates NATECH risk assessment into its regulatory oversight of NPPs. The ANVS published several guidelines regarding disaster management strategies, includes specific provisions for addressing the combined risks of natural and technological events. For example, the ANVS has published guidelines on meteorological, hydrological and seismic hazards site evaluation for nuclear installations. (ANVS, 2016), (ANVS, 2017)

The EU has integrated NATECH risk assessment into its wider disaster risk management and nuclear safety frameworks. The Directive (Directive 2012/18/EU), on the control of major-accident hazards involving dangerous substances includes provisions for assessing and mitigating NATECH risks. This directive requires operators of industrial sites, including NPPs, to provide the competent authorities with safety reports and establish adequate safety measures and procedures, making sure these plans are tested and revised. Furthermore, demonstrating in these reports that appropriate measures are taken to mitigate the domino effect of these events.

Moreover, the (Directive 2014/87/EURATOM), establishes a community framework for lessons taken from the Fukushima Daiichi incident investigation. Mainly surrounding enhancing transparency on nuclear safety matters and the establishment of training programs.

The regulatory and policy frameworks at both the national and EU levels significantly influence the operation and strategic planning of NPPs in the Netherlands. Compliance with EU directives ensures that Dutch nuclear operations meet safety standards and contribute to the overall goal of sustainable, peaceful and secure energy within the EU. The potential expansion of nuclear capacity in the Netherlands will require continued adherence to these regulatory frameworks, preserve stakeholder engagement, and strategic alignment with EU energy and environmental goals. Additionally, the specific focus on NATECH risks highlights the importance of integrated risk management strategies that account for the complex interplay between natural hazards resulting in technological disasters.

In summary, the nuclear energy industry is well-aware of the risk these systems face, policy and regulations are implemented EU-wide. Whilst several published guidelines and directives do address risk management surrounding NATECH events. A distinct and clear systematic learning process guideline aimed at learning from historical disaster data taken from various NATECH events and other disasters, regarding resilience enhancement of NPP systems considering the utilization of digital tools for this learning process has not been addressed in the published directives and guidelines. Therefore, underlining the need for a resilience engineering enhancement learning guideline, utilizing digital tools, to be developed and adopted into NPP systems in the face of natural hazards.

Considerations

Nuclear power plant systems are subject to stringent policy and regulation (IAEA, 2024), (Euratom, 2024), (European Parliamentary Research Service, 2017), (Frost, 2024). To ensure safe and compliant operations. Where complexity of the surroundings and ever-evolving environment, as well as safety standards. Requires continuous adaptation and improvement of the NPP system, on both infrastructure and technology.

However, when regarding the policy and regulatory documents and resilience literature, current resilience learning practices contain limited structured learning mechanisms. That systematically integrate lessons from past events. Where digital technologies are underutilized in supporting these processes. Underscored by the feedback given by the expert. Which highlights the need for a resilience learning approach that systematizes learning form the past within NPPs, leveraging digital tool capabilities to strengthen learning and support the enhancement of resilience strategies.

Additionally, apart from wear and tear of the facility due to continuous operations, the effect of aging infrastructure needs to be considered also. Necessitating maintenance and upgrades of the system to stay compliant with current safety standards. To extend their operational life. Therefore, retrofitting older plants with modern safety features and technologies is warranted. Establishing collaboration and clear communication between the various stakeholders, and maintaining public support is therefore crucial. This is achieved through transparency and implementation of diligent safety practices, effective communication on requirements and weaknesses within the system, and pro-active engagement throughout the learning process (ESReDa, 2015).

To re-iterate, an adequate, well-designed and resilient physical and technical infrastructure of NPP systems is integral to safe and efficient operations.

3.2 Stakeholder Engagement

This sub-chapter highlights the findings from the literature on stakeholders surrounding the NPPs and the importance of stakeholder engagement for resilience enhancement and successful strategy and guideline implementation. Emphasizing that stakeholder engagement is an integral part of strategy development and resilience learning processes within NPPs.

3.2.1 The importance of stakeholder engagement

For any organization or system to perform well from a socio-technical perspective, who the key stakeholders are, needs to be clear and understood (Ottens et al., 2006). Their individual roles within the (socio-technical) system, as well as the relationships between them need to be acknowledged for optimal organizational performance (Nguyen & Mohamed, 2018), (Beach, 2014). Moreover, regarding policy and guidelines documents, various directives discussed in previously in this chapter further underline the importance of stakeholder management when aiming to improve safe operations and mitigate risks (Directive (2011/70/Euratom), (Directive 2012/18/EU), (Directive 2014/87/Euratom).

To maintain and grow an organization, stakeholders need to be kept in the loop of any changes in the system or any decisions made (Aaltonen et al., 2008). Some stakeholders possess an active decision-making or regulatory role, whilst others play a more observant role, however all need to be made aware, to a certain extent, of any developments (Nguyen & Mohamed, 2021). Furthermore, Herazo & Lizarralde (2016) state that stakeholder engagement is essential because of strengthened decision-making within a process, development or project. Building on that, International Atomic Energy Agency (2021) underline that by incorporating the different perspectives of the stakeholders, risks or points of improvements can be identified early on. Creating a sense of ownership, thus cultivating support and trust in a project and each other. Comparatively, Yamashita & Takamura, (2015) discuss the importance of preparedness training within CIs resilience engineering as part of stakeholder engagement. And identifies various stakeholders to engage in training. Engaging stakeholders aligns expectations, established support for fair resource allocation and can create vital feedback loops that contribute to project iterations and continuous development (Cantelmi et al., 2021), and contributes to a culture of learning. Stakeholder engagement also ensures compliance with changes, rules and regulations (Mayer et al., 2016), (Ilseven & Puranam, 2021). Moreover, it fulfils a project or systems ethical responsibly towards those affected by a systems' actions (Meskens, 2020). Aiding in gaining community support (Eggers et al., 2021). Establishing trust in the project and contributing to long-term success of a project (International Atomic Energy Agency, 2021).

Consolidating the various aspects of the importance of stakeholder engagement, in the realm of NPP resilience learning and learning guideline development; Engaging stakeholders, fosters transparent communication and collaboration, building trust in the organization and the project (Eggers et al., 2021). Being transparent in their operations, especially for resilience measures is important for NPPs to create public awareness and trust in nuclear energy. Transparent communication with all actors in the industry can enhance safety strategies, emergency preparedness, in the face of a natural disaster. Establishing community support and mitigate public concerns. Trickling down from strong communication and transparency, creates enhanced decision making. By actively involving stakeholders, considering their various requirements, concerns, and perspectives, drives well-supported decision making and support in new-to-be implemented projects, or guidelines. Moreover, a collaborative approach can lead to greater operational efficiency when everyone is on the same page. Such a collaborative culture, where all actors within the organization are involved ensures that concerns and expertise is properly addressed in the decision-making process. Lastly, by engaging with regulatory bodies and policy makes, aligning the operational policies and strategic goals, can create long-term support for the industry and proper resource allocation. Allowing for the NPP systems to fund and develop enhanced resilience engineering approaches, building systemic resilience.

Summarizing, the operation and management of NPP systems depend, for a large part, on the collaboration with a wide range of stakeholders. Therefore, employing adequate management practices, incorporating stakeholder engagement, is needed for the integration of a learning process guideline for resilience enhancement within NPP systems. Where stakeholder engagement has shown to have a positive influence on aspects of resilience learning. Engagement not only generates support by all stakeholders but can also improve learning and the learning process guideline itself, through continuous feedback establishing adequate decision-making and compliance with regulations.

3.2.2 Identification of stakeholders

The primary stakeholders in the NNP ecosystem can be broadly categorized into regulatory bodies, Policy Makers and Governmental Bodies, plant management, employees of the plants, Research and Academic institutions, other non-governmental organizations (NGOs), local residents and emergency services. The specific categories used in this analysis are indexed and expanded on in Table 1, below.

Stakeholder Category	Description
Regulatory Bodies	Institutions responsible for overseeing the compliance of NPPs with national and international safety and environmental standards.
Policy Makers and Governmental Bodies	(International) National and local governmental bodies, who create energy sector policies and regulations.
NNP Management	Stakeholders that own and/or operate an NPP, this includes plant engineers and managers.
Employees	The workforce operating the plants.
Suppliers and Partners	Organizations supplying equipment or technology and providing services.
Research and Academic Institutions	Universities and research organizations, conducting research on nuclear energy operations and safety.
NGOs	Environmental organizations who advocate for sustainable practices, protecting the environment.
The General Public	Residents living in the vicinity of NPPs as well as the aggregate public.
Emergency Services	Emergency responders (Firefighters, Police and Medical services).

Table 1: Listing of stakeholder categories

For this study to lay a basis for the stakeholders present in the context of NPPs, and actors having an influence on the resilience learning processes. The stakeholders present in part, especially in learning process of NPPs was also discussed in the expert consultation. These categories above will be further elaborated on by discussing examples and their role within the realm of NPP systems and their influence on learning processes.

Regulatory Bodies

Regulatory bodies, such as the Authority for Nuclear Safety and Radiation Protection (ANVS, 2024) in the Netherlands, which is a regulatory body on national level responsible for nuclear safety, security, and radiation protection. The ANVS, established rules, issues permits and monitors compliance.

On a European-wide level, there is the European Nuclear Safety Regulators Group (ENSREG, 2024) having significant power due to their role in licensing, regulation, and inspection of NPPs. Their high interest stems from their mandate to ensure nuclear safety and compliance with stringent standards.

These regulatory bodies both have a high level of power to exert and high level of interest in the operation of resilient NNPs, upkeeping safety standards on national and international level. The expert consultation with an advisory coordinator of the ANVS, furthermore enlightened this study on the role that these regulatory bodies play and the influence they have on the learning processes. It was discussed that the regulatory bodies need to be made aware of the lessons learnt and reporting of incidents happening at an NPP. Establishing a dynamic of information exchange to improve overall industry safety and resilience. However, this conversation, does not happen in a systematic manner, mainly relying on human interpretation and manual input. Without the support of digital systems or platforms to strengthen the information exchange.

Policy Makers and Governmental Bodies

Government entities and policy makers shape the regulatory and policy landscape affecting NPP operations, influencing resource allocation and strategic mandates. The European Commission and its' various agencies are responsible for the EU's energy policy, this includes development and implementing policy for secure, sustainable and peaceful nuclear energy (EU Commission, 2024), (ESA, 2024). The Dutch Ministry of Economic Affairs and Climate, establishes national energy policies, including nuclear energy (Rijksoverheid, 2024), (Ministry of economic affairs and climate, 2024). Other international bodies such as, the International Atomic Energy Agency (IAEA, 2024), addresses nuclear safety issues and providing information supporting public involvement. Setting safety standards and providing guidelines for responsible NPP operations (IAEA, 2024).

These governmental bodies and policy makers influence the operations of NPPs. Especially local governments and municipalities, who need to be involved in developing response strategies in case of disasters for emergency preparedness and response protocols. Being responsible for its' inhabitants and working together with emergency services. Ensuring safe operations and influencing strategies for entire sectors however, thus having a position of a more distant nature.

NPP Management

Operators and their management directly oversee the day-to-day operation and are responsible for the safety of NPPs. They have the technical expertise and operational control necessary for implementing safety measures. The Elektriciteits-Produktiemaatschappij Zuid-Nederland (EPZ, 2024) is the owner and operator of the

Borssele plant, the only operational nuclear plant in The Netherlands. Being the operator of the NPP, they carry the responsibility for safe operations. And need to communicate and collaborate closely with outside stakeholders, up to a certain level, on their resilience and learning processes development and changes. Such as incident reports or various (natural hazard) risk assessments.

Employees

Employees are essential for the safe and efficient operation of NPPs. Regarding the resilience learning from the past process, the employees of an NPP can be divided into various experts, such as data scientists and engineers. And support staff or other employees. Depending on management strategy and culture of a NPP, they possess a certain level of influence over the learning processes. However, they possess a high level of interest, due to health, safety and economic reasons. Underlining the importance of stakeholder engagement, employees often have a real-world picture of the day-to-day operations and possess incredibly valuable regarding knowledge and input that can improve the operations strategies of a NPP, including the resilience enhancement. And should be supported in sharing their input through feedback mechanisms. (ESReDa, 2015), (UNDRR, 2015)

Suppliers and Partners

Suppliers and partners provide essential equipment, technology and services needed for the operation and maintenance of NPPs. In the case of the Borssele Plant, Siemens/KWU (Siemens-Energy, n.d.) is the reactor supplier (Borssele, 2024). The Borssele plant has important partnerships with associations such as Nucleair Nederland (Nucleair Nederland, 2023). Often employed by the operators and thus are subject to needs and requirements of the plant and their operators.

Research and Academic Institutions

These institutions, such as labs and universities, conduct research on a large range of aspects in the nuclear landscape, for example, innovations and technology, safety improvements, and environmental impacts and sustainability. Thus, contributing valuable knowledge and innovations. The Reactor Institute Delft is an example of such an institution (*TU Delft Reactor Institute*, n.d.). Collaborating with other institutions and being the Dutch knowledge centre related to radiation research and education. They play a fundamental role in applied scientific research. These institutions have a high level of interest in the operations of these NPPs, utilizing many resources in conducting research into these NPPs and nuclear energy, as well as improving safety practices.

NGO

Environmental organizations advocate for environmental impact protection and may oppose nuclear energy due to concerns about safety and waste. Greenpeace (Greenpeace International, 2024), advocates for strict and stringent regulations and transparency regarding NPP operations. These non-regulatory organizations, advocate for sustainable and safe operations. And may exert a certain level of influence over public opinions and concerns.

General public

The public can voice opinions and concerns, regarding rules and regulations set by regulatory bodies, or operations strategies of operators. Local residents residing in the vicinity of NPP, are directly impacted by their operations. Especially in case of a disaster. Therefore, they are particularly involved with safety and the environmental impact of NPPs. Even though they possess a relative low amount of power, being merely inhabitants of the surrounding area of a nuclear power plant. With potentially some influence over local governments. Their level of interest on the other hand is high, due to health and safety reasons during regular operations, as well as during the first to be impacted in case of disasters. Having transparency of communication and proper engagement strategies implemented by operators is essential. Ensuring public safety and trust (Murakami et al., 2021).

Emergency Services

These are key players in emergency response and preparedness. Thus, are crucial for managing incidents and minimizing impacts, in case of disasters. Working together with NPPs and communicating with local municipalities and their inhabitants is essential (EPZ, 2024). They mostly possess a reactive role, however, need to be part of the emergency protocol development, and should be able to share their insights in best practices. Having a responsibility towards the public. Employing proper engagement strategies considering their input and expertise (Herazo & Lizarralde, 2016), through feedback mechanisms is a key part of resilience enhancement in case of disaster.

In conclusion, being informed by the literature and the expert input. Has highlighted that stakeholder engagement, throughout the learning processes. Inside the NPP and with external stakeholders is needed for an effective process. And shown light on room for improvement. Especially regarding systematic and continuous knowledge exchange between the NPP and outside stakeholders. Therefore, there is much value to be made in the support of comprehensive and automated information exchange. And here the advantages of digital tools can be used to facilitate these enhanced communication lines. Furthermore, the expert consult has shown that it is imperative that the various actors that are part of the learning process need to converse under and with a shared understanding or knowledge base. For them to communicate efficiently and effectively.

An interesting finding on the importance of stakeholder engagement coupled with identification. Is that high-power stakeholders, such as regulators. May slow down the learning process, due to them imposing rigid and stringent compliance frameworks. Whereas lower power stakeholders, such as operational staff, may drive meaningful learning through their hands on experience input. Underlining the importance of stakeholder engagement and facilitating feedback mechanisms within the learning process when aiming to enhance resilience.

3.3 Risk Management and Resilience Engineering Methods

To have a clear view of how resilience enhancement engineering strategies are to be understood in this study, current risk management and resilience engineering methods need to be discussed. And a clear distinction between the two concepts needs to be made, for this study to fully comprehend the meaning of a resilient NPP. Using this synthesized approach and considering the lens that STS theory provides, to support the ELP-model development. This section will synthesize the data gathered on the concepts revolving risk management and resilience engineering. As well as discuss patterns and insights, which flowed from the data analysis process, discussed in Chapter 2.1. From the review and synthesis of the literature, it became evident that there is not a clear consensus on what risk management and resilience engineering entail. The concepts of risk management and resilience engineering are not rigid and used interchangeably in the literature. Therefore, the current landscape of both concepts will be introduced separately, and building upon that, the relation between the two will be discussed. Furthermore, emergent challenges and barriers from the literature within resilience enhancement engineering will be discussed and outlined. To help gain an understanding of what needs to be addressed when attempting to develop a theoretical potential enhanced reflection on the past learning process for resilience enhancement. And build a clear distinction between current practices and the proposed model, developed in this study. To be consolidated in Chapter 6, to highlight how the pillars of the proposed theoretical model, DT-utilization and STS application, moves away from contemporary resilience learning processes within the industry.

3.3.1 Status Quo

This section dives deeper into the current state of the risk management and resilience engineering strategies and practices. Highlighting the notion of traditional risk management and how resilience engineering moves away from the traditional practices. And explores current practices and frameworks at use within the literature surrounding NPPs.

Risk Management

Risk management within CIs is a systematic approach aimed at identifying, assessing, and mitigating risks that could compromise the safety, security, and operational continuity of these infrastructures, as defined by Mottahedi et al. (2021). Risk management is considered on multiple levels of NPP system operations and at different stages of a hazardous scenario. As demonstrated by Shimada et al. (2024), the integration of Level 3 Probabilistic Risk Assessment (PRA) into the risk management process, represents a significant advancement in this area. Providing a more realistic approach to assessing the consequences of accidents within NPP systems, particularly within multi-hazard events such as an earthquake. This approach extends traditional PRA methodologies by incorporating real-time data, through simulating evacuation transport, enabling more dynamic and realistic evaluations of potential accident scenarios. Shimada et al. (2024) emphasize that such integration is crucial for improving the accuracy of risk assessments and ensuring that evacuation plans are feasible under real-world conditions, where factors such as road closures and changes in evacuation speeds can have significant impacts on outcomes.

In addition to advancements in PRA, Kim et al. (2017) bring a critical perspective on risk management during the construction phase of NPPs. Their comparative analysis reveals that NPP construction projects face considerably higher risks compared to those of fossil fuel and gas power plants. These elevated risks stem from the complexity of nuclear technology, the stringent regulatory requirements, and the extended timelines often associated with NPP construction. Kim et al. (2017) argue that effective and improved risk management during construction should require continuous monitoring and proactive strategies tailored to the unique challenges of NPPs. Their work suggests that incorporating real-time data analytics and simulation tools during construction could help identify potential issues before they escalate, thereby preventing costly delays and ensuring a smoother transition from construction to operation. This underlines the notion that risk management needs to take place throughout all stages of a Nuclear Power Plant systems' life cycle. Moreover, it shows that the use of data-driven digital tools for predictory benefits is advantageous in risk management practices.

Comparatively, focussing on the stages of restoration post-disaster, Moglen et al. (2024) put emphasis on the development of optimization frameworks, such as the Mixed-Integer Linear Programming (MILP), which are designed to generate optimal restoration plans that consider environmental hazards. These frameworks can be used for NPPs, where timely restoration and minimizing exposure to hazards are essential for reducing overall risk and long-term effects of natural hazards on the infrastructure and the environment. Moglen et al. (2024)'s work highlights the importance of integrating optimization techniques into risk management practices, ensuring that decisions are not only based on safety but also on efficiency and environmental sustainability. Therefore, strengthening the recovery capabilities of the system.

Shan and Ding (2024) on the other hand provide a unique perspective by addressing the environmental risks associated with nuclear incidents, particularly in the context of nuclear-contaminated water discharge into the ocean. Their study emphasizes the importance of emergency management systems that include enhanced monitoring technologies and international cooperation. Shan and Ding (2024) argue that managing these environmental risks requires a multi-faceted approach, involving both technological advancements and policy interventions. Their work underscores the need for NPPs to adopt comprehensive risk management strategies that extend beyond operational safety to include long-term environmental impacts, which is a step towards resilience engineering. Furthermore, establishing the use of digital technologies, within risk management strategies. Calling for an improvement in NPP policy considering long-term effects.

Resilience Engineering

Resilience engineering goes beyond traditional risk management by addressing the root-cause of a hazard or crisis, strengthening the capacities of a system mitigating the impact of a disaster. By integrating strategies for adaptability, recovery, and continuous improvement in the face of catastrophes. As considered by (Petrenj et al. 2018) and (Mottahedi et al. (2021). Since resilience engineering is a broad concept, to re-iterate, the review in this study focuses on its application to NPPs, in the context of natural hazards. Liu et al. (2022) provide a comprehensive review of resilience in infrastructure systems, identifying key research streams and gaps that are critical for NPP resilience. Their work emphasizes the importance of resilience assessment, improvement, and prediction, all of which are essential components in developing robust NPP systems. The International Atomic Energy Agency (IAEA) in its' 2020 bulletin (IAEA, 2020) in the article by Fisher, stress the importance of resilience and safety of NPP systems against extreme events. Underlining the global perspective on resilience, calling for the application of lessons learned from extreme events, such as those caused by pandemics, climate change and natural hazards. Laying out how the actions of the IAEA and their safety standards reflect the call for international cooperation and sharing of best practices. The IAEA aims to strengthen global resilience and harmonizing approaches across the nuclear sector, ensuring nuclear infrastructure safety on a global scale. (IAEA, 2020)

The Fukushima Daiichi nuclear power plant disaster, triggered by an earthquake, resulting in a tsunami, highlighted the need for an improved understanding of how natural hazards, such as earthquakes and tsunamis, impact nuclear plants (Directive 2014/87/Euratom), (UNDRR, 2015). As stated by (StanfordReport, 2021), one of the most significant findings in the decade following the Fukushima disaster is that volatile radionuclides, such as the isotopes of cesium, were transported by micro- to nano-scale particles rather than existing as simple chemical complexes (IAEA, 2015). These particles may persist in the environment for a prolonged period, suggesting that they may pose long-term contamination risks far from the original site of release (Ewing, 2021 as cited in StanfordReport, 2021). Additionally, advancements in local tsunami warning systems have improved significantly since 2011, offering better real-time data and more accurate predictions of tsunami impacts. These advancements are crucial for protecting coastal communities and mitigating the risks associated with future natural disasters (Dunham, 2021 as cited in StanfordReport, 2021).

Following the Fukushima nuclear power plant disaster, Aitsi-Selma et al. (2016) highlight the implications of the so-called Sendai Framework (UNDRR, 2015) for reducing disaster risk. Together with other disasters such as Hurricane Mitch in 1998 and the 2004 Indian Ocean tsunami, has taught the international community the vulnerability of its contemporary safety systems in critical infrastructure, against natural hazards. Additionally, several studies further advocate for disaster risk management through resilience enhancement within NPPs, post-Fukushima Lipscy et al. (2013), Hollnagel & Fujita, (2013) or Murakami et al. (2021). Labaka et al., (2015) and Azadeh et al., (2015) highlighting the complex interdependencies between infrastructure resilience and human factors, which goes together with STS theory and underlines the importance of the use of this framework within this study. Comparatively, Kawane et al. (2024), discuss the social aspects of resilience engineering. Calling for a multi-dimensional approach to reducing risk. Lessons learned from these events has motivated the international community to broaden the approach in risk management strategies. "Moving its' focus in recent years from response, to including prevention, preparedness, recovery and rehabilitation. By embracing multisectoral and multidisciplinary action that links with sustainable economic development and climate change." - Aitsi-Selmi et al. (2016)

Bruneau et al. (2003) try to quantify resilience. And propose a comprehensive resilience assessment framework. Where one should consider eleven dimensions when trying to assess the resilience of a system. Broken down into four dimensions, as stated by Bruneau et al. (2003), (Technical, Organizational, Social and Economic). And four properties (Robustness, Rapidity, Redundancy, Resourcefulness). As well as three outcomes (More reliable, Faster recovery, Lower consequences). Where Robustness is considered to be the ability of a system to survive in severe and dangerous scenarios. Which are considered to be the most critical. Alzideh & Sharifi, (2020) and Sambowo & Hidayatno (2021) endorse this. Extending the so-called, 4R's of resilience has gained some traction. Huck et al. (2020) applied these 4R properties to assess the resilience in power infrastructures to establish a form of disaster management. Additionally, the work of Toroghi & Thomas (2020) employed a framework, adding a 5th R: Readjust-ability, whilst trying to assess the resilience of electric infrastructures systems.

Adding to the literature defining resilience, Mohanty et al. (2024) further elaborate on the importance of sustainable infrastructure in resilience engineering. Their review highlights the need for redundancy, diversification, and the integration of renewable energy sources as strategies for enhancing the resilience of power systems. These strategies can be directly applied to NPPs, where sustainable infrastructure can play an important role in maintaining operational continuity during and after NATECH events.

In a different industry, but NATECH event related, Lucio et al. (2024) introduce a probabilistic framework for assessing climate-related risks in ports, which could be adapted to NPPs to enhance their resilience against natural disasters. This framework emphasizes the importance of probabilistic tools in evaluating both routine and extreme events, providing a comprehensive approach to resilience engineering. Comparatively, Labaka et al. (2015) provide a fundamental resilience framework specifically designed for critical infrastructures. Their framework emphasizes the importance of adaptability and recovery, two core components that are essential for NPPs facing natural disasters. Labaka et al. (2015) argue that resilience engineering must prioritize the ability of systems to bounce back from disruptions, which is crucial for maintaining the safety and functionality of NPPs during and after natural hazards. Their work suggests that NPPs should integrate resilience engineering principles into all aspects of their operations, from design and construction to maintenance and emergency response. This integration ensures that NPPs can quickly recover from unexpected events and continue to provide essential services whilst mitigating downtime. This framework coincides with the overarching goal of resilience engineering in NPPs (IAEA, 2020) and could serve as a fundamental analytical model for incorporating resilience strategies into NPP system operations.

Contributing to the literature, Taner et al. (2017) introduce a robustness-based framework for evaluating infrastructure design under changing environmental conditions, which is particularly relevant for NPPs. With their approach is based on the principle of balancing robustness with operational efficiency. So that critical infrastructure can withstand and adapt to extreme events. Integrating these design principles into NPP systems enhances their resilience, making them more capable of handling a wide range of environmental stresses. Adding to this discussion Curt and Tacnet (2018), highlighting the interdependencies within critical infrastructure systems and how these interconnections can amplify the impacts of disruptions. Their comprehensive review of resilience engineering emphasizes a systems-level approach that considers the cascading effects of failures across interconnected systems. For NPPs, Curt and Tacnet (2018)'s insights are particularly relevant, as these plants are often part of broader energy networks. Their work underscores the importance of designing resilience strategies that account for these interdependencies, ensuring that a failure in one system does not lead to widespread outages or safety hazards across the entire infrastructure network. Implementing a guideline that considers the position of NPPs within the entire energy grid, will help mitigate the cascading effects of a natural disaster, and ease the burden on society.

Similarly, Mottahedi et al. (2021) also explore the challenges of ensuring resilience in interconnected infrastructure systems. Arguing that resilience engineering for NPPs must account for both direct impacts from natural hazards and the indirect effects that disruptions in other infrastructure systems can have on NPP operations. Mottahedi et al. (2021) suggest strategies for mitigating these risks, such as redundancy practices. Which can improve coordination between different infrastructure sectors. Also adopting flexible design principles that allow quick adaptations in the face of changing conditions.

Their work provides a basis for developing resilience plans that are adaptable to the complex and dynamic nature of interconnected systems.

Combining the work of Lucio et al. (2024), introducing probabilistic tools for resilience engineering practices, with the understanding that NPP systems are complex systems and part of a larger web of interconnected critical infrastructures, as posed by Curt & Tacnet (2018) and Mottahedi et al. (2021). Yan et al. (2023), propose a Petri net model-based resilience analysis, allowing for the assessment of NPP system operations under threat of natural disasters. The framework proposed in the study of Yan et al. (2023), uses advanced modelling tools which are especially valuable for encompassing the complex landscape surrounding NPP systems. Allowing for a detailed analysis of weakness within the system and ways to recover. Simulating various disaster scenarios, providing actionable insights how to enhance system resilience, mitigating the disruptions caused by natural hazards.

Proposing an innovative methodology, El-Maissi et al. (2024) advocates for using digital technologies, such as VR and GIS, in integrated assessment models for critical infrastructure resilience during multi-hazard incidents. This approach brings for a new avenue for enhancing NPP resilience by enabling more accurate simulations and assessments of potential disaster scenarios. In the realm of digital technologies, Möhrle et al. (2021) introduce advanced tools such as deep learning and AI-driven early warning systems that can enhance resilience in critical infrastructures. Their approach focuses on using predictive analytics to identify potential failures before they occur, which supports proactive interventions that can prevent disruptions. For NPPs, integrating such smart technologies into resilience engineering frameworks can significantly improve the ability to anticipate and respond to natural hazards, thereby enhancing overall safety and reliability. Möhrle et al. (2021)'s contribution is particularly relevant in the context of enhancing NPP systems to meet the challenges of NATECH events in an increasingly interconnected world.

3.3.2 Risk Management vs. Resilience Engineering

While both risk management and resilience engineering aim to enhance the safety and reliability of NPPs, they differ in their approach and focus. Risk management typically involves identifying and mitigating potential risks before they materialize, whereas resilience engineering emphasizes the ability of systems to adapt to and recover from disruptions. Meaning the capacity of a system to predict, adapt to, protect against, absorb, and recover from disasters. Traditional risk management revolves around reducing vulnerabilities and mitigating risk, Resilience engineering on the other hand put additional focus on addressing a systems adaptive capacity and swift recovery strategies. (Mottahedi et al. 2021), (Setola et al. 2017), (Möhrle et al. 2021), (Kim et al. 2021)

Risk management, as discussed by Shimada et al. (2024), focusses on pre-event mitigation and post-event restoration, using advanced PRA methods. This approach allows NPPs to effectively manage risks associated with specific hazards, such as earthquakes, by predicting potential outcomes and planning accordingly. In contrast, resilience engineering, as outlined by Lucio et al. (2024), Mohanty et al. (2024), Labaka et al. (2015) and Taner et al. (2017), focusses on building systems that are capable of adapting to and recovering from disruptions and unexpected events. Emphasizing on sustainability, long-term planning and robust design. Labaka et al. (2015) introduces a framework that advocates for a comprehensive approach to resilience that incorporates adaptability and recovery into every aspect of NPP operations.

Contrarily, Murakami et al. (2021), emphasize that the securing NPP system resilience revolves around mitigation measures and post-disaster recovery strategies. Which, according to other literature discussed in sections above, is more related to traditional risk management practices. Additionally, Murakami et al. (2021) highlight a point of improvement in traditional resilience practice. And discuss the need for resilience to cover both the physical and non-physical infrastructure of a system. Focussing on creating multi-hazard preparedness in regions more susceptible to natural hazards, this is supported by El-Maissi, (2024). Underlining that current practices should be adjusted to focus more on prevention and recovery strategies whilst being aware of the natural environment of nuclear plants for minimizing the effects from potential natural hazards is necessary. Furthermore, Widjanarko et al. (2024) provide a practical example of how seismic risk assessments are conducted for NPP site evaluations. Their focus on hazard identification and risk control measures offers valuable insights into building resilience from the ground up, particularly in regions prone to seismic activity. By integrating these risk assessment practices into resilience engineering, NPPs can better prepare for and mitigate the impacts of seismic events. Curt & Tacnet (2018) further highlight the importance of considering interdependencies within critical infrastructure systems when developing resilience strategies. They emphasize that resilience engineering must account for the cascading effects of failures across interconnected systems, which are often overlooked in traditional risk management approaches. By focusing on these interdependencies, resilience engineering can provide a more comprehensive approach to ensuring the long-term safety and functionality of NPPs.

Complementing this perspective, Mottahedi et al. (2021) provide practical strategies for enhancing resilience in interconnected systems. They argue that NPPs must develop resilience plans that are adaptable to changing conditions and capable of responding to both direct and indirect disruptions. Their work reinforces the notion of integrating resilience engineering within risk management to create systems that are both robust and flexible.

Moreover, Möhrle et al. (2021) add a technological dimension to this discussion by demonstrating how deep learning can be integrated into resilience engineering frameworks to enhance predictive capabilities and improve real-time decision-making. Their work suggests that by leveraging these digital tools, NPPs can transition from a reactive to a proactive approach, further blurring the lines between risk management and resilience engineering. Contributing to this integration, Shan and Ding (2024) emphasize the importance of addressing long-term environmental risks within resilience engineering. Their focus on the environmental impacts of nuclear incidents highlights the need for resilience strategies that go beyond immediate operational concerns and consider the broader, long-term implications of NPP operations. Calling for sustainable perspective within resilience building. This perspective shows how remaining resilient not only in the face of natural hazards but also in their ability to manage ongoing environmental risks, is important.

Additionally, Liu et al. (2022) highlight that resilience assessment frameworks should be integrated with risk management practices to create a comprehensive approach to NPP resilience, covering various dimensions, properties and outcomes (See figure 6, below). This is particularly important in understanding how different dimensions of resilience (i.e. robustness, redundancy, and recovery) can be measured and improved in NPPs as based on the work of Bruneau et al. (2003).

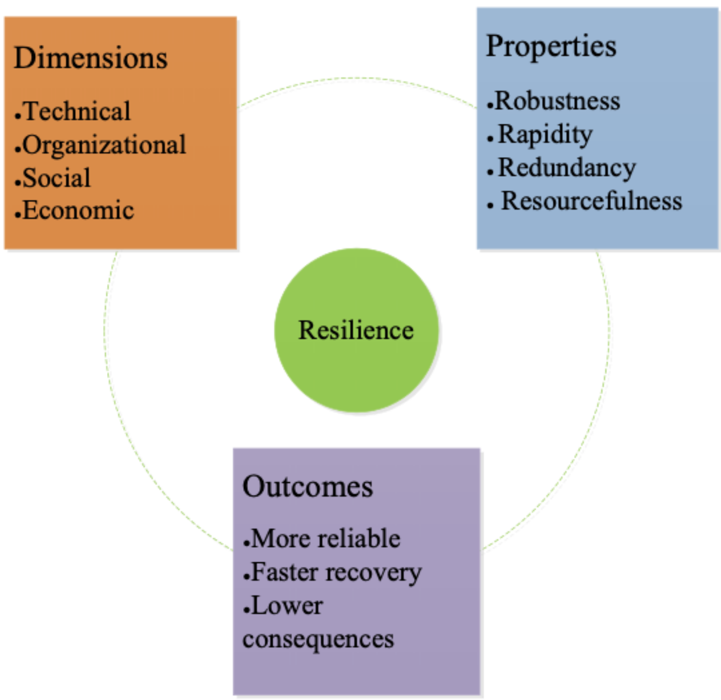

Figure 6: 11 aspects of the resilience assessment framework (Liu et al. 2022)

3.3.3 Challenges and Barriers

Current practices in CI resilience have been extensively addressed in the literature. While resilience engineering as an evolution of risk management practices has gained widespread traction throughout the literature, several challenges for the implementation of resilience enhancing practices remain. One of the key issues is the variability in resilience practices and approaches to resilience engineering, as mentioned by Mehvar et al. (2021). Creating the potential for inconsistent levels of preparedness and response capabilities. Once again highlighting why a systematic approach to resilience enhancement and learning is of paramount importance for effective resilience (learning). As was underscored by the feedback given during the expert consultation. These inconsistencies can cause fragmented learning. And inadequate resilience, possibly aggravating problems in areas prone to natural hazards such as earthquakes and tsunamis, where the disastrous effects are high (Sänger et al., 2021).

Specific challenges associated with ensuring resilience in interconnected infrastructure systems, are highlighted by Mottahedi et al. (2021). They emphasize that the complexity of interdependencies within critical infrastructures often leads to vulnerabilities that are not immediately apparent. For example, a disruption in the energy grid could cascade into failures in communication networks or water supply systems, creating a domino effect that aggregates the impact on society of the initial hazard. Mottahedi et al. (2021) argue that addressing these challenges requires comprehensive resilience strategies that account for the broader network of critical infrastructures. Their work underscores the importance of developing resilience plans that are not only focused on the plant itself but also on the surrounding infrastructure that supports its operation. Allowing for a collaborative resilience strategy between systems, will lead to mitigation of overall effects of a disaster, where one system fails, another can take over. This approach ensures recovery from direct, natural hazards and indirect, cascading, impacts. Highlighting the importance of stakeholder engagement and enabling of feedback mechanisms when aiming to achieve resilience enhancement.

Another challenge, especially relevant to this study, is the integration of new methodologies and technologies into contemporary NPP safety and risk strategies. Shimada et al. (2024) demonstrate that while the incorporation of transportation simulations with an advanced PRA model offers a more realistic approach to risk management, implementing such advanced methods requires significant resources, such as investments in infrastructure, training, and technical expertise. This highlights an emergent barrier to adopting new risk management techniques: the cost and complexity of implementation. Shimada et al. (2024) stress that overcoming these barriers is essential for enhancing the resilience of NPPs, particularly in regions where natural hazards are likely to strike. Highlighting to the notion of complexity as an emerging barrier of integration.

The adoption of sustainable infrastructure practices also presents challenges, as emphasized by Mohanty et al. (2024). Their work highlights the resistance that often arises due to the costs and logistical complexities involved in updating existing systems. Mohanty et al. (2024) argue that while sustainable infrastructure is critical for enhancing long-term resilience, particularly in the face of climate change, convincing stakeholders to invest in these upgrades can be difficult. Further underlining the importance of stakeholder engagement practices, such as aligning interests, discussed in Chapter 3. The barriers of the added financial stress, together with wanting to disrupt ongoing operations as least as possible, often leads to delays or incomplete implementation of sustainability measures.

The environmental aspect, as highlighted by Shan & Ding (2024), adds another layer of complexity to the challenges. Managing long-term effects post-disaster, such as contamination risks, posed by nuclear-contaminated water discharge, requires not only technological advancements but also international cooperation and regulatory frameworks. Particularly challenging in scenarios where the impacts of a nuclear incident extend beyond national borders, as is the case with contaminated nuclear water discharge into the ocean (Argyroudis et al. 2020), (Shan & Ding, 2024). To mitigate such far-reaching implications, Shan & Ding (2024) emphasize the need for coordinated international efforts to manage transboundary environmental risks, highlighting the role of international governance in ensuring that nuclear safety measures are consistently applied and enforced across different regions. Once more, underlining the importance of stakeholder engagement strategies to address barriers and challenges.

Additionally, the continuous evolution of environmental conditions due to climate change presents a continuously changing and complex landscape for resilience engineering. Taner et al. (2017) emphasize the importance of robustness in infrastructure design, particularly in the adaptations to unpredictable and severe climate-induced events. However, Taner et al. (2017) acknowledge that achieving a balance between robustness and operational efficiency is a complex task. As climate conditions become more volatile, NPPs must be designed to withstand a wider range of environmental stresses while maintaining efficiency and safety. Advocating for a dynamic approach that allow for flexibility and adaptability over time, ensuring that NPP systems can evolve in response to changing environmental conditions.

To conclude, the challenges discussed above, underscore the need for resilience enhancement strategies that leverage past disasters as useful learning opportunities. By systematically analysing the failures and successes of previous incidents, NPPs can develop more effective strategies for resilience engineering. Establishing that a learning process guideline should not only focus on technological advancements but also on improving communication, coordination, and decision-making processes across all levels of NPP operations with the aim of improving resilience. Furthermore, highlighting how inconsistencies in current practices and the complex nature of NATECH events and the NPP landscape, warrants a structured resilience enhancement through systematic historical lessons integration mechanism in the form of a technical guideline. Additionally, the integration of digital technologies, as will be further discussed in Chapter 3.4 and 3.5. Which possess the capabilities to strengthen the learning process, ensuring that NPPs remain adaptable and resilient in the face of emerging challenges.

3.3.4 Considerations for enhancing resilience

The findings from this chapter so far have established the current situation within the realm of resilience engineering and risk management. Recognizing the need for improved resilience engineering practices. As laid out in this report, there is a knowledge gap regarding the utilization of digital technologies to process data of past NATECH events and extract lessons to enhance system resilience. Therefore, highlighting the need for a structured learning mechanism, leveraging digital technologies to enhance learning capabilities, resulting in resilience in NPPs. The previous section in this chapter brought forth the challenges and barriers emergent from addressing resilience methodologies. Such as the variability of resilience practices, the complexities of integrating new methodologies, and the environmental dimensions of nuclear incidents. Further highlighting that the advancements given by using digital tools to overcome these hurdles could potentially hold value. Synthesizing and combining these findings on enhancing system resilience to suit the goals of this study, brought forth the following discussion.

As stated by Mohanty et al. (2024), the adoption of new strategies or practices is often met with resistance, often due to resource restriction or misalignment of stakeholder needs and perspective. When regarding this in the context of this study, translating these insights towards implementation of a learning process guideline, for NPP systems within this study. Barriers exist when new practices need to be implemented. Therefore, creating an understanding of these practical challenges and barriers that lie before learning from the past and learning process guideline implementation into the NPPs organizational procedures, is key. This organizational resistance will be further elaborated in Chapter 3.4.

Current resilience practices have its limitations and challenges exist, as discussed in the previous sections of this chapter. However, the integration of advanced methodologies, such as those proposed by Shimada et al. (2024) and Widjanarko et al. (2024), can aid in overcoming these barriers. As mentioned before, Shimada et al. (2024) advocate for the use of transportation simulations and a PRA model to improve evacuation planning during NATECH events. This approach provides a more realistic assessment of potential outcomes by accounting for variables such as road closures and changes in evacuation speeds, depending on seismic severity. By incorporating methods such as scenario simulations, into resilience practices, more accurate and effective evacuation plans can be created. Better suited to real-world conditions. Strengthening the NPP systems response capabilities.

Additional strategies for enhancing resilience are introduced by Mottahedi et al. (2021), considering the interconnectivity of the critical systems landscape. This approach is directly applicable to the operations of NPP systems. Their work emphasizes the importance of creating resilience plans that are adaptable and capable of responding to disruptions across the broader network of critical infrastructures. Tying into the importance of stakeholder engagement discussed in Chapter 3.2. Mottahedi et al. (2021) further argue that NPPs should focus on enhancing coordination between different sectors, such as energy, water, and transportation, to ensure that disruptions in one area do not lead to cascading failures across the greater landscape of critical systems. Their strategies for improving redundancy and flexibility in infrastructure design are particularly promising for NPP systems, being in a high-stakes environment where the potential for long-term impact is significant. Shan & Ding (2024) adds to this by advocating for governance and regulatory frameworks which goes beyond national borders, addressing policy directives issued by bodies such as Euratom (Directive 2014/87/Euratom), (ESA, 2024).

Similar to the discussion on interconnectivity of CI systems by Mottahedi et al. (2021), Curt & Tacnet, (2018) emphasize the necessity of practical frameworks that address the interdependencies within critical infrastructures. Their approach supports the idea that site-specific assessments are essential for evaluating and enhancing resilience in NPPs, particularly in regions vulnerable to natural hazards. By adopting the framework such as those proposed by Curt and Tacnet (2018), NPP systems can better understand the potential cascading effects of hazards and implement measures to mitigate these risks. Their work reinforces the importance of taking a comprehensive approach to resilience that considers the interconnected nature of critical infrastructures.

Regarding environmental challenges, Shan and Ding (2024) highlight the need for robust environmental monitoring and emergency response systems to manage the long-term impacts of nuclear incidents. Incorporating these strategies into current NPP resilience practices ensures that both operational and environmental risks are addressed comprehensively. Their emphasis on international cooperation and advanced monitoring technologies is particularly relevant in the context of globalized risks, where the impacts of a nuclear incident can extend far beyond national borders. Adding to the evidence that resilience engineering practices should be implemented on a cross-system scale (Mottahedi et al., 2021). And regulatory frameworks regarding resilience should be deployed beyond borders (Shan & Ding, 2024).

Taner et al. (2017) also contribute to this discussion by providing practical guidance on how robustness in infrastructure design can be achieved, particularly in the context of climate change. Taner et al. (2017) emphasize the need for flexible design principles that allow NPPs to adapt to changing environmental conditions while maintaining safety and operational efficiency. Their work suggests that NPPs should prioritize infrastructure designs that are both robust and adaptable, ensuring that they can withstand a wide range of environmental stresses while continuing to operate effectively. Thus, considering the (geo)location of NPP systems is important, as is supported by the work of El-Enam et al. (2024) in their critical review and Murakami et al. (2021). Depending on the natural environment, such as fault lines and proximity to large bodies of water, nature can have bigger impact. Setting up a learning process guideline to enhance resilience and the ensuing resilience practices that take the (geo)location of the NPP system into account is paramount. Within the realm of NPP system safety, Wheatley et al. provide a critical review by reassessing the safety of NPP systems. Through the use of statistical analysis of incidents and accidents. The paper by Wheatley et al. (2016), introduce the use of historical event analysis, not limited to natural hazards, to increase NPP system safety and risk management. By quantifying four dimensions of risk: historical frequency of accidents, historical costs, the presence of rare and extreme events and expected future costs. Analysing the frequency and severity of NPP system disasters, Wheatley et al. (2016) highlight the intrinsic risks within NPP system operations and the need for continuous alertness. This study recognizes that digital technologies can support this analysis. This perspective is of key importance for building understanding for the necessity for historical event analysis, within NPP system resilience engineering and theoretical enhanced learning process development in this study.

In summary, as identified by the literature synthesis so far. Current resilience practices primarily adopt reactive methodologies, with fragmented reflection on the past and digital tool integration. Focussing on disaster response and risk mitigation, rather than adaptability enhancement through learning from the past and considering the environment and realities of the NPP. Despite various studies calling for adaptable and comprehensive resilience frameworks, such as those discussed by Mottahedi et al. (2021), Shan & Ding, (2024), El-Enam et al. (2024) and Curt and Tacnet, (2018). Together with the lack of systematic reflection of the past practices shared throughout the industry. Highlighting that the existing resilience learning processes emphasize risk assessment and preparedness, however structured, iterative mechanisms to systematically extract lessons from past disasters is underrepresented. With the addition of DT-utilization, as will be further discussed in this section and in Chapter 3.5, to support such a systematic approach to learning and enhance the plants' capabilities to generate lessons and extract actionable insights for resilience strategies. Therefore, the ELP-model developed in this study, aims to advance resilience engineering by incorporating digital tools, structured by the principles of STS theory, to support effective DT-integration and ensure continuous adaptation and learning within NPPs. Through alignment of human, organizational and technical factors to optimize the resilience learning outcomes.

Addressing challenges with digital solutions

The considerations mentioned in Chapter 3.3.4 warrant a strong approach for NPP systems to enhance their resilience. Leveraging digital tools and various frameworks discussed in the literature, NPPs can develop a comprehensive strategy that not only mitigates risks but also ensures quick recovery and continuous improvement. This combined approach allows the overall resilience of NPPs against a wide range of natural hazards to be enhanced. Reducing the change for a NATECH event to occur. Additionally, as emphasized by Shan and Ding (2024) the importance of addressing long-term environmental risks within recovery strategies of resilience engineering, where NPPs are not only protected from immediate threats but also capable of managing prolonged environmental impacts.

Regarding digital tool incorporation, El-Maissi et al. (2024) propose that tools such as Virtual Reality (VR) and Geographic Information Systems (GIS) can enhance the accuracy and effectiveness of resilience assessments in NPPs, particularly during multi-hazard incidents, such as NATECH events. These technologies can simulate various disaster scenarios, allowing decision-makers to better prepare and respond to potential risks. El-Maissi et al. (2024) argue that by using these digital tools, NPPs can test different resilience strategies in a virtual environment, making it easier to identify potential weaknesses and refine plans before they are implemented in the real world. Contributing to this discussion, Möhrle et al. (2021) demonstrate how advanced digital technologies, such as deep learning and AI-driven warning systems, can be employed to anticipate and mitigate potential disruptions. Focussing on the development of predictive analytic tools that can identify vulnerabilities before they lead to critical failures. Regarding NPP systems, implementing these digital technologies allow operations to shift from reactive strategies, more common within traditional risk management to proactive approach seen within resilience engineering approaches. Möhrle et al. (2021) argue that by integrating deep learning into resilience frameworks, NPP systems can enhance their ability to respond to natural hazards more swiftly and effectively, thus reducing the likelihood of far-reaching impacts. Digital technologies can bridge the gap between traditional practices and the emerging needs of resilience engineering. For instance, the use of Digital Twins, as discussed by Brucherseifer et al. (2021), offers a solution to improve real-time monitoring, data integration, and decision-making during disaster response phases in complex systems, this is supported by Geihs (2023). Brucherseifer et al. (2021) explain that Digital Twins create virtual replicas of critical infrastructure, allowing operators to simulate various disaster scenarios and assess the effectiveness of different response strategies. This technology provides a platform for testing and refining resilience strategies in a controlled environment, thereby reducing the risk of failure during actual events. Brucherseifer et al. (2021) emphasize that Digital Twins can be particularly useful in identifying interdependencies and potential points of failure within interconnected systems, making them a beneficial tool for enhancing the overall resilience of NPP systems.

In addition, Argyroudis et al. (2022) highlight how the Internet of Things (IoT) and digital technologies such as Artificial Intelligence (AI) can significantly enhance the climate resilience of critical infrastructure. Argyroudis et al. (2022) indicate that IoT sensors and AI-driven analytics provide real-time data on infrastructure health and operational status, enabling rapid assessments and timely interventions. Regarding NPP systems, this proactive approach to managing risks associated with natural hazards can enhance resilience by allowing operators to detect and address issues before they escalate, mitigating the severity of disruptions. Arguing that the integration of IoT and AI into resilience strategies ensures that NPPs are better equipped to handle both immediate threats and long-term challenges posed by climate change-induced natural hazards. Liu et al. (2022) emphasize that measurement frameworks are essential for evaluating the effectiveness of these digital tools and ensuring that resilience strategies are impactful and sustainable. Liu et al. (2022) argue that by integrating measurement frameworks into digital resilience strategies, NPPs can continuously assess and improve their resilience. This allows for the ongoing refinement of resilience plans, ensuring that they remain effective as new challenges and technologies emerge.

Moreover, the integration of digital tool within cybersecurity measures in critical to protecting these digital systems have been proved to be a useful strategy building resilience against cyber-hazards, as emphasized by Imran et al. (2024). Möhrle et al. (2021) also touch on this aspect, stressing that critical infrastructures increasingly rely on digital tools for resilience and risk management, the potential for cyber threats grows. Möhrle et al. (2021) argue that cybersecurity must be seen as an integral component of resilience engineering, particularly as digital tools become more embedded in operational processes. This ensures that the benefits of digital technologies are understood within the organization and will not be undermined by vulnerabilities to cyber-attacks.

A pattern in focus on digital tools and methodologies for resilience assessment, emerges. The discussion on Digital Twins by Brucherseifer et al. (2021) and Geihs (2023) emphasizes the use of digital simulations to improve real-time decision-making and resilience planning. Similarly, Argyroudis et al. (2022) highlight the role of Internet of Things (IoT) and Artificial Intelligence (AI) in enhancing climate resilience by providing real-time data for infrastructure assessments. Comparably with El-Maissi et al. (2024) and El-Enam et al. (2024), call for digitization via integration of advanced technologies into resilience engineering strategies. Additionally, the focus on measurement frameworks for assessing resilience, as discussed in the comprehensive review by Liu et al. (2022). Both El-Maissi et al. (2024) and El-Enam et al. (2024) support the work of Liu et al. (2022), stressing the importance of robust frameworks to evaluate the effectiveness of resilience strategies. However, El-Maissi et al. (2024) specifically advocate for the use of digital technologies to enhance these frameworks, making their approach more practical and adaptable to complex scenarios. Furthermore, the environmental highlighted by Shan & Ding (2024), particularly in managing long-term risks like nuclear contamination, underscore the need for continuous monitoring and data-driven decision-making. Argyroudis et al. (2022) emphasize that digital technologies, such as IoT and AI, provide the infrastructure necessary to track environmental impacts over time and adjust mitigation strategies accordingly. This proactive approach to environmental risk management is essential for ensuring that NPPs remain resilient in the face of the multi-faceted nature of NATECH events.

In conclusion, by adopting digital technologies such as IoT, AI, and Digital Twins, NPPs can overcome many of the challenges they face in enhancing resilience against NATECH events. These technologies enable a more integrated, proactive approach to resilience engineering, ensuring that NPP systems are better prepared to handle imminent natural threats and mitigate long-term impact. The integration of these tools into a comprehensive learning process, informed by past disasters and continuous data analysis, offers a promising path forward for enhancing the safety and resilience of nuclear power plants in an increasingly uncertain world. The integration of Digital Tools within the learning process will be further explored in Chapter 3.5.

3.4 Learning from the past

The nuclear energy industry has seen several disastrous historical events (IAEA, 2015), (UNDRR, 2015), (Aitsi-Selmi et al. 2016). Showing the potential of disruptions affecting nuclear power plant systems. Thereby exposing the vulnerabilities of these systems and their operations. Emphasizing the importance of learning from these historical disasters, for continuous improvement and adaptation. This study considers that learning from the past does not simply cover reviewing historical data, it involves systematic integration of practices that support learning, and integrating lessons learnt to enhance NPP resilience.

This sub-chapter discusses the importance of historical lessons as a basis for enhancing resilience. Examining the challenges and barriers emerging in the process of learning from NATECH events. Furthermore, this sub-chapter highlights the concept of absorptive capacity, how NPP systems can strengthen their ability to extract and absorb useful knowledge, improving learning capabilities. This capacity can be improved by implementing appropriate organizational practices, through digital technology integration into systematic learning mechanisms in the form of a learning process guideline. The discussion below is aimed at synthesizing the insights taken from the literature and utilize these insights to propose a structured theoretical potential learning form the past process, outlined in Chapter 4. Laying the basis for a structured a learning mechanism in the form of a technical guideline. By creating a strong basis on which NPP systems can strengthen their understanding of the importance of learning from past disasters. By learning from the past, strengthening their absorptive capacity and implementing STS theory principles to structure and the process and understand the dynamics within.

3.4.1 The importance of historical lessons

A recurring theme throughout this study has been the importance of learning from historical disasters to better prepare for future events. Enhancing system resilience in NPPs. Where respecting the importance of historical incidents is key to creating a safe future.

Historical disasters such as the Chernobyl accident in 1986 (Aitsi-Selmi et al. 2015) and the Fukushima Daiichi incident in 2011 (IAEA, 2015), remind us of the inherent vulnerability of NPP systems. These events have shaped the global landscape of nuclear power plant safety strategies. The Chernobyl disaster has created a shift in the transparency of operations and collaboration on international scale within the global nuclear industry (Aitsi-Selmi et al. 2015). Similarly, as is evident from (StanfordReport, 2021) on lessons learned from Fukushima and the IAEA report (IAEA, 2015) and bulletin (IAEA, 2020), the Fukushima Daiichi incident established a greater understanding for the need for more comprehensive risk management practices, and disaster risk assessment. Particularly with regards to natural disasters such as earthquakes and tsunami.

As highlighted by IAEA (2020), nuclear power plants must adapt to global events, such as natural disasters and pandemics, to ensure continuous safe operations. The IAEA (2020) emphasizes that improvements in safety standards and the incorporation of advanced technologies, such as alternative cooling systems and robust infrastructure, are there to support risk mitigation associated with disastrous events. By integrating these lessons using technological advancement, NPPs can develop dynamic frameworks that not only address past vulnerabilities but also anticipate future challenges.

Learning from past disasters, has been integrated into procedures. The nuclear industry has gained valuable insights into the infrastructural and procedural vulnerabilities. As well as the behaviour of radioactive particles, such as caesium isotopes, which were released during the meltdown of the Fukushima plant following the tsunami (IAEA, 2015), (Stanford, 2021). Contrary to initial assumptions, these particles are more durable and widespread, traveling significant distances from the reactor site. This discovery underscores the importance of ongoing data analysis and knowledge generation in informing strategies and enhancing resilience. Shah et al. (2019), discuss utilizing digital technologies, such as big data analytics and environmental monitoring systems so that NPPs can track the movement of these particles and adapt their safety procedures accordingly, ensuring that lessons from past disasters continue to inform future practices. (IAEA, 2020)

Aitsi-Selma et al. (2016), highlight the importance of considering other disasters and NATECH-type events, when enhancing resilience. Creating internationally agreed upon best practices. This was underlined during expert consultation, where NPPs are mandated to 'look outside' into the world around them. To re-assess their own resilience. Nuclear disaster events, together with other natural hazards effecting critical infrastructures. (Aitsi-Selma et al, 2016), have highlighted weaknesses in current risk management and resilience practices. Such as over reliance on reactive measure instead of prevention, fragmented approaches only looking at a particular sub-set of risks and insufficient addressing of underlying vulnerabilities. As previously discussed in Chapter 3.3. Historical disasters provide vital lessons on early warning signs, weaknesses of operations, failures and mistakes made during these events and why. Learning from these historical lessons has in part led to enhanced safety and resilience strategies, regulatory frameworks and preparedness practices. However, learning is to be enhanced for these systems to become even more resilient, not only to avoid repetition of mistakes and strengthen the ability to recover. Minimizing the cascading effects, thus putting less stress on the critical infrastructure grid, and society. Underlining the importance of preparedness as part of resilience in mitigating the impact of disruptions throughout NPP systems and greater society caused by natural disasters. When reflecting on the literature in the previous sections of Chapter 3. An actionable systematic learning mechanism however is lacking. The expert consultation underlined this. Learning process are very much existent, however are not systematic and supported through automatization and digital tool utilization. One must understand that the process of learning from past disasters goes beyond reactive measures, requiring a more pro-active stance where historical data is continuously integrated and analyzed to improve operational practices.

Pęciłło (2020), support this, by highlighting a clear gap within safety management systems, where reactive measures are prioritized over pro-active learning. Emphasizing the need for a shift in focus, towards continuously learning (Cantelmi et al., 2021), (Thomas et al., 2019). Pęciłło (2020) shows that response capabilities often are well developed, however learning is underdeveloped. Adding to this discussion, Jain et al. (2018), highlights how resilience metrics can improve process-risk decision-making. Suggesting that by applying a structured approach, NPP systems are better capable in quantifying their resilience. Integrating a systematic learning process guideline into NPP system operations can support continuous learning and constant adaptation to new insights (Awad & Martín-Rojas, 2024). An actionable learning process enhancement mechanism within NPPs to actively and continuously learn from the past, therefore enhancing their systems absorptive capacity, not only creating preparedness. But also strengthens their ability to recover swiftly and efficiently, considering proper resource (datasets) interpretation and stakeholder engagement is yet to be developed and implemented. To fulfill the needs and goals, as stated in the Sendai Framework Document (UNDRR, 2015), a structured approach to learning is warranted.

Learning from past events, as considered by this study, should not only constitute preparedness and avoiding repetition of mistakes, it also is about systematically improving resilience engineering through historical data analysis. Furthermore, analyzing the historical events, on a moment-to-moment basis. By allowing flexibility (Taner et al. 2017) and examining the root-causes (StanfordReport, 2021), weak points in the system and the organization, technical failures, cascading effects (Curt & Tacnet, 2018) and historical response. NPPs can become more resilient against future natural hazards, and mitigate NATECH events (Mottahedi et al. 2021), (Kim et al. 2021). Successful learning from the past requires an understanding of the interconnectedness of natural hazards, human factors and technical failures (Ahmad et al. 2021).

3.4.2 Challenges and Barriers of the learning process

Safety and resilience practices are already in place in NPP systems; however challenges exist in addressing the enhancement of these practices (Shan & Ding, 2024), (Liu et al. 2022). Implementing a new strategy, such as a learning process guideline, has its barriers (Mohanty et al. (2024), but will result in a more resilient system. The challenges within the process of learning from the past revolve around the complexity of such events (Girgin et al., 2019) and difficulties in extracting actionable insights from past events (Wang et al., 2018), (Tabesh et al., 2019). Further barriers can be identified as lack of data extraction and analysis capabilities (Liu et al., 2024), the availability and quality of historical data (Fanelli et al., 2022) and organizational culture (Tabesh et al., 2019). This study uses the findings on the challenges within learning to inform the development of the ELP-model, aimed at addressing these challenges.

Complex nature of historical data

One of the main challenges in learning from the past, is the complexity of natural disasters and NATECH events (Girgin et al., 2019). Contrary to more straightforward industrial accidents, these events often involve multiple factors that interact in unpredictable ways, such as natural hazards, technical failures and human error (Mesa-Gómez et al., 2020). This interconnectedness creates a complexity that makes it difficult to extract clear, actionable lessons from past incidents. The cascading of effects that is characteristic of NATECH events, makes it challenging to isolate and address specific root-causes of the incident (Curt & Tacnet, 2018). For example, the Fukushima disaster involved an earthquake and tsunami triggering a domino effect of mishaps, ultimately resulting in a nuclear meltdown (IAEA, 2015).

The complexity of NATECH events complicates the process of learning from a historical disaster, as it is challenging to pinpoint the root-cause and disentangle all contributing factors as well as ascertaining the correct course of future actions and measures (van den Homberg, 2016). NATECH events provide a vast range of data that is to be collected. From meteorological and environmental data to infrastructural data and socio-economic data (Krausmann et al. 2016), (Mesa-Gómez et al., 2020). This study has laid out the various categories of available data during a NATECH event. The data categories are divided in the 3 stages of a disastrous event and has been laid out in the Table 2 below, highlighting the complex landscape of NATECH events. (UNDRR, 2015), (Misuri & Cozzani, 2024), (Krausmann et al. 2016), (Mesa-Gómez et al., 2020)

Types of data available and description during three stages of a disaster	
Pre-stage	
Risk Assessment	Data on weaknesses within the NPP infrastructure and organization, and potential environmental hazards.
Monitoring Data	Geological and meteorological data. (Such as water levels, weather patterns and seismic activity)
Safety Compliance	Data on compliance with regulations and safety protocol within the facilities and operations.
Event stage	
Real-time Data	Natural hazard data. (Such as: earthquake magnitude, hurricane categories, flood levels) Technological impact data. (e.g. Infrastructure destruction, chemical spills)
(Emergency) Response Data	Emergency services response time, Distribution of resources, containment measures.
Environmental/Situational Data	Monitoring of air, water, soil quality for contaminations, Aerial data on reach of disaster and physical damages to infrastructure. Public safety information.
Post-stage	
Damage Assessment	Reports on pollution contamination, structural damages, and public casualties.
Recovery Data	Information on loss of resources, clean-up efforts and long-term impact.
Organizational failures	Reports on weaknesses within organization (e.g. human errors, technical failures, weak spots in risk management)

Table 2: Type of data available during the three stages of a disaster

Concluding, as is evident from Table 2, vast amounts of various types of data are to be collected in the event of a disaster. For NPPs to learn from the past, addressing organizational weaknesses, systematic failures and errors made, going through the sea of data, provides a challenge of its own. From all this collected data, useful information needs to be extracted and processed (Wang et al., 2018), (Tabesh et al., 2019). Leading to the emerging challenge; sifting through all the historical data and determining the information that is useful for enhancing the systems resilience.

Furthermore, after the useful data is extracted, in turn actionable insights and lessons are to be taken from the extracted data (Tabesh et al., 2019). Meaning, what to do with all the new gained information, and turning it into knowledge and lessons for the NPP system operations. For NPP organizations to be able to turn information into knowledge, NPPs need to possess a certain level of absorptive capacity, calling for an integrated learning culture within NPP organization. The notion of absorptive capacity will be further elaborated upon in Chapter 3.4.3.

The challenges surrounding the complexity of NATECH event data, call for establishing strong absorptive capacity within the organization. To become more resilient against these events. As well as the integration of digital technologies into the collection, extraction and analysis of the historical data. Serving as tools for the human operators and the organization, to be able to be more comprehensive and efficient in their information extraction and knowledge generation. Utilizing DTs as tools will enable these human operators to simply cover more ground and be more pragmatic in their process of learning from the past.

Quality and availability of data

Other challenges in learning from past disasters revolve around the availability and quality of data (Fanelli et al., 2022). This was underscored during the expert consultation. Data from these NATECH events or other disasters is often incomplete, inconsistent, or difficult to access due to regulatory constraints or reasons of security. For instance, detailed information about the Chernobyl disaster was initially limited due to the geopolitical environment at the time (Aitsi-Selmi et al. 2016), which stood in the way of global learning efforts. In the case of the Fukushima disaster extensive data is available, however due to the volume, variety and, as stated before, complexity of the event data, challenges persist for the analysis of the data and extraction of lessons (Willis, 2021).

Regarding data quality, information or reporting might be incomplete, due to shifting of focus, during these events, on immediate saving and recovery efforts. Important details about the events might be overlooked. Leading to gaps in the data, hindering learning efforts. Furthermore, building on the information gap, exists the collaboration gap as mentioned by van den Homberg, (2016), during data collection and reporting on these events, certain important stakeholder might be overlooked. Due to lacking practices in reporting, leaning on verbal communications or aggregating data obtained by communities (van den Homberg, 2016). Overcoming this barrier means developing standardized data collection protocols, ensuring consistent and transparent data from all incidents to learn from.

Organizational Inertia

Another significant barrier exists within the organizational culture (Tabesh et al., 2019). Particularly the organizational inertia or resistance to change of existing practices and overall mindset within an organization as mentioned by Moradi et al., (2021). These established practices are paramount in ensuring safety, being so dependent on these practices creates a resistance to change mindset. There needs to be a commitment of management towards improvement of resilience (Azadeh et al., 2015). Moreover, innovations and new practices and their implementation are a burden on a systems resource. Especially financial aspects encourage more organizational resistance (Moniz et al., 2023). Resulting in the hindrance of adoption of new approaches and the integration of new lessons learnt from past disasters. This resistance mindset comes from several factors; reluctance to acknowledge past failures, resource cost of implementing a new approach, (over)confidence in existing strategies and systemic commitment (Moradi et al, 2021), (Moniz et al. 2023). Overcoming the barrier of organizational inertia requires a change in mindset, creating a culture of continuous learning (Bucovetchi et al., 2024), (Grösser et al., 2017), (Lundberg & Johansson, 2015). NPP operators and management should establish a culture that is open to change and supports learning, whilst striving for continuous iteration and improvement (Farrell, 2016). Where a structured learning mechanism can support such a culture learning and Iteration also. Leadership that encourages innovative thinking and addresses institutional barriers, will overcome the resistance to the adoption of new practices such as a learning process guideline, leading to enhanced resilience (Azadeh et al. 2015).

Furthermore, as highlighted by STS theory, human factors need to be considered, influencing all the challenges mentioned above. Factors such as cognitive errors and biases or miscommunication (Nissen et al., 2014), (Hasan et al., 2023) have an influence on critical decision-making (Walker & Lloyd-Walker, 2016), (Joseph & Gaba, 2019), (Hasan et al., 2023)., during high-pressure situations (Schöbel et al., 2021). Many disastrous events, such as the Chernobyl and Fukushima disaster, highlighted the critical impact human-error has. Technical systems may still fail under human operators, after wrong decisions made and wrong actions taken when adequately informed or prepared. Therefore, this study advocates that improving the human aspect in the learning process, requires clear communication (Herazo & Lizarralde, 2016) and transparency and traceability (Wohlrab et al., 2016), (Albu & Flyverbom, 2016), proper training (Rehak et al., 2018), (Trucco & Petrenj, 2017) and adequate organizational culture. Where actors working under a shared knowledge base has shown to improve learning capabilities (Maguire (2013), (He et al., 2022), (Joseph & Gaba, 2019), Musawir et al., 2019). Furthermore, advocating that implementing digital technologies in a learning process guideline can also improve the decision-making capabilities during disruptions, ensuring another safety barrier and enhancing the information available to the operators, to make adequate decisions in moments of crises (Walker & Lloyd-Walker, 2016), Schöbel et al., 2021). This study also considers, based on the literature, that improving communication channels, through strengthened accountability, transparency and feedback channels (Antunes & Pinheiro, 2019) leads to strengthened lesson retention (Cantelmi et al., 2021), (Rehak et al., 2018). Where enhanced stakeholder engagement will ensure that critical information reaches the appropriate stakeholder in a timely and efficient manner, especially during a disruptive event.

In conclusion, the importance of improving communication is highlighted by the findings from the literature. By exemplifying the successful implementation of such an approach in resilience enhancement. A key recommendation from the Sendai Framework (UNDRR, 2015) is the need for enhanced scientific and technical work in disaster risk reduction, particularly in understanding risk patterns and disseminating information to the public (Aitsi-Selmi et al., 2016). Aligning with the ongoing efforts to improve nuclear risk communication by enhancing stakeholder engagement. Ensuring that communities are better prepared to respond to nuclear incidents. The framework's emphasis on people-centred, multi-hazard early warning systems reflects the lessons learned from past nuclear disasters, where timely and accurate information could have mitigated some of the long-term impacts.

Technological Challenges

Finally, technological challenges can also impede the learning process. While advanced digital tools, proposed by Brucherseifer et al. (2021), Argyroudis et al. (2022), (Spencer et al., 2019), (Shah et al., 2019) or El-Maissi et al. (2024), such as big data, digital twins, AI, and machine learning offer significant potential for enhancing NPP resilience, their implementation is not without difficulties. These studies emphasize that integrating these technologies into existing systems requires substantial investment, technical expertise, and a willingness to adapt. And possibly the need to overcome various biases in human-technology dynamics (El-Assady and Moruzzi, 2022), (Orikpete & Ewim, 2023). Such as that human data interpretation may be subject to personal bias Morton, 2024), (Nassauer & Legewie, 2018). The rapid pace of technological change can create a lag between the availability of new tools and their adoption in the nuclear industry. This delay can prevent NPPs from fully leveraging the latest technologies to learn from past incidents and improve their safety protocols.

To overcome the technological challenges, this study advocates that NPPs must prioritize the adoption of new technologies and ensure that they are integrated into the organization's broader learning and safety processes. This involves not only investing in the necessary infrastructure but also developing the skills and knowledge required to use these tools effectively. Additionally, the relation between the complexity and adoption is explored within the propositions, outlined in Chapter 6.2.

3.4.3 Absorptive capacity

Defining absorptive capacity

Absorptive capacity is defined by Cohen and Levinthal, (1990) as a system's ability to recognize, extract and implement new and valuable knowledge. Enhancing absorptive capacity in the context of NPPs and this study therefore means improving the ability of these systems to learn from past disasters and implement lessons learnt into their operational practices. Thus, integrating a data-driven systematic learning approach continuously adapting from new knowledge extracted. Absorptive capacity is a dynamic trait, constantly improving and evolving as the system gains new knowledge and experiences. (Labaka et al., 2015), (Brucherseifer et al., 2021), (Argyroudis et al., 2022), (Shah et al., 2019).

Considering that having a high level of absorptive capacity is a key aspect for enhancing resilience. It empowers NPPs to adapt, anticipate, absorb and recover from disruptions caused by natural hazards. Being the basis for building a learning culture that is aimed at safe operations and continuous improvement Ensuring a pro-active approach in enhancing resilience as established by Pęciłło (2020), allows the system to be more flexible and responsive in face of a disaster. A trait that is very valuable within the complexity of the ever-evolving landscape of the nuclear industry.

Enhancing absorptive capacity

For NPPs to enhance their own absorptive capacity, therefore strengthening their organizational learning capabilities. Several steps should be considered, adjusting their operational practices.

For starters, Naqshbandi & Kamel, (2017) establish that the importance of fostering a learning culture within the organization must not be overlooked. A culture that prioritizes values of continuous learning, adaptation and improvement. Whilst being open to new ideas and inputs, creates awareness for weaknesses in the system. A learning culture should encourage employees on all levels to share knowledge, reflecting on past failures and experiences. Jerab & Mabrouk, (2023) highlight the importance of leadership and its' responsibility to stimulate such a culture and align organizational goals. Stating that having an organization with a learning culture, will harmonize social and technical aspects of the system, by continuous iteration (Maguire, 2013), Thus, enhancing organizational and operational performance, which is underlined by STS theory. The implementation of a structured learning approach, namely a learning guideline, should aid in identifying, capturing and executing knowledge, in the form of lessons learnt, from past events or experiences. Such a formalized mechanism provides the tools for enhancing the absorptive capacity. Institutionalizing practices, such as continuous improvements of operations via pro-active disaster reviews and enhanced disaster data analysis, will support the implementation of new knowledge and regular iterations of organizational operations. (Jerab & Mabrouk, 2023)

Also, there are various dimensions that one should consider, when aiming to strengthen the absorptive capacity of an organization, and it's learning process. As Pearson & Sutherland, (2017), Parris et al. (2016) and Eggers et al. (2021) have highlighted, transparent operations and accountability is important to supporting strong learning. Additionally, Albu & Flyverbom, (2016) show that when, as discussed before, working with a shared knowledge base helps make the learning process more efficient. This is underlined by Maguire, (2013) and (He et al., 2022). When a process is more efficient, results and insights made become more consistent and reliable (Kundu et al., 2019). And the process become more goals orientated (Lumpkin & Lichtenstein, 2005), when there is clear task division. Furthermore, a learning process that Is supported by data accessibility, in turn supports transparent operations (Lepri et al., 2017), Parris et al. 2016). Where having clear role definitions and task management further support the underlying communication, accountability and hierarchy (Ghorbel et al., 2021). Thus, strengthening an organizations absorptive capacity through an enhanced learning process, warrants transparency, accountability, and a shared knowledge base to secure efficiency, reliability and goals orientation. Additionally, data accessibility and clear role definitions reinforce structured communication and accountability. Resulting in a learning process that is more effective in extracting and generating lessons. This structured means of knowledge exchange is important for sensitive data and information (Williams et al., 2022), (Schwartz et al., 2022). Which was underlined by expert input received and is characteristic to the context of this study.

To summarize, underlining the value in generating lessons from the past. Through DT-supported enhanced data analytics, have merit in enhancing the absorptive capacity of NPP systems. Adding to this, Ma et al. (2021) discuss the impact of information technology in enhancing absorptive capacity resulting in better organizational performance. More in-depth discussion on the utilization of DTs within learning from the past practices and the integration within a learning process guideline will be held in Chapter 3.5. A fundamental limitation in existing learning from the past practices was identified. Which surrounds the absence of systematic reflection on historical disaster data and the integration of this data into decision-making processes surrounding resilience enhancement. As was also highlighted in Chapter 3.1. Conventional organization learning within the industry has been constrained by partial, unsystematic knowledge generation and integration. And an underutilization of structured feedback mechanisms with minimal engagement with digital tools to support this resilience learning process. Which shows this study that to advance resilience learning. The proposed enhanced learning process should structure and institutionalize learning. Going beyond conventional practices, by enhancing the learning process through DT-integration and refining and iterate resilience strategies based on continuous learning.

3.5 Leveraging digital technologies

The objective of this sub-chapter is to explore the utilization of digital technologies and industry 4.0 capabilities in supporting resilience learning enhancement. Understanding how digital technology utilization has been applied to CIs resilience and what insights this study can gather from that and transform into NPP resilience enhancement. To inform the possibilities of digital technology utilization within the theoretical enhanced learning process in the ELP-model, presented in Chapter 4. Creating an overview of what digital technologies could potentially be supportive in enhancing the resilience learning process of NPPs and in what way they are able to address challenges within the learning process and resilience enhancement. Furthermore, discussing how the adaptation of DTs helps the proposed learning process extend beyond the existing learning process. Through enabling a pro-active approach to historical data analysis and the processing of insights into lessons for resilience strategies. As discussed in previous sections of this chapter. Streamlining organizational dimensions, with internal actors and outside stakeholders, through automatization and utilizing the enhancing capabilities that digital tools have to offer. Supporting the ability of NPPs to enhance their learning processes.

3.5.1 Utility of digital technology integration

Digital technologies have the ability to play a role in enhancing the absorptive capacity of systems. When integrated into a systematic learning mechanism, extractable knowledge and lessons learned from the past, can transformed into actionable insights, facilitating an integrated data-driven decision-making process, aiding the enhancement of systems resilience. Both Chapter 3.3 and 3.4 have touched upon the usefulness of DT integration into resilience engineering practices, as part of enhanced historical data analysis and processing. Thus, improving absorptive capacities. These digital technologies, when utilized as tools, can improve data collection, analysis and predictive capabilities of the NPP, when learning from the past (Wheatley et al., 2016). By providing more comprehensive and systematic identification of weaknesses and environmental risks assessment processes in the NPP. Supporting a more effective and pro-active approach in the process of learning from past disasters. Digital tools, such as those discusses by Brucherseifer et al. (2021), Argyroudis et al. (2022), Rad et al. (2021), Shah et al. (2019), or El-Maissi et al. (2024) have the ability to address data collection, analysis, and predictive capabilities, allowing for more in-depth identification of risks and support a more effective learning from past incidents process. To underline the potential of digital technologies, Oikawa et al., (2024), explore the use of health records during a disaster, including nuclear accidents. They emphasize the potential of digital technologies and importance of valuable data, for enhancing resilience by improving communication and decision-making during a disruption.

Another example, big data analytics, as discussed by Shah et al. (2019) can be used to analyse large datasets from past nuclear incidents, identifying patterns and trends that may not be immediately apparent through traditional analysis methods. IoT and other digital tools (Argyroudis et al. 2022) can help NPPs to track and monitor various operational parameters in real-time, enabling quicker responses to potential risks. And aggregating the data gathered on risks from outside. By integrating these technologies into a learning process guideline, NPPs can potentially develop more sophisticated strategies for disaster prediction, response, and recovery. Adding to resilience enhancement of the system.

Evolution of DTs in CIs

Industrial infrastructures have seen a digital transformation over the past decade, generating advancements in the flexibility and adaptability of organizations as well as their processes (Dalenogare et al., 2018), (Vogel-Heuser & Hess, 2016). The Fourth Industrial Revolution, commonly referred to as industry 4.0. Has played a transformative role in increased automatization, digitalization, flexibility and efficiency of business processes across industries Rad et al. (2021), (Javied et al., 2018), (Bhatia & Kumar, 2023), (Wisniewski et al., 2022). At the base of industry 4.0 stands the utilization of digital technologies. Such as AI, ML-models, Digital Twins, Cloud computing and the overall IoT (Ghobakhloo et al., 2021). These technologies have shown to be able to enhance operational performance, such as improving decision-making processes, communication lines or expediting of tasks. Digital technology adoption has proven its value within critical infrastructures (Wisniewski et al., 2022). Rad et al. (2021) have analyzed the application and contribution of Industry 4.0 in Disaster Risk Management (DRM) in their critical review. Including mitigating risks of natural disasters. Where the introduction of the SENDAI framework (UNDRR, 2015) has encouraged DRM to investigate the potentials technological advancements, to address the complex challenges, also outlined in Chapter 3.4, throughout disaster recovery practices Rad et al. (2021). However, upon closer investigation of the SENDAI framework, as also discussed in Chapter 3.1, clear actionable guidelines for technology adoption are underrepresented. Which this study aims to take a step into the direction of providing the nuclear industry with a structure for digital technology integration within a systematic learning mechanism.

Ragia & Antoniou, (2020) have shown how disaster management strategies in smart cities utilizing digital technologies, have provided human actors with enhanced decision-making capabilities with intelligence from various data sources benefitting resilience. Building on the resilience literature surrounding smart cities, Geihs (2023) has found digital twin technologies and language models to be particularly useful in disaster management in smart cities. And Abreu et al. (2016) propose the utilization of IoT for resilience architecture. Numerous studies have been conducted into the use of particular DTs in DRM, Shah et al. (2019) have investigated the application of IoT devices and Big Data Analytics for disaster resilience. Comparatively, Argyroudis et al. (2022), found that AI in particular is useful in predicting and monitor multi-hazard warning systems and extract information, enhancing alertness. As stated by (Nazari & Musilek, 2023), digital solutions have enabled real-time monitoring, predictive actions, data-driven evaluation and automated decision-making. By combining the serviceability of digital tools within risk management and the energy sector. The applications of digital technologies in resilience engineering and NPPs is a natural progression within the evolution of Industry 4.0. Adding to this discussion, (Brookbanks & Parry, 2024) have investigated the potential of IoT and Blockchain technology to alleviate information asymmetry and enhance resilience of supply chains. Establishing how data-driven solutions improves collaboration and trust between stakeholders, as well as improving organizational agility and adaptability to challenges. Furthermore, cloud-based platforms, and advanced communication tools have to potential to support transparent communication, enhance collaboration among actors and uphold compliance in an automated and systematic manner (Ogie et al., 2018), (Rad et al., 2021), (Shah et al., 2019). Coupled with the advantages that visualization tools have to offer regarding resilience enhancement. Shah et al., 2019, discuss how data visualization capabilities have shown to support resilience, through enabling decision-makers with enhanced comprehension of data results. Where Argyroudis et al. (2022), pose that data visualization supports data interpretation and is an enabler of (climate resilience). The work by El-Maissi et al. (2024), support this by discussing the value of visualization tools in translating resilience metrics and emergency procedures. Transforming those insights into the context of this study. Utilizing these technologies within learning process for resilience enhancement among NPPs. The potential for these tools to support accountability, and the development of a shared-knowledge base emerges. Allows actors within the resilience learning process to achieve better outcomes through shared learning and understanding (Wong et al., 2014), (Hosseini et al., 2017). As well as reduce risk of personal interpretation (Schwartz et al., 2022), (Elsbach & Stigliani, 2018). Through this automated and systematic knowledge and communication sharing abilities of these tools. Where a data-driven decision-making process supports performance of the organization (Walter et al., 2013). In this case of this study, the learning process (Albu & Flyverbom, 2016), (Tamasiga et al., 2024), (Ilseven & Puranam, 2021). This insight, the advantages that cloud-based communication or governance platforms have to offer regarding supporting an enhanced resilience learning process, is further reinforced by the expert input given during the consultation session. Where it became evident that current communication and compliance dynamics, largely rely on human labour and the pro-activeness of the human actor in disseminating information. Where compliance is tested through periodic checks, even though regulatory oversight is frugal. The expert confirmed that is value to be generated in automating the systematic information exchange, within the learning process inside the plant. And regarding compliance. Additionally, the expert input highlighted ongoing explorations within the nuclear industry into the potentials of AI capabilities to address the challenge of data quality. Where AI tools can process datasets and information on an aggregate level (Alkhaleel, 2024). To balance out poor data quality through pattern recognition and filling data gaps. So that usable lessons can still be extracted. This ability further strengthens the stance this research takes, regarding the role that DTs can play in resilience engineering and NPP learning processes.

To summarize, digital technologies possess certain advantages for enhancing resilience learning. Providing advancements in NPP learning processes, creating sophisticated resilience engineering strategies. However, was evident from the literature synthesis. Their systematic integration into resilience (learning) practices remains underdeveloped. When observing the scholarly literature and regulatory and policy documents. This was verified by the feedback given by the expert. Even though the potentials of DTs are discussed in various studies. As became clear in the section above. Highlighting a gap between theory and practice. The literature is aware of the utility that DTs have to offer, however these are not yet represented in practice. This study and its' developed model, seeks to bridge this gap by proposing a learning process that embeds digital technology utilization during each stage of this process. From data collection to strategy development. By compiling the advantages of digital tools, addressing the particular challenges of learning from the past, that NPP face against natural hazards, this study produces several categories of benefits to the NPP and its' resilience learning. Which are consolidated below.

Digital technology integration in NPP resilience enhancement learning processes

Consolidating the advantages that DTs have to offer. The integration of DTs in NPPs, presents various opportunities to strengthen learning. These advantages allow for a systematic and pro-active approach to resilience enhancement learning processes. This section consolidates the core advantages of DTs, forming the theoretical foundation for the utility that DTs offer in enhancing the learning process as outlined in the ELP-model, in Chapter 4. And helps structure the learning process into four stages: data collection, data analysis, outcome evaluation and strategy development. DTs can enhance each of these stages by improved predictive capabilities, enabling automated and continuous monitoring and governance, strengthening simulation-based learning and supporting data-driven decision making (Walter et al., 2013). Mapping their theoretical potential and integrated into the structured learning process in this research. A more detailed overview of the digital technologies identified in the literature, that show potential to address NPP resilience and strengthen learning processes can be found in Appendix B.2. Further discussion on the benefits of a DT-integrated learning process guideline can be found in Appendix B.3.

Pro-active risk identification and predictive learning

Predictive analytics, supported by ML models and AI-capabilities, enables NPPs to analyze historical data. Where these datasets can be processed on an aggregate level. To anticipate and mitigate risks posed by natural hazards or system weaknesses before they escalate or before they might occur (Shah et al., 2019), (Argyroudis et al., 2022), Taking a pro-active approach to incident data reflection and therefore learning, allows for predictive operations, mitigation of risk**.** Where these AI-based predictive tools can provide NPPs with automated insight that enhance preparedness and reduce the likelihood of operational downtime. AI-driven predictive analytics can aid in historical data extraction and real-time monitoring of potential hazards. Where ML-models can identify patterns in datasets, such as on system performance or root-causes and domino effects in incidents. Enabling systemic risk evaluation and learning form past events. Helps anticipate failures and supports thorough risk assessment practices. Moreover, regulatory compliance tracking systems (Ogie et al., 2018), can automatically record and verify predictive insights, ensuring that the hazard assessments align with safety standards and policy. These tools therefore can facilitate transparent decision-making and traceability throughout the learning process.

Continuous monitoring, automated compliance and learning

Continuous, real-time, monitoring with IoT-devices, automated governance and communication platforms can provide continuous oversight of not only critical internal operational parameters (e.g., radiation levels, pressure, temperature) and outside-world data (e.g., weather patterns, seismic activity). Such tools can help ensure that operative parameters are kept within nominal range and hazards are detected. These digital technologies when integrated into the learning processes can improve the situational awareness of the NPP regarding natural hazards and risks (Nazari & Musilek, 2023). But also, the automated monitoring supports collaborative decision-making between specialists, and plant managers by supporting systematic and automated risk assessment. Reducing human bias by offering data-backed insights instead of relying solely on expert judgement. The integration of governance systems enables automatically recording and verification of steps and decisions made, ensuring regulatory transparency and adherence to safety standards. Automated monitoring helps with timely adjustments of the plant and its' procedures, improving system resilience and reduces the likelihood of human error oversight of risks.

The digital platform enabled systematic and automated communication Internally and with regulators. Enhances communication between actors and compliance leading to transparency (Walter et al., 2013). Ensuring all relevant actors (plant representatives i.e. managers, specialists and inspectors) have access to critical data. Fostering a shared knowledgebase, where all actors can communicate in a meaningful way. Turn supporting organizational hierarchy, by allowing role-based access to monitoring systems, helps ensure a controlled flow of sensitive information and accountability.

Simulated scenario-based learning and validation of assumptions

Simulation technologies such as Digital Twins, VR or AR. Can provide a controlled simulated environment for the testing and training. Allowing NPPs to model their plants and simulate disaster scenarios. Including that of potential NATECH events. Replicating operational environments and test plant responses to hazardous scenarios (Brucherseifer et al., 2021), (Kropaczek et al, 2023). These tools can serve as a compliment to existing simulation learning and training practices. Such as analytical models or physical simulators, as became evident from expert consultation. By supporting both staff training and strategic decision-making, by allowing testing and training in a controlled environment. The added value of these digital simulation tools, allow for far reaching or unlikely scenario's to be released onto the simulated plant. Creating an understanding of the implications for the plant in extreme scenarios. Having virtual and immersive training programs in place, supports the improvement of knowledge transfer, reducing human errors in emergency responses. And support feedback mechanism within the learning process, by allowing iterations of resilience practices based on simulated outcomes.

Further insights gained from the expert input, revolve around a gap in current simulation practices. Where DT-integration can support the front-end of the current simulations, where the assumptions made on the effect of a natural hazard on the NPP, and its' infrastructure remain largely unverified and tested. Also, on the back end of the existing simulation practices, surrounding generation of insights or conclusions from the simulation results. Regarding this gap, digital simulations can support the documentation of training results and automate performance tracking. Helping with the review process of simulations.

Data-driven learning and decision-making processes

As mentioned before, ML-models or Big Data Analytics have the ability to support aggregated data processing. Analysing extensive datasets, containing historical, operational and environmental data to create actionable insights. These capabilities support the learning from past events and make informed, data-driven decisions on resilience strategies. Where DT integration can help with filtering, classifying and prioritizing relevant data based on the situational status of the plant. And create realistic disaster scenarios as outcomes of the analysis. In a structured and transparent manner.

Since the chances of certain natural hazards are more likely than others, depending on where the NPP is situated. The added value of digital simulation tools, helps with preparedness of all types of (natural) hazards. By test and evaluating the resilience of the plant in simulated scenarios of the most unlikely or extreme events. Automated insights support the NPP in aggregating data and generating lessons. And can provide actionable insights to develop realistic simulation scenarios or refine resilience strategies.

Coupled with a communication and governance system, supports accountability, and ensures that outcomes are traceable and explainable. This study proposes the adoption of these communication and governance platforms coupled with visualization tools. Since they have shown to strengthen actor engagement, and a shared-knowledge base between them (Shah et al., 2019). Supporting data accessibility and interpretability throughout the learning process. And as mentioned before, based on the insights provided by the expert, the nuclear industry is exploring the potentials that AI-capabilities have to offer regarding overcoming challenges with data quality. Aggregating data analysis and pattern recognition to still extract meaningful insights from incomplete datasets.

Chapter 4: The ELP-model

The aim of this study was to explore the learning from the past process within NPPs to enhance resilience against natural hazards. By leveraging digital technology capabilities to strengthen the learning process. Laying the foundation for a structured learning mechanism. The Enhanced Learning Process (ELP) model outlined in this chapter is aimed at serving as a basis for an enhanced learning process technical guideline document.

The results of this study encompass the development and visualization of a theoretical potential enhanced learning process in the form of the ELP-model. Based on the information gathered, the insights and findings generated throughout the literature synthesis. On the current landscape of resilience engineering, challenges and barriers of learning and digital technology adoption. Surrounding the literature of resilience engineering, organizational learning and digital technology utilization, in the context of this study. And show how the ELP-model aims to advance the existing resilience learning processes within NPPs. This chapter consists of an introduction to the ELP-model and the steps taken to construct a theoretical potential enhanced learning process. Including a visual diagram in Figure 7 of the model. A brief overview of the model is given to support the readability of the visual. Followed by a more in-depth analysis of the various sub-parts of each of the stages (data collection, data analysis, outcome evaluation, strategy development), according to STS theory principles.

4.1 Development of the ELP-model

This sub-chapter provides the introduction to the Enhanced Learning Process (ELP) model, which visualizes a structured theoretical potential learning approach, leveraging digital technologies to strengthen learning in various ways. Aligning social and technical elements to strengthen the organizational learning capabilities, based on the principles of STS theory (Ottens et al., 2006), (Dainoff et al., 2023), (Thomas, 2017), (Reiman, 2007), discussed in Chapter 2.4. The model is aimed at supporting a well-informed data-driven learning process for the development of resilience strategies. And takes a continuous and iterative approach to further strengthen learning (Jain et al., 2018), (Awad & Martín-Rojas, 2024). Aimed at enhancing systemic resilience learning within NPPs.

Concluding from the SLR and consolidating literature synthesis, surrounding resilience engineering practices (Liu et al., 2024), (Labaka et al., 2015), (Kim et al. 2017), (NEA, 2015), organizational learning from historical disaster data (Krausmann et al., 2016), (Kim et al., 2018), (Tabesh et al., 2019), (ESReDa, 2015). And the utilization of DTs to address resilience enhancement within NPPs (Kropaczek et al., 2023), (Argyroudis et al., 2022), (Gohel et al., 2023), (Möhrle et al., 2021). Compared to industry wide policy and regulatory documents, such as the Sendai Framework (UNDRR, 2015) and various Council Directives (Directive 2012/18/EU), (Directive 2014/87/EURATOM). Underscored by the expert input given during the consultation session, consolidated in Chapter 5.2. Current resilience engineering practices are aware of the importance of learning from past events or incidents. However, there is room for more systematic learning mechanisms that adopt digital technology capabilities. For enhanced (historical) data processing and lesson generation, validating of assumption made in current learning practices, supporting a strong information exchange dynamic and shared knowledgebase between actors. Thereby enhancing the learning processes. Building on these insights and findings extracted from the literature synthesis of resilience engineering and organizational learning strengthened by industry 4.0 capabilities in Chapter 3. Taking an STS theory perspective to the organizational learning process. Validation of the model happened through a case study and expert feedback. This thesis has developed a model that lays out a theoretical potential systematic learning, from historical data, approach to strengthening nuclear power plants' resilience.

This model's purpose is to visualize a potential learning process, to inform NPPs resilience building, serving as an addition to current learning processes. Where implementation is at the discretion of the NPP. With the augmentation of digital technology utilization to strengthen this process in various ways. Applying STS theory as a framework to structure this process, align and strengthen the relationships between the social dimensions within the stages of the process and digital technology integration. The enhanced organizational learning process model focuses on the process surrounding learning from historical natural disasters affecting these critical infrastructures. Helping NPPs to take lessons from historical data analysis and turning them into actionable insights to enhance the resilience of the nuclear power plant against natural disasters.

By incorporating STS theory, the ELP-model, acknowledges that learning is achieved by strengthening the interconnected relationships between actors, social and technical elements. By strengthening the organizational absorptive capacity (Labaka et al., 2015), through digital technology utilization, the capabilities of critical infrastructures, such as NPPs, to learn from the past can be enhanced (Brucherseifer et al., 2021), (Argyroudis et al., 2022), (Shah et al., 2019). Has helped to shape each stage in the learning process; data collection, data analysis, outcome evaluation and strategy development, respectively. Strengthening the Social Elements (SEs) highlighted by metrics within resilience policy documents (Directive 2012/18/EU), (Directive 2014/87/EURATOM), part of the Sendai Framework (UNDRR, 2015) and learning guidelines (ESReDa, 2015). As being emergent from the literature and the dynamics of the network of actors present in the learning process (Manna et al, 2013), (Azadeh et al., 2015), (Yamashita & Takamura, 2015), (ESReDa, 2015). Digital technology integration strategies (Tabesh et al., 2019). Has further shaped the outlined learning process. These dynamics were underscored by expert consultation. And were regarded as influential to the learning process. Together with the utilization of Technical Elements (TEs), the DTs, influencing and enhancing the organizations' capabilities to learn from the past. To strengthen these SEs, specific goals for each stage are set. These goals guide the required utility and choice of the type of TEs. Based on their capability to support and achieve these goals and strengthen the SEs and therefore the overall stage. By utilizing the appropriate technologies that have the capability to address these goals. The organization can enhance its' learning process, informing systemic resilience enhancement.

In order to incorporate the elements of the STS as described in Chapter 2.4, and to construct the ELP-model, the following approach commenced. To identify which parts of the STS are present within each of the stages of the ELP-model. These were the steps taken in relation to literature synthesis and existent resilience policy documents/frameworks and are underscored as relevant by expert input.

1. During each stage of the model, the question is asked to the gathered information; what actors are present within the organizational resilience enhancement learning process? From this the interpreted actor network emerges.
2. Another question is asked, to gain insight into the SEs present; What are the relationships between the actors present in this stage and what social elements are at play in this part of the process. This shapes the list of SEs per stage.
3. Building on this, the relationship between SEs and TEs is considered. To understand what is needed to strengthen the SEs. Quantifying this into goals, that function as objectives to strengthen the Social Elements. This shapes the goals for the stage.
4. These goals, form the basis for the required capabilities of the TEs to be considered for integration into the learning process. The TEs, therefore the potential digital technologies should address these goals
5. This informs the requirements of the TEs, to influence the SEs in such a way that the learning process is enhanced.
6. Lastly, the outcome of the now strengthened stage and the overall learning process is discussed.

Since the ELP-model represents an iterative and structured process of learning, one must understand that the learning does not stop once strategies are developed. Building on the developed strategies and their deployment. Moving away from the more traditional approach to learning as a more reactive measure, than a pro-active operation. Based on a continuous learning approach (Awad & Martín-Rojas, 2024), following the development stage, the process continuous. Where more data is collected and analyzed. Thus, more lessons are learnt, and insights are gathered, which further influences and informs the resilience strategies.

A visual of the model and all the elements within is shown In Figure 7 on the next page.

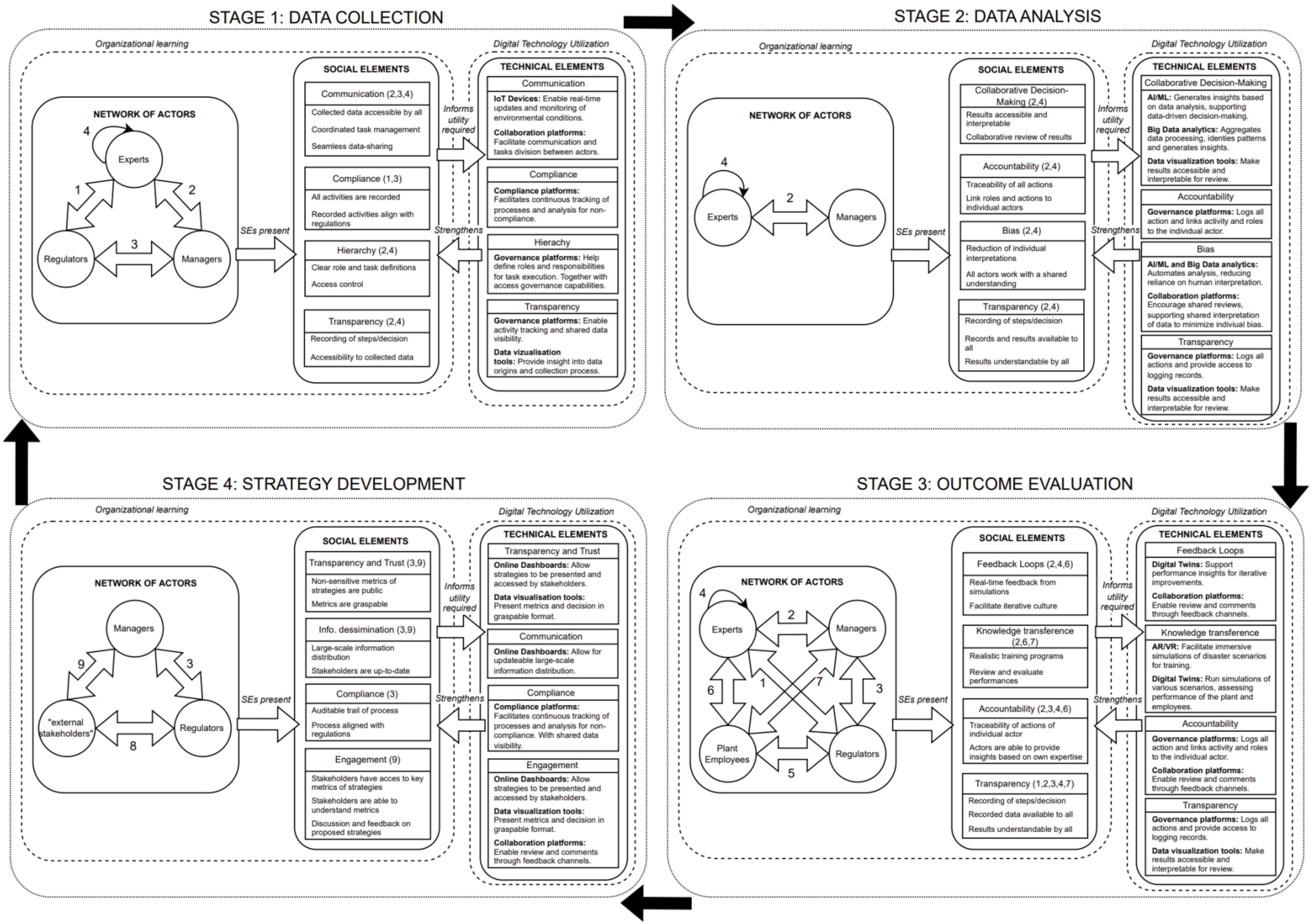

Figure 7: The ELP-model

4.2 Overview of the ELP-model

To provide guidance for comprehension and readability of the model developed in this study and introduced in the previous section and in Figure 7 above. This sub-section is focused on an overview of the model, in a step-by-step manner. Divided into the four stages of the model.

Stage 1: Data collection

The process begins with the identification and gathering of historical disaster and real-time data. Relevant to the NPP and its' operations. Experts, such a engineers and data scientists focus on identification of scenarios and gathering of datasets, while plant managers provide oversight on the alignment with resilience goals. Whilst regulatory inspectors verify compliance. The emerging SEs present, influencing the learning process in this stage cover, communication, between actors presents. Compliance with regulations, organizational hierarchy and transparency of operations. Goals to strengthen the data collection stage, in relation to the SEs, revolve around data accessibility, visibility and sharing. Coordinated task management, regulatory compliance and traceability of actions. Which in turn informs the required capabilities of various digital technologies. To address these goals and aid in strengthening the learning process in the context of the data collection stage. Utilizing digital technologies that possess capabilities that facilitate seamless data-sharing, real-time updates and traceability. Ensuring accessible data. As well as task and role governance and automated compliance monitoring building a holistic approach and lays the foundations for the subsequent stages.

Stage 2: Data analysis

In the next stage, the collected datasets are analyzed to extract actionable insights and generate lessons. Experts collaborate, supported by digital tools to identify patterns, root-cause of disasters, cascading failures and vulnerabilities of the plant within the data. Facilitating the ability to verify whether the datasets and insights are relevant to the NPP. Through this analysis, the plant and its' experts can shape disaster event scenarios, to be integrated into scenario-based learning in the next stage. Helping to support the verification of assumptions made on the real-world impact a natural hazard has on the plant and it' infrastructure and systems. Plant managers oversee this process, ensuring alignment of findings and results with organizational goals. The SEs present in this stage, and network of actors, surround overcoming human actor biases, collaborative decision-making between relevant actors regarding data analysis outcomes. And fostering accountability and transparency during this stage of the enhanced learning process. The goals to strengthen the data analysis stage, revolve around accessibility of data or results and actors working with a shared understanding. As well as traceability of actions during the stage. The requirements for the capabilities of the to be integrated digital technologies, enable advanced predictive data analytics. And data visualization and sharing, collaboration and responsibility governance. Supporting the actors to work with a shared understanding, enabling data-driven informed learning.

Stage 3: Outcome evaluation

Insights and lessons gathered in the analysis stage are processed, to evaluate the resilience performance of the NPP. The identified potential disastrous scenarios, based on historical events informs the simulations and training within this stage. The experts, aided by digital tools supporting the existing simulation practices, collaboratively establish simulations, interpreting plant performance, and identify operational vulnerabilities. Plant managers oversee the evaluation process, ensuring alignment with organizational resilience goals, and the meeting of compliance together with regulatory inspectors. The plant employees undergo training simulations to enhance their disaster preparedness, at the same time providing feedback on the simulations and plant performance based on their respective expertise. The SEs present surrounds evaluation and review of performance in the form of feedback loops, knowledge transference from training programs, accountability and transparency for an effective outcome evaluation stage and ensure organizational learning based on iterative improvement. The goals of this stage therefore surround NPP and employee resilience performance review, learning lessons from the simulation results. And the support of an iterative learning culture. The capabilities that the digital technologies in this stage have to offer help to achieve this. Enabling advanced simulations to be performed. Governance platforms and data visualization tools to allow for feedback mechanisms on the simulation outcomes. As well as monitoring systems for compliance governance. Together, improving the overall preparedness and refines the NPP resilience mechanisms.

Stage 4: Strategy Development

The last stage of the model, is focused on further automated informing of resilience strategies, based on the dissemination of the developed strategies among the various stakeholders, including the general public. The plant managers function as the representative of the plant and its' direction of resilience practices. Additionally including alignment of these strategies with regulatory and policy frameworks. The SEs and subsequent goals, therefore, surround transparency and trust to gain support among the stakeholders for the developed strategies. By communicating the strategy metrics in a continuous and graspable fashion. Thus, engaging stakeholders through interaction with these metrics and allowing them to provide feedback. Lastly compliance governance to ensure alignment and at the same time influence future industry policies. The required capabilities of the digital technologies, facilitate information dissemination and strategy awareness through visualization tools and communication platforms. Collaboration platforms support feedback channels and governance platforms can be utilized for continuous compliance monitoring and allows for future policies to be influenced. Not only informing the enhancement of resilience of the plant but also can support the industries approach to resilience learning.

4.3 Detailed description of each stage

Stage 1: Data collection

The purpose of the data collection stage of the ELP-model, is the identification and gathering of historical disaster data on NATECH events and other natural disasters relevant to the geophysical landscape surrounding the NPP. As well as real-time environmental data. Forming the basis for the subsequent analysis, evaluation and development stages. Selection of datasets need to be made on which historical disastrous event to investigate, up to the experts within the plant, to identify the adequate scenario's and collect the appropriate datasets. The data on the historical events should be in line with the surroundings and the past events striking the area of the nuclear plant (IAEA, 2015b). Supported by digital technology utilization, ensuring accurate assessment, relevancy and applicability to the plants' unique operational context (IAEA, 2020), (OECD, 2020) during the learning from the past process and decision-making on adequate resilience strategies. The network of actors involved in the data collection stage, contributing to the identification and collection of historical and real-time data encompass the following (ESReDa, 2015), (UNDRR, 2015), (Directive 2012/18/EU).

Experts: Such as engineers and data scientists are responsible for identifying relevant disaster scenarios and identify the appropriate datasets to be analyzed in the next stage of the learning process. While plant managers may guide the data selection, engineers confirm technical feasibility and data scientists verify relevance of scenarios to resilience objectives.

Plant managers: Oversee the data collection process, making sure that the collected data aligns with the organization's resilience goals. Providing a targeted scope for data selection by prioritizing datasets that are relevant to historical natural disasters and environmental conditions. Acting as intermediary between the plant and its' staff and external actors, such as regulatory inspectors. Ensuring that compliance of the plant with regulations and policy.

Regulatory Inspectors: Representing regulatory agencies, to make sure that compliance with regulations and policy is upheld during the data collection process. They validate and confirm whether the plant's procedures meet the established safety standards and best practices.

Social Elements

Communication: Effective communication is crucial to make sure all actors involved are engaged and aware of the efforts made during this stage, strengthening decision-making and operational performance (Nguyen & Mohamed, 2018), (Herazo & Lizarralde, 2016). Clear and accessible data between departments supports shared data visibility and real-time updates. Fostering an environment of open communication, enabling collaboration. (UNDRR, 2015), (ESReDa, 2015)

Compliance: One of the roles of the plant manager is to meet compliance with established safety and operational standards during the learning process and thus also the data collection phase. On the other hand, the regulatory inspectors are present to enforce these standards and regulations. Supporting an operational approach of integrity and accountability (Tamasiga et al., 2024). Compliance requires that the steps taken during the data collection stage are traceable. Enabling that each activity can be reviewed by regulatory inspectors as well as managers. Furthermore, compliance has shown to strengthen the learning process, through enhanced knowledge retention and dissemination within organizations (Ilseven & Puranam, 2021). (UNDRR, 2015), (Directive 2012/18/EU), (Directive 2014/87/EURATOM)

Hierarchy: Hierarchical structures within the organization define the roles and responsibilities of the actors involved (ESReDa, 2015). Having clear role definitions helps in task management, reduces ambiguity and enhances coordination, enabling efficient operations (Kundu et al., 2019). Controlled data access, based on these roles and responsibilities supports safe and efficient operations (Botha & Eloff, 2001). By allowing actors to access relevant datasets to their roles and activities. (Directive 2012/18/EU), (Directive 2014/87/EURATOM)

Transparency: Ensures that all the actors involved are aware of the procedures and datasets collected. Meaning that the steps taken, and decisions made are clear and accessible by all actors involved (Albu & Flyverbom, 2016). Where transparency enables accountability and informed decision-making (Lepri et al., 2017). Therefore, establishing trust and accountability (Eggers et al., 2021), and leads to a strengthened learning process (Parris et al. 2016). (ESReDa, 2015), (UNDRR, 2015), (Directive 2012/18/EU), (Directive 2014/87/EURATOM)

Goals

The goals for this stage surround making sure this stage of the learning process is performed in a documented and comprehensive manner. While also being transparent and in line with regulatory compliance and strategical objectives. The goals for this stage are summarized as follows:

Data accessibility, visibility and sharing: The collected data should be made accessible to all relevant actors. Increasing data visibility and collaboration throughout the process. Maguire (2013) and He et al. (2022) both highlight the importance of increasing data visibility to enable more effective collaboration and learning.

Furthermore, seamless data-sharing mitigates delays. And allows for a smoother and efficient process (Maguire, 2013), (He et al., 2022).

Coordinated task management: A structured approach to task management ensures that procedures and activities align with strategic goals (Maguire, 2013), (Shah et al., 2019). Moreover, clear role and task definition ensures that all tasks are allocated to the appropriate actor. Together with role-based access control, ensures that actors are able to gain access depending on their responsibilities. This supports efficiency during the data collection. (ESReDa, 2015)

Regulatory compliance and traceability: To ensure the learning from the past process and the data collection phase complies with regulatory standards. Recording of all steps and decisions is critical. Creating an auditable trail for regulatory inspectors to review and evaluate. Taking a transparent approach, promotes accountability and availability to all relevant actors, enabling insight into the data collection process through traceability. (Ilseven & Puranam, 2021), (Directive 2012/18/EU), (Directive 2014/87/EURATOM)

Informing DT utility

Communication: Integration of DTs to facilitate real-time updates and communication between departments within the plant and with external actors. Providing real-time, cross-departmental data-sharing capabilities with access control. This supports collaboration by enabling relevant actor access, depending on role or activity, to the datasets and working together on the same data seamlessly.

Compliance: DT enabled governing of compliance through constant monitoring and flagging of inconsistencies. Supports compliance without manual oversight. DTs could provide traceable records of the data collection activities. Supporting the logging of who has accesses, modified or validated datasets.

Hierarchy: Leverage DTs to support tasks management with access control, to ensure hierarchy is upheld. Supporting user-specific access. Incorporating approval mechanisms and limited accessibility upon request.

Transparency: DT integration to support recording of steps taking during data collection, such that whenever a certain dataset is accessed or adjusted, this is logged. As well as provide access to data and reports or data summaries. Therefore, enabling data access in a transparent manner. Allows for all involved actors to view the source of the datasets, steps taken and decisions made.

In conclusion, by integrating the digital technologies effectively, the data collection phase enhances the plant's learning capacity, ensuring that the organization is better prepared to develop and deploy resilience strategies in future phases of the ELP model.

Making sure that the data collection process with reliable datasets aligns with technical capabilities and are regulatory compliant. Supported by transparent communication, data traceability and clear role and tasks management. Preparing the datasets collected to be analysed in the next stage of the learning process.

Stage 2: Data analysis

The data analysis stage of the ELP-model transforms the collected data in the previous stage into actionable insight to be implemented into the development of resilience strategies. By utilizing digital technology capabilities to identify patterns, root causes, potential weaknesses and credible disaster scenarios. With the purpose to extract data from vast datasets that is relevant to the situation of the plant and devise disastrous scenario's to be implanted into scenario-based learning in the next stage. By identifying possible failure points and the influence of specific natural hazard conditions on the plant, assumption made in contemporary learning practices can be verified or refined. The data analysis stage provides the basis for the evidence-based data-driven outcome evaluation and decision-making in the subsequent stages of the ELP-model.

The data analysis relies on the combination of historical disaster datasets and real-time environmental data. To extract lessons from the (historical) data, utilizing digital technologies. By identifying any causes of the disasters, weaknesses and generating scenarios. Supporting the comprehension of these disastrous scenario's, understanding parameters for criticality, mistakes made and cascading effects. Thus, generating credible accident scenarios. Through determining the influence and impact of various identified scenarios, therefore, determining critical threshold parameters for emergencies. Supporting the disaster preparedness of the plant. The actors involved in this stage.

Experts: Such as data scientists analyze the datasets collected in the previous stage, employing digital technologies to identify patterns, predict system weaknesses and potential cascading effects. Working with engineers to interpret the analytical results in the context of the plants' operations. Engineers review the insights generated, on root-causes of the disasters and patterns within the data, to identify the operational weaknesses.

Plant managers: Their roles are to oversee the data analysis process and guide data scientist and engineers in prioritizing findings. Making sure that lessons learnt and insights generated are relevant to the organizational strategies and resilience goals of the plant. Utilizing the results of the data analysis to support their decision-making on future resilience strategies.

Social Elements

Collaborative decision-making: The collaboration between experts and plant managers, makes sure that the interpretation of the results of the analysis is in alignment with organizational capabilities and operational goals. Where collaboration is important for learning across the organization (UNDRR, 2015), (ESReDa, 2015). At the same time minimizing interpretative deviations between actors. Where a shared understanding supports collaboration and leads to a more cohesive decision-making process (Walker & Lloyd-Walker, 2016), (Joseph & Gaba, 2019), (Hasan et al., 2023).

Accountability: The roles and responsibilities of the actors should be clear and well documented. In the analysis process this means, ensuring that the results and insights made are reliable, consistent and actionable (Kundu et al., 2019). This reinforces accountability, in turn supporting transparency and traceability (Wohlrab et al., 2016), (Albu & Flyverbom, 2016). Insights generated within the digital space, require physical implementation. Therefore, needs accountable actors, so they operate reflectively which fosters learning. So, they can translate these insights into actions. (UNDRR, 2015), (ESReDa, 2015)

Bias: Human actor bias can influence the way data and results is interpretated (Morton, 2024), (Nassauer & Legewie, 2018). And plays a significant role in barriers to the learning process (ESReDa, 2015). Taking a collaborative review approach on analytical procedures not only ensures alignment with resilience goals but also reduces the potential for individual interpretations and biases (Nissen et al., 2014), (Hasan et al., 2023).

Transparency: Ensures that all the actors involved are aware of the procedures and datasets collected, which contributes to the learning processes (Directive 2014/87/EURATOM). Meaning that findings and results are accessible and interpretable to actors involved (Albu & Flyverbom, 2016). (ESReDa, 2015), (UNDRR, 2015), (Directive 2012/18/EU

Goals

The data analysis stage is crucial for generating valuable insights from the historical data and supporting a well-informed learning and decision-making process. This involves goals constructed to make sure the analysis is transparent and inclusive to all relevant actors.

Shared knowledgebase: Results of the analysis must be accessible and interpretable by all actors (Directive 2012/18/EU), (Directive 2014/87/EURATOM). Allowing them to interact with each other and the data to make informed decisions. Making the learning process effective and efficient (UNDRR, 2015). Supporting a collaborative review of the results (Walker & Lloyd-Walker, 2016), (Joseph & Gaba, 2019), (Hasan et al., 2023). Furthermore, enabling the results of the analysis to be accessible by all relevant actors, ensures transparency throughout the data analysis stage and the learning process (Albu & Flyverbom, 2016). Moreover, when all relevant actors involved work with a shared understanding. Human actor bias and individual interpretations are mitigated. (Nissen et al., 2014), (Hasan et al., 2023).

Traceability of roles and actions: Linking roles and actions to individual actors promotes accountability and transparency (Wohlrab et al., 2016), (Albu & Flyverbom, 2016). Making it possible for all decisions to be traceable, by logging actions performed and relating them to the correct actor. And making these recorded steps during the data analysis available for review. Promotes consistent and reliable results (Kundu et al., 2019). (ESReDa, 2015), (Directive 2014/87/EURATOM)

Informing DT utility

Collaborative Decision-making: Facilitating real-time collaboration and accessibility, with data visualization tools. To support a common understanding of the findings and results for all actors involved.

Accountability: Digital technology capabilities to facilitate recording of the process. Supporting logging of the steps taken in the analytical process. As well as documentation, linking roles and actions to individual actors.

Bias: Integrate platforms that encourage shared data interpretation. And tools that can generate insights on its' own, without human intervention. Tagging assumptions made during the analysis.

Transparency: Digital technologies to support recording of steps taking during data analysis. As well as provide access to data and reports or data summaries. Supporting human interpretation and understanding of the results, regardless of technical expertise.

In summary, the data analysis stage transforms data inputs from the collected datasets into actionable insights. Establishing a foundation for evidence-based data-driven decision-making and (simulation) learning. Addressing the goals of the Ses, such as collaboration, accountability and transparency, makes sure that the potential Tes are aligned with the social goals and requirements of actors, and are in line with plant capabilities. Integrating digital technologies during this stage, enables the plants to identify vulnerabilities, root-causes and cascading effects of hazardous events. Verify assumptions and shape disaster scenarios relevant to the NPP. And emphasizes the support for actors to work with a common understanding of data and information. Strengthening the predictive and reactive capabilities of the plant against natural hazards. And through a shared-knowledge base. Supporting the development of adequate and sophisticated resilience strategies.

Stage 3: Outcome evaluation

The outcome evaluation stage of the ELP-model assesses the plants performance by validating the insights gathered during the data analysis stage. By running the generated disaster scenarios based on the results of the data analysis, through simulations, the plant is able to assess the reactiveness of the plant in such scenarios. Thereby validating the results of the data processing. And, as emphasized during expert consultation, the extraction of actionable insights based on the results from the simulations. Such as insights into plant infrastructure vulnerabilities, in case of a natural hazard or weaknesses in emergency procedures. Shapes actionable insights to improve infrastructure or emergency reactive procedures. Strengthening hazard and vulnerability awareness and helps ensuring that the developed resilience strategies are aligned with plant and operational capabilities as well as organizational goals for resilience. This stage also includes the training of plant employees, to strengthen the preparedness in case of a disasters, mitigating the chance of human-errors resulting in cascading effects.

The network of actors present in this stage ensures that the generated accident scenarios as well as the resilience strategies are realistic and integrable within the operations of the plant. And training practices, based on the results of the data analysis, are held to increase staff preparedness. Integrating the utility that digital technologies offer supports enhancement of the learning capabilities, through continuous learning and improvement of the results of the analysis and the resilience practices. The actors involved in this stage (ESReDa, 2015), (UNDRR, 2015), (Directive 2014/87/EURATOM), (Directive 2012/18/EU).

Experts: Supported by digital tools, ensure that the outcomes of the analysis align with the operational capabilities and infrastructure of the plant. Verifying assumptions and validating scenarios generated through simulations. Setting up and managing existing scenario simulation, supported by digital technology integration. Providing their expert judgement so that the simulations reflect real operational conditions. As well as identification of any weaknesses in the plants and its' staffs' response to these simulations.

Plant managers: Provide oversight to the evaluation process, ensuring the outcomes of the analysis and simulations align with the strategic objectives of the plant. Review the findings from the engineers and translate them into the decision-making process on resilience strategies.

Regulatory inspectors: Inspectors are involved to validate whether the tested scenarios meet regulatory standards and are in line with industry best practices. Guiding managers and engineers to focus on compliance-centered outcomes.

Plant employees: Employees of the plant participate in the training simulations. Gaining familiarity with procedures by becoming better prepared and learning how to adequately and effectively respond in the event of a potential disaster. Guided by engineers to refine the training programs and generate feedback. Ensuring that the simulations and outcomes are in line with operational capabilities.

Social Elements

Feedback loops: Incorporating feedback on scenario simulation throughout the evaluation stage, support a continuous iteration process (Grösser et al., 2017), leading to enhanced organizational learning (Antunes & Pinheiro, 2019). Refining the simulations and ultimately the resilience strategies (Bucovetchi et al., 2024), (Lundberg & Johansson, 2015). (ESReDa, 2015)

Knowledge transference: Training employees, through simulated scenario, to mitigate human error in the event of a disasters (Franchina et al., 2021), (Rehak et al., 2018). Supporting hands-on practice, preparing them to respond effectively in the event of a disaster. (ESReDa, 2015), (UNDRR, 2015), (Directive 2012/18/EU), (Directive 2014/87/EURATOM)

Accountability: Enables all actors to be responsible for their own roles and activities. Furthermore, to provide feedback and insights based on their own expertise and roles (Pearson & Sutherland, 2017). Which is supportive of the learning process. (ESReDa, 2015), (UNDRR, 2015), (Directive 2014/87/EURATOM)

Transparency: Facilitates that all actors are aware of decisions, and steps taken in this stage. Furthermore, transparency ensures that outcomes of the simulations are accessible to all actors, (Gualandris et al., 2015), (Farrell, 2016). Together with enabled continuous documentation, supports a strong learning process. (Rehak et al., 2018), (Trucco & Petrenj, 2017) (ESReDa, 2015), (UNDRR, 2015), (Directive 2012/18/EU), (Directive 2014/87/EURATOM)

Goals

The goals for this stage revolve around implementing the results and insights generated during the data analysis stage, to build informed simulations and training programs based on the derived disaster scenarios. Evaluating the plants' performance, identifying vulnerabilities and enhance employee preparedness.

Plant performance evaluation and employee training: Outcomes of the data analysis stage, such as disaster scenarios and critical parameters. Should inform the development of realistic training programs, with various scenarios. Supported by digital technology capabilities. Containing immersive simulations to mirror reality. Furthermore, the conducting the evaluation and review of the performance of the plant and its' employees to address weaknesses and points of improvement. Enhancing the systematic resilience. (Bucovetchi et al., 2024), (Lundberg & Johansson, 2015).

Iterative learning culture: To further strengthen this stage of the enhanced learning process, making real-time feedback from these simulations possible (Grösser et al., 2017). Documentation and reports of the simulations, the training excersizes and improvements further establishes an iterative learning culture (Bucovetchi et al., 2024), (Lundberg & Johansson, 2015). And made accessible to all actors involved to further support this learning (Gualandris et al., 2015), (Farrell, 2016). By making the results and outcomes of this stage interpretable by the actors involved, they can provide insights based on their own expertise. Additionally, strengthening the overall process (Pearson & Sutherland, 2017).

Informing DT utility

Feedback loops: Real-time simulation performance insights and feedback should be enabled. With the ability for actors to review and comment on their experience. Allows for a continuous learning culture to be cultivated (Cantelmi et al., 2021).

Knowledge transference: Realistic scenario simulations for training purposes should be supported. Allowing trainees to review and evaluate their responses. This refines scenarios as well as lessons learnt (Cantelmi et al., 2021). Supporting a strong learning process. (Rehak et al., 2018), (Trucco & Petrenj, 2017)

Accountability: Collaborative access to reports and results should be supported. Allowing for simulation records to be stored and results to be accessible by the relevant actors. And provide the possibility for actors to provide feedback and insights based on their roles and expertise.

Transparency: Supporting the collaborative access to reports and results. And accessibility on results of the outcome evaluation for the relevant actors. In such a manner that mutual understanding is established.

To conclude, the outcome evaluation stage allows for the outcomes of the data analysis, in the form of insights, generated scenarios and resilience strategies. To be tested, evaluated and improved upon. Through simulations and training. Being aware of what is required to strengthen the SEs, shapes the decision-making process of the DTs to be utilized. And with the strengthened SEs, the plant is able to continuously improve through simulation-based learning. Incorporating transparent feedback loops, continuously refines the resilience strategies, based on organizational needs. Leading to enhanced system resilience against natural hazards.

Stage 4: Strategy development

The strategy development stage of the ELP-model is focused on the development of resilience strategies, based on the lessons and insights gathered, and validated outcomes from the previous stages. Furthermore, involving communicating these developed strategies with various stakeholders, such as the general public in an automated manner. Fostering support for these strategies, as well as trust and transparency. Informing the regulatory bodies ensures not only compliance but can shape future policies on resilience in the industry. The actors involved in this stage (ESReDa, 2015), (UNDRR, 2015), (Directive 2014/87/EURATOM), (Directive 2012/18/EU).

Plant managers: Managers lead the development of the strategies through strategic decision-making for resilience improvements. And in this stage act as representatives of the plant when communicating the strategies to other stakeholders. Supported by digital technology integration, making this a data-driven decision-making process. Translating validated insights into actionable strategies, aligned with organizational goals and targets. At the same time, meeting compliance of the regulatory bodies.

Regulatory inspectors: Validate the developed strategies, ensuring they are in line with safety standards and best practices. Their approval supports managers in formalizing these strategies, making them reliable, actionable and enforceable (Meskens, 2020), (International Atomic Energy Agency, 2021). Also translating the strategies, if effective, into the regulatory frameworks and policies to be adopted by the wider industry.

“other” stakeholders: Meaning external stakeholders such as the general public, industry suppliers, (research) organizations or governmental bodies. Or even other CIs. As mentioned in Chapter 3.2. Are engaged through informing them on the (non-sensitive) metrics of the strategies. They provide feedback on the proposed strategies, based on their expertise and expectations. Ensuring the strategies are well-rounded and in line with the requirements of the contextual surroundings of the plant.

Social Elements

Trust: Transparency, as mentioned before, supports the building of trust (Eggers et al., 2021), (Parris et al. 2016). Establishing an understanding on how resilience strategies safeguard the community. By communicating non-sensitive details of the strategies in an open fashion with external stakeholders. Additionally, building trust, through informing the public on the proposed strategies. Supports acceptance of the strategies by the public (Murakami et al., 2021), (Bronfman et al., 2016). (ESReDa, 2015), (Directive 2012/18/EU)

Information dissemination: Communicating and distributing information on resilience strategies to various stakeholders, with varying levels of sensitive information to be shared. Establishes engagement and support for the resilience strategies (Aaltonen et al., 2008), (Nguyen & Mohamed, 2021). (ESReDa, 2015), (UNDRR, 2015), (Directive 2012/18/EU)

Compliance: Strategy development should maintain a clear process structure, for inspectors to review. Facilitating consistent documentation and alignment with regulations (Tamasiga et al., 2024). As mentioned before, compliance has shown to strengthen the learning process, through enhanced knowledge retention and dissemination within organizations (Ilseven & Puranam, 2021). (UNDRR, 2015), (Directive 2012/18/EU), (Directive 2014/87/EURATOM)

Engagement: Stakeholder engagements, ensures that the strategies align with expectations and stakeholder needs (Aaltonen et al., 2008), (Nguyen & Mohamed, 2021). Building communication channels that support feedback from stakeholders for improvement on the strategies. Thereby, creating resilience strategies that are well-informed, supported and sophisticated (Herazo & Lizarralde, 2016). (ESReDa, 2015), (UNDRR, 2015)

Goals

The goals for the last stage revolve around creating awareness and support for the devised resilience strategies. And through engagement with stakeholders iterate the strategies based on their expertise, requirements and expectations.

Information dissemination: Key (non-sensitive) metrics of the proposed strategies should be accessible to the public. And stakeholders should be provided with up-to-date information. Therefore, establishing engagement and support for the strategies (Aaltonen et al., 2008), (Nguyen & Mohamed, 2021). Informing the public in a transparent manner and furthermore, establishes trust and support for the strategies (Murakami et al., 2021), Bronfman et al. (2016).

Enable stakeholder interaction: The key metrics of the strategies should be translated into a graspable fashion. Ensuring a wide variety of stakeholder are able to interact with the metrics of the data. Also support discussion and feedback on the proposed strategies. Creating well-informed, supported strategies (Herazo & Lizarralde, 2016).

Regulatory compliance: All steps in the strategy development process should be carefully recorded, creating an auditable trail for regulatory inspectors to review and evaluate (Tamasiga et al., 2024). Moreover, strategy development procedures should align with regulatory standards to ensure an enhanced learning process (Ilseven & Puranam, 2021).

Informing DT utility

Trust: Automated distribution and visualization of metrics in a comprehensible, by the general public, fashion. Distribution and accessibility to the public should be made possible. External communication should be possible and offer insights into the strategies, safeguarding sensitive information.

Communication: Integration of platforms that can distribute information on a large-scale. Providing various levels of sensitive information depending on the intended receiver. As well as ensuring all stakeholder are updated on strategic changes.

Compliance: Development steps should be documented and stored for review. Developed strategies, should be made accessible in a structured manner, allowing for regulatory audits.

Engagement: Facilitate stakeholder engagement, through automated communication channels. That support distribution of information and allow for feedback to be documented.

In summary, this stage ensures that resilience strategies are well-informed, collaborative, transparent, and future-focused, enhancing public trust and stakeholder support. Creating a proactive approach to natural hazard resilience engineering. Collaboration with policy makers ensure future policies continuously improve, not only making the plant more resilient but the industry as a whole. Engagement with stakeholders during strategy development cultivates a transparent approach, generating support for the strategies, compliance with regulations and trust from stakeholder, including the general public. Taking a transparent approach to strategy development, with a clear and well-documented process strengthens the learning process, by informing stakeholder, addressing their expectations and requirements. Builds well-informed and supported resilience strategies. Enhancing the resilience of the nuclear plant.

4.4 Theoretical outcome

The ELP-model developed in this study aims to address the learning gaps and digital technology underutilization identified in Chapter 3. It attempts to visualize the theoretical potential of DT utilization to strengthen the learning process and enhance NPP resilience. This sub-chapter serves as the discussion on the theoretical outcome of STS alignment in this model. The contents and aim of the model were validated in the case study in Chapter 5.1 and through expert feedback, Chapter 5.2. Which emphasized the importance of structured learning mechanisms in resilience enhancement practices. As well as the value to be gained within learning processes when implementing such a structured and systematic, DT-supported learning process guideline. Surrounding automated systematic knowledge exchange, aggregated data analysis and the need for validated scenario-based learning and review. As well as the limitations of digital tool and learning process guideline adoption.

Stage 1

The expert confirmed that current NPP learning processes lack automated systematic approaches and rely on manual evaluation, periodic assessments and expert judgement. The ELP-model attempts to address this by integrating IoT enabled real-time monitoring to automate environmental data collection, adding the historical incident datasets, for continuous situational awareness. Governance & compliance platforms, that support enhancement of traceability and reduce the dependency of manual compliance control. Strengthening compliance. Contributing to the resilience of organizations against disruptions (Florez-Jimenez et al., 2024). And inter- and intra-organizational collaboration and governance tools, that facilitate structured knowledge-sharing dynamics between the actors present in the learning processes.

Real-time information updates and data-sharing ensure that all actors have access to the data. Together with coordinated task management abilities. Supports smooth, coordinated efforts across departments. (Maguire, 2013), (He et al., 2022), (Shah et al., 2019). Enabling user-specific tasks and access control supports accountability (Ghorbel et al., 2021) and efficiency (Lumpkin & Lichtenstein, 2005) throughout the learning process. Collaboration and governance platforms can provide organizations with the capability to limit actor access and give access when approved for a limited timeframe and only particular sets of data and information. By supporting transparency during data collection, all actors are able to confirm the origin of the datasets and their reliability. Through the utilization of governance platforms, to track actor activity and support shared data visibility (UNDRR, 2015). Trust, accountability and organizational learning is reinforced through these practices (Farrell, 2016). Whilst supporting compliance with regulations (Kiesel & Grünewald, 2024).

Stage 2

The model suggests the utilization of ML models or Big Data Analytics tools to analyze past NPP incidents, aggregating data processing. And support the identification of operational vulnerabilities and cascading effects. And translate them into lessons for the plant. And support the building of realistic disaster scenarios that are relevant to the plant. Which the simulated scenario-based learning can build upon. Extending beyond the current learning process practices, by mitigating human cognitive biases in data filtering and relevancy by introducing automated insight generation. Together with data visualization tools, can make the results of the analysis interpretable by actors for their review. This DT-enabled access to results for review in a collaborative manner, fosters a shared understanding with managers and experts (Wong et al., 2014), (Hasan et al., 2023). Further mitigating human interpretation bias. And supports a well-informed data-driven decision-making process, resulting in enhanced organizational performance, ergo learning (Walter et al., 2013). Furthermore, accountability mechanisms in place, in turn enhances organizational learning (Gualandris et al., 2015), (Williams et al., 2022).

Establishing a shared understanding for actors to work with, through digital platform integration (Rad et al., 2021), (Shah et al., 2019) Encourages shared reviews and comprehension. Further reducing individual interpretation biases. Addressing some of the barriers surrounding human bias in the learning process (Orikpete & Ewim, 2023), (ESReDa, 2015). Having accessible and understandable steps and results, through governance platform utilities combined with data visualization tools. Ensures all actors are able to interreact with the results, regardless of expertise. Allowing for all actors to engage with the findings and results in a meaningful way (Hosseini et al., 2017). Further supporting a shared knowledgebase as emphasized to be a key factor within resilience learning, by the expert. Strengthening the capability to learn lessons from the analysis and the ability to make well-informed decisions (Gualandris et al., 2015).

Stage 3

The model suggests a DT environment that facilitate feedback loops, enabling and integrating feedback mechanisms, fosters an iterative improvement process. Supporting continuous learning culture (Cantelmi et al., 2021), (Thomas et al., 2019). Such as Digital Twins that provide real-time performance insights. Synergized with collaborative platforms, enabling review and comments on the plants' performance through feedback channels. Allows for developed resilience strategies to be based on actor experience and insights. This addresses an area of improvement for the learning process, as highlighted by the expert. Where lessons and insights extraction from performance results is still challenging. Building on the existent simulation and scenario-based learning practice. Support the training exercises to address human actor vulnerabilities (Franchina et al.,

2021) and address potential disruptions (Rehak et al., 2018). Where AR or VR tools can provide immersive simulation-based training. Whilst Digital Twins could run simulations of various, identified in the previous stage, scenarios to evaluate the plants performance and indicate critical parameters. This training and simulation-based performance evaluation and documentation, serves as an addition to existing practices. Establishing the possibility for the plant and trainees to track their responses, vulnerabilities and improvements over time. Resulting in enhanced resilience (Yamashita & Takamura, 2015). (Franchina et al., 2021), (Trucco & Petrenj, 2017), (Cantelmi et al., 2021).

Digital platforms can enable recording and documentation of simulation results. Allowing actors involved to observe and review based on their expertise, the performance of the resilience strategies and response of the plant and its' employees. Which re-enforces learning (Pearson & Sutherland, 2017), (Musawir et al., 2019). Also enabling the logging of activities and providing access to these records to the appropriate actors. Makes all actors aware of the steps and decisions made during the process. Coupled with data visualization tools to support a mutual understanding of the data and the outcomes (Albu & Flyverbom, 2016). Allowing for all actors to engage with the outcomes in a meaningful way (Hosseini et al., 2017). Strengthening the capability of organizational learning (Gualandris et al., 2015).

Stage 4

The model suggests using online dashboards and visualization tools to disseminate and visualize non-sensitive information on the resilience strategies in an automated manner. Enabling public confidence and support from stakeholders for the developed strategies. Thereby establishing trust and showing a transparent approach to safety and resilience (Eggers et al., 2021), Bronfman et al. (2016). Enabling the communicated resilience strategies to be graspable, updated and accessible. Supporting well-informed stakeholders surrounding the nuclear plant. (Aaltonen et al., 2008), (Nguyen & Mohamed, 2021). Additionally facilitating feedback channels, through digital platform usage, ensures that the resilience strategies align with the expectations and requirements of stakeholders (Bucovetchi et al., 2024). Allowing stakeholders to provide input, resulting in a comprehensive approach to resilience building. Engagement has also been shown to ensure compliance with rules and regulations (Mayer et al., 2016). Furthermore, the adoption of compliance governance platform enabled documentation and accessible records automates compliance evaluation by inspectors. Supporting continuous alignment with industry resilience standards (Tamasiga et al., 2024), validating strategies (Meskens, 2020 and strengthens the learning process (Ilseven & Puranam, 2021).

In summary, the ELP-model aligns the interconnected relationship between social and technical components of the learning from the past process within NPPs. Where digital technologies are not only tools for data analysis or simulations, but also facilitates enhanced compliance, transparency, communication, accountability, through automated systematic knowledge exchange dynamics and a shared knowledge base among actors. Helps to mitigate human bias within the traditional learning process. By integrating DTs, the ELP-model supports data-driven decision-making, enabling organizations to identify vulnerabilities, predict cascading failures, generate actionable insights and validate assumptions. Leading to amplified lessons learning. The ELP-model informs the plant operators in devising sophisticated resilience strategies. Respecting that engagement with stakeholders surrounding the plant and regulatory compliance is needed for supported and efficient resilience strategies. Incorporating feedback and review mechanisms for stakeholder engagement and accountability, the model supports trust and transparency, ensuring that resilience strategies are comprehensive and aligned with the needs and expectations of all relevant actors. The communication of the devised strategies with the nuclear energy community can lead to strengthening the resilience of the industry as a whole and inform future policies and regulations. Lastly, the continuous nature of the ELP-model ensures that the learning process becomes iterative and adaptive. The model emphasizes that each stage of learning builds upon the previous stage. And each cycle goes back to the first stage.

Chapter 5: Validation process

The verification and validation process of the outcomes of this research is two-fold. It revolves around a case-based evaluation and an expert consultation. This chapter outlines the verification and validation process undertaken in this study to evaluate and assess the model's theoretical application and this research's practical relevance in the space of natural hazard resilience learning of NPPs.

5.1 Case based evaluation

This sub-chapter is aimed at demonstrating the theoretical application and value of the ELP-model. By way of case-based evaluation. Through the demonstration of the model on the Fukushima Daiichi disaster as a real-world historical event. Provides a relevant and well-documented scenario for assessing how a structured learning process could support the enhancement of a learning from the past process within NPPs. Ensuring relevancy and applicability of the model to support real-world learning. The Fukushima disaster exposed vulnerabilities within disaster preparedness, emergency protocols and infrastructure design of the nuclear plant. Highlighting the importance and need for systematic resilience learning mechanisms. Guiding the reader through the model's four stages (data collection, data analysis, outcome evaluation and strategy development). Discussing how this research aims to augment current resilience learning processes. Applying the ELP-model to this historical case, this research aims to illustrate how a systematic learning approach with a socio-technical perspective, combined with digital technology integration, can theoretically improve resilience learning practices within NPP operations. The Fukushima case study serves to evaluate the value of the model in comparison to traditional resilience learning approaches. Where prior works have mainly focussed on physical infrastructure failures and reactive measures, neglecting the importance of structured learning mechanisms.

The ELP-model is developed to visualize and structure a continuous and iterative learning process. Enabling NPPs to systematically analyse historical events and extract lessons from them. This demonstration highlights how the model can improve organizational learning by aligning socio-technical dimensions, utilizing the capabilities that digital technologies have to offer. Thereby contributing to the improvement of traditional learning processes and the development of enhanced resilience strategies. The case-based evaluation method allows for a comparative analysis between insights from the Fukushima disaster and the proposed learning process model. Showcasing how digital technologies, such as ML-models, digital twins and digital platforms, could support more effective learning form historical incident data.

5.1.1 Description of the scenario

The Tohoku Earthquake of magnitude 9.0 which occurred on the 11th of March 2011, centred at 130 Kilometres of the shores of Japan and about 180 Kilometres from the Daiichi nuclear plant. Resulted in a tsunami with a maximum height of 13 meters at the plant (WNA, 2024b). A visual of the location of the plant relative to the earthquake epicentre is shown below in Figure 8. The impact of the tsunami led to cascading failures, including several core meltdowns, hydrogen explosions and subsequent radiation leakage.

Initially the plants' infrastructure and its' reactors were able to withstand the initial seismic impact cause by the earthquake. But proved to be vulnerable to tsunami. The reactors in operation at the time of the earthquake were shut down automatically in response to it. However, the off-site power supplies were lost due to damages cause by the earthquake. This triggered the emergency diesel generators (EDGs) to be started, located in the basement of the plant. Furthermore, cooling of the reactors, as part of the shutdown was maintained initially by rerouting the main steam circuit past the turbines and flowing through the condensers. However, when the tsunami waves hit, the residual heat removal cooling system, the seawater pumps for the cooling circuits and the EDGs were flooded and damaged. This meant that adequate shutdown of the reactors could not be maintained. Due to flooding, roads to the plant were also obstructed, making the plant inaccessible. (WNA, 2024b), (Hollnagel & Fujita, 2013) (Lipscy et al., 2013)

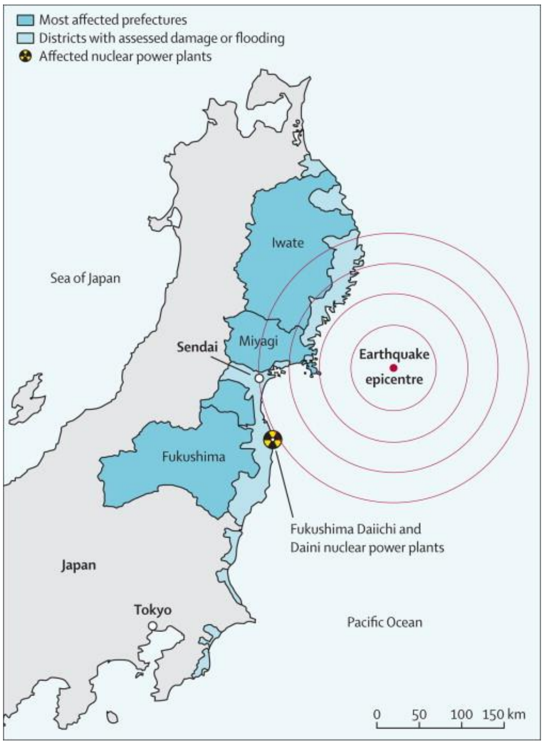

Figure 8: Location of Fukushima Daiichi plant relative to earthquake epicenter (McCurry, 2011)

When the power failed, due to the submerged EDGs, the shutdown procedure was not finished yet. Meaning they were still producing some thermal power, about 1.5% of their nominal levels thus about 22-33MW from the 3 reactor units in operation at the time. Since the heat removal to the heat exchangers by circulation was incapacitated due to the tsunami. Pressure started to rise due to the amounts of steam building up inside the reactors. This was later accompanied by hydrogen build up through the interaction of the reactor fuel's hot zirconium cladding with the steam. To suppress temperatures, water was injected, but this meant internal pressures needed to be relieved. Auxiliary venting of the pressure was designed to flow from an external stack, however due to the power loss, much of this vented steam back flowed into the reactor building, together with the gasses from the by now exposed fuel and hydrogen caused a hydrogen explosion. After the hydrogen mixed with air ignited. Which blew off the roof and cladding of the reactor building. This together with water leakage through the bottom, released radiation contamination into the environment. Moreover, the design and disaster countermeasures of the Fukushima Daiichi plant were based on the knowledge the industry had in the 1960s. And were deemed acceptable at the time. The siting and tsunami defenses were designed based on the 1960 Chile tsunami, with a design base height of 3.1 meters. Thus, the plant and the seawall barrier were built 10 meters above sea-level. Even though the design base height of tsunami was revised in 2002 from to 5.7 meters, thus sealing off the seawater pumps set at 4 m above sea-level. This was not enough for the 13-meter-high tsunami on March 11th 2011. However, in years between the construction of the Daiichi plant, and the events of March 11th 2011. Multiple tsunamis have occurred and affected the region surrounding the plant. For example, 1983 with a maximum height of 14.5 meters, and in 1993 a maximum height of 31 meters, at origin. Both induced by earthquakes of magnitude 7.7. With other tsunami occurring caused by earthquakes up to 8.4 in magnitude. (WNA, 2024b), (WNA, 2017), (Hollnagel & Fujita, 2013), (Lipscy et al., 2013),

Despite newly acquired knowledge on the likelihood of an earthquake, resulting in a tsunami of 15.7 meters affecting the Daiichi region. Some 18 years before the 2011 disaster. As well as a report that was due to be released in April of 2011 of the Japanese Earthquake Research Committee. Which included an analysis of an earthquake with magnitude 8.3 having struck the region some 1140 years ago and caused subsequent flooding of major areas of the Fukushima Prefecture. Showcases there were ample learning opportunities for the plant to alter and improve their safety measures and resilience. As well as vulnerabilities in the collaboration between stakeholders on timely communication of insights from past events. (Hollnagel & Fujita, 2013), (Lipscy et al., 2013)

The disaster was further aggravated by weaknesses in (real-time) communication channels, decision-making, and coordination across different actors, including plant operators, governmental bodies, and emergency responders. The Fukushima Daiichi disaster serves as a strong example for the complexity of socio-technical dynamics existent in nuclear plant operations. And thus, an exemplarily case for addressing resilience enhancement engineering through a structured learning process, the ELP model. (Hollnagel & Fujita, 2013), (Lipscy et al., 2013), WNA (2024b)

In general, data collection from such a historical disaster can include seismic activity data, historical weather patterns and tsunami development. As well as critical parameters from inside the plant, such as pressure build up, temperature and substance (in)balances. Furthermore, emergency response times, and information dissemination between stakeholders. And accident reports made post-disaster. For the plant to gain a comprehensive amount of data on natural conditions leading to the earthquake and resulting tsunami. Towards cascading failures within the plant that led to the accident. Also, data on how the context and stakeholders surrounding the plant reacted and decisions made during and post-disaster. Supported by the utilization of IoT devices, enables real-time monitoring of NPP and environmental conditions. To extract valuable data of the situation of the NPP to be compared with the Fukushima plants' conditional and situational data, during the data analysis. Which help shape an understanding of realistic disaster scenarios from which NPPs can learn from and inform their resilience strategies.

5.1.2 Objectives

The purpose of this case-based evaluation is to validate the ELP-model through the demonstration of the theoretical application of the ELP-model in visualizing a structured and systematic learning process supported by digital technology utilization. For analysing and learning from historical disastrous events. Focusing on the case of the Fukushima Daiichi disaster, the study demonstrates how the model structures and supports a systematic approach to learning from past events. Identifying gaps and opportunities for improvement in the learning from the past process within NPPs. Guiding the reader through how the model enables organizational learning. The demonstration of the model not only helps identify operational vulnerabilities uncovered by the Fukushima disaster. But also highlights opportunities for improvement within the resilience learning processes of NPPs. Such as, data processing, feedback mechanism, and stakeholder engagement. Examining the disaster through the ELP-model's perspective, the study validates how a structured, iterative and continuous learning process can be applied to improve a NPPs resilience. Through operational vulnerability reduction, mitigation of cascading effects and strengthening of organizational preparedness. Against future potential natural disasters as well as safeguarding the nuclear sector. Showcasing how each stage of the model contributes to the enhancement of nuclear power plants' organizational learning. Where learning so far from the Fukushima disaster is based on post-disaster evaluations, with specific effects for the operations and physical infrastructures of NPPs. However limited systematic integration of lessons learned, and reflection on such disasters to evaluate own plant performance, regarding the specifics of the plant and its' environment. Addressing the intricate dynamic between socio-technical elements of the learning process. Validating the model's socio-technical alignment by highlighting the relationship between goals of social elements and digital technology utilization. Giving explicit examples of digital technologies and their capabilities. Providing insight into how NPPs can adopt continuous iterative learning mechanisms to enhance their resilience. The case-based evaluation is aimed at achieving the following objectives:

Demonstrate the application of the ELP-model: Guiding the reader through the stages of the model. Applied to the Fukushima case, to highlight how the model supports systematic learning from the past.

Identify areas for improvement in the learning process: The study uses the case to illustrate gaps in the learning process of NPPs. Such as lack of transparent data sharing and collaboration, reflection on historical data and inadequate stakeholder engagement. And to demonstrate how the ELP-model addresses these opportunities for improvement.

Highlight the value of the model within resilience enhancement: By comparing the application of the ELP-model, with existing studies on the Fukushima case. Highlighting the contribution, particularly in aligning socio-technical elements within the learning process and the utilization of digital technologies to enhance it. To the existing resilience learning practices within NPPs. Thereby discussing the value of the model within resilience engineering and learning frameworks.

By addressing these objectives, this sub-chapter helps validate the ELP-model as a basis to support learning from the past processes for NPPs. Demonstrating how the model can support NPPs in reflecting on past events and vulnerabilities and turn them into learning opportunities for enhancing their resilience. And extends beyond current learning processes. By integrating a structured, iterative learning mechanism from an STS perspective and supported by DT utilization. forming the basis for a resilience enhancement learning process in the form of a technical guideline.

5.1.3 Application of the model

Stage 1: Data Collection

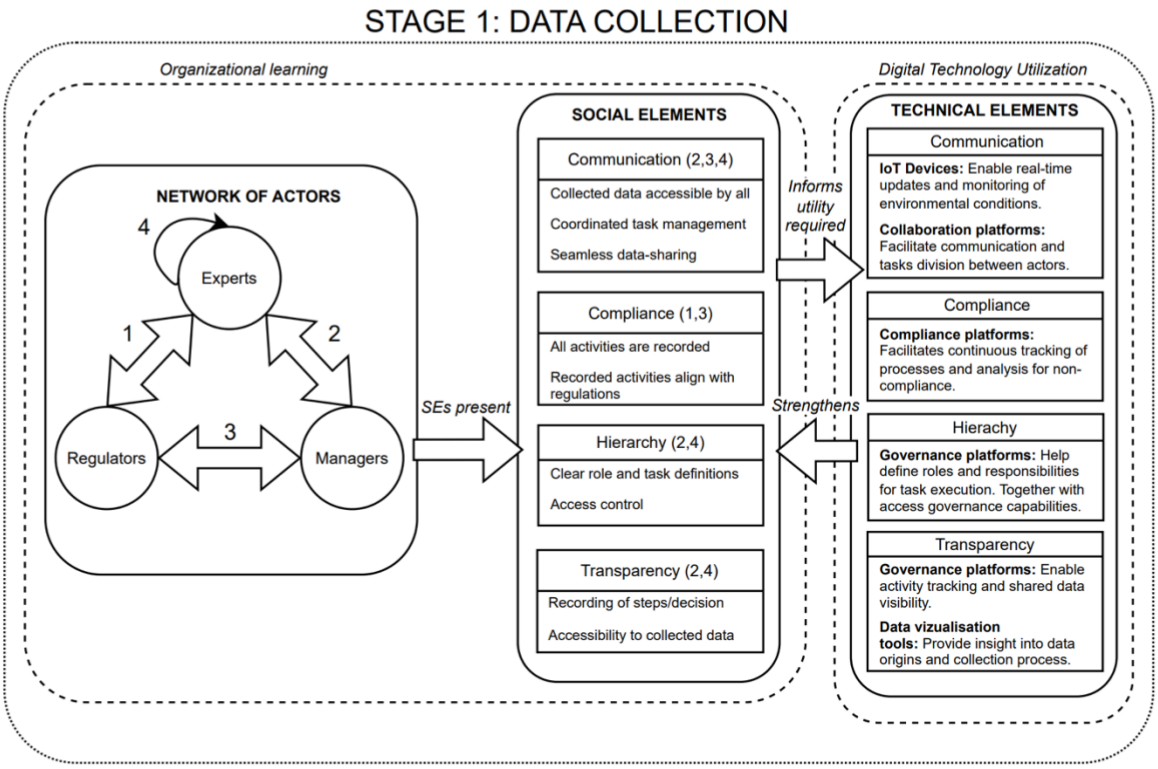

Figure 9: Stage 1: Data Collection

Demonstration

Going through the first stage, shown in Figure 9. Starting at the network of actors. Shows experts such as, engineers and data scientist, plant managers and regulatory inspectors. These actors are communicating and collaborating with each other through digital governance & compliance platforms (Gartner, 2024), (Shah et al., 2018). To make the various collected data from the Fukushima disaster accessible, supporting coordinated tasks management and seamless data-sharing. Which facilitate strong communication and clear tasks division between actors. So, the vast amounts of the Fukushima disaster data to be collected from various sources is easily appointed to the various actors assigned to data collection. And on the same platform they can share data and/or documents with each other in one place, seamlessly. These platforms can also facilitate continuous tracking of non-compliance. Helps regulatory inspectors and NPPs at the same time, to ensure that the process and collected data is in line with regulatory standards. Where the lack of compliant operations, led to the Fukushima Daiichi plant to become underprepared and vulnerable to tsunami. Furthermore, strengthening clear role and task definitions during data collection. They have the ability to provide access control to sensitive data depended on the role of the actor. Building on this, using these governance & compliance platforms. Every step and decision taken is recorded. Such as identifying data sources such as IAEA (IAEA, 2024) or the Japanese government's Earthquake Research Committee (WNA, 2024b) for disaster reports from emergency responders and governmental bodies, or the Fukushima Nuclear Accident Independent Investigation Commission (IAEA,2024). Ensuring that collection and consolidation of datasets is traceable. Coupled with data visualization tools, incorporated into the platforms (Gartner, 2024) to provide insights into the data origins and the overall process. To strengthen transparency and generate accessibility to data and a shared-knowledge base for the relevant actors.

To conclude, demonstration of the first stage validates the models' role in enhancing the learning process, by introducing a structured, digital technology supported approach to data collection. Utilizing tools such as governance & compliance platforms coupled with data visualization tools and IoT devices (Rad et al., 2021). The model is able to address gaps in the operations and learning process seen in the Fukushima disaster. Where past seismic and tsunami data were not integrated into risk models of the plant and misalignment with regulators. The structured format of the ELP-model helps ensure NPPs collect and organize historical and real-time data, enabling transparency, accessibility and traceability for pro-active risk scenario identification. Where information exchange is automated. This systematic approach provides a solid basis for learning from the past, where critical data is not overlooked.

Stage 2: Data Analysis

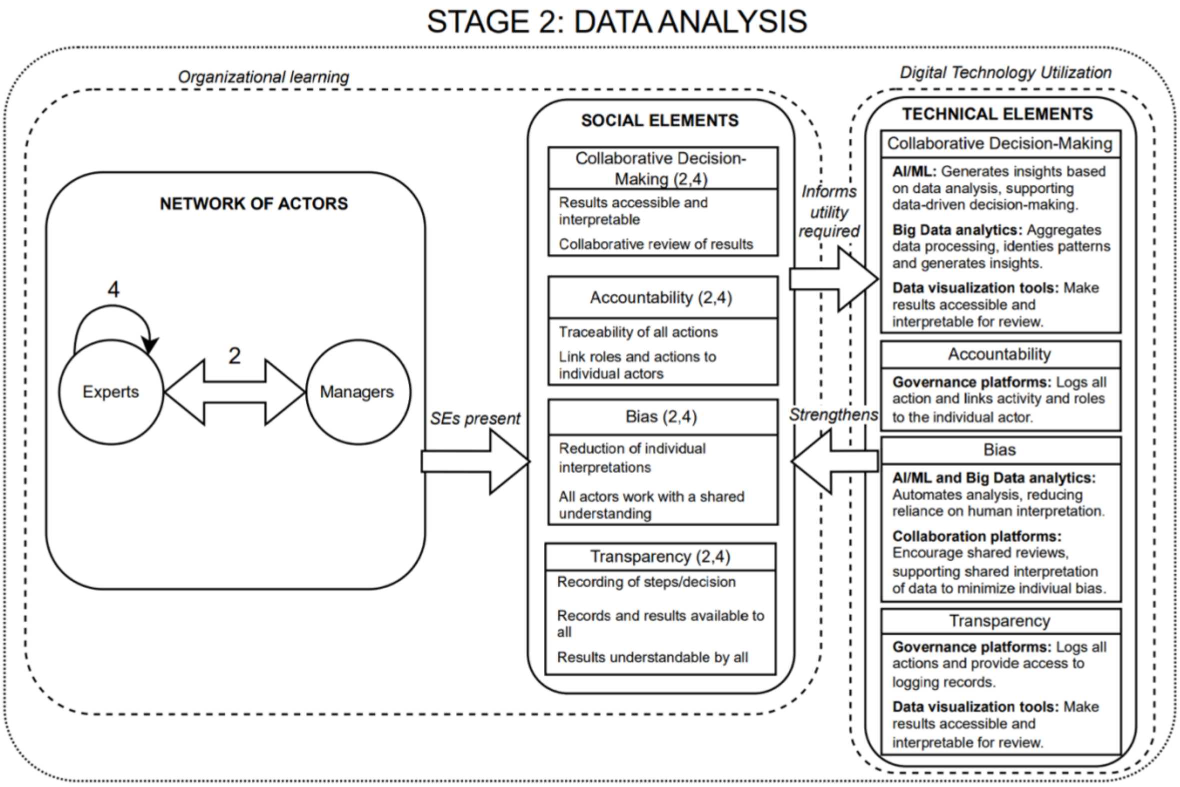

Figure 10: Stage 2: Data Analysis

Demonstration

At stage 2, shown in Figure 10, data analysis commences. The collected data from events such as the Fukushima case, as listed in the previous section is examined. This includes seismic activity, tsunami wave heights and plant operational data during the event such as reactor pressure, temperature, hydrogen build-up. As well as contextual data such as emergency response timelines, decision-making logs, and post-event reports. Regarding the Fukushima disaster as a historical event to learn from. This data help provide the foundation to understand what went wrong, and why certain cascading failures occurred leading to system failures. Data processing through the ELP-model shows how learning can be enhanced.

One of the ways the ELP-model can strengthen the learning process, is by introducing a structured aggregated approach to pattern recognition and root-cause identification. Through the utilization of ML-models or Big Data analytics tools (Argyroudis et al., 2022), to examine the collected data and extract insights on patterns or failures from the data. Thereby promoting an extensive analysis approach of why these failures occurred. Going beyond surface-level observations of the Fukushima disaster, such as the seawalls were not high enough or the generators became flooded. For example, in the case of Fukushima, the natural hazard risk assessment was based on outdated assumptions. Proved to be an important root-cause to the disaster. Historical data indicated the possibility of tsunami wave heights exceeding the existing seawall height (10 meters) from earlier events such as in 1983 (14.5-meter-high wave). Which had not been effectively incorporated into their risk assessments. Furthermore, operational data such as reactor pressure logs could be analysed to highlight critical parameters for system failure. By automating pattern recognition, digital technologies help improve the accuracy of the analysis and mitigate the pitfalls of human bias, during data interpretation. The structured analysis approach, visualized by the ELP-model enables potential root-causes, such as failure to update tsunami risk assessment, to be uncovered and addressed. Whilst reducing the influence of individual bias. Supporting objective, evidence-based learning through data analysis. Ensuring that insights and lessons generated are relevant to the context of the plant, depending on geolocation and natural hazard posing the largest threat.

Collaborative decision-making among the actors present, is visualized through the ELP-model. Which emphasize on the importance of the actors to work through a shared review of the analysis. Further mitigating individual interpretation of the data. Governance & compliance platforms that enable access to data analysis results, allowing actors to interact and validate with the insights, and collectively interpret the data. For example, engineers can assess the cascading failures caused by flooded generators, while managers ensure the alignment with operational and resilience goals. By fostering a collaborative approach, the ELP-model supports learning by ensuring a shared understanding of the lessons learned. To further support the results of the analysis is accessible and interpretable by all the relevant actors, the model proposed the incorporation of data visualization tools. Visualizations of the data in the form of charts, graphs and other diagram, allow the complex findings to be presented in a clear understandable format. For instance, a visualization of the timeline of cascading failures of the Fukushima disaster. Can help actors to engage with the results of the analysis in a meaningful way, regardless of their expertise. Thus, allowing the lessons to be communicated effectively. To support transparency and accountability throughout the process, the model proposed the use of governance & compliance platforms (Gartner, 2024), to document the steps taken. Including the logging of steps taken during the analysis and linking roles and activities to the individual actor. Going back to the Fukushima case, the assumption that the 10-meter-high seawall was sufficient would be tagged, documented and open for review. This traceability not only strengthens accountability but also lays the basis for future learning through review and iterations.

In summary, stage 2 of the ELP-model helps transform the gathered data in stage 1, into actionable insights and lessons for the NPP. By emphasizing root cause identification, cascading failures, pattern recognition, and scenario generation. Provides NPPs with a clear understanding of the historical disastrous event and uncover what went wrong and why. And how the historical event relates to their own plant. This structured analysis approach, supported by data analytics tools, collaboration platforms and visualization tools. Mitigates human biases and generates a mutual understanding among actors. To learn objectively. The Fukushima disaster exposed vulnerabilities in outdated risk assumptions. The ELP-model addresses this by ensuring systematic tagging and analysis of assumptions, making lessons more objective and transparent. And promotes evidence-based learning and its' ability to uncover and document root causes of failures for resilience enhancement.

Stage 3: Outcome Evaluation

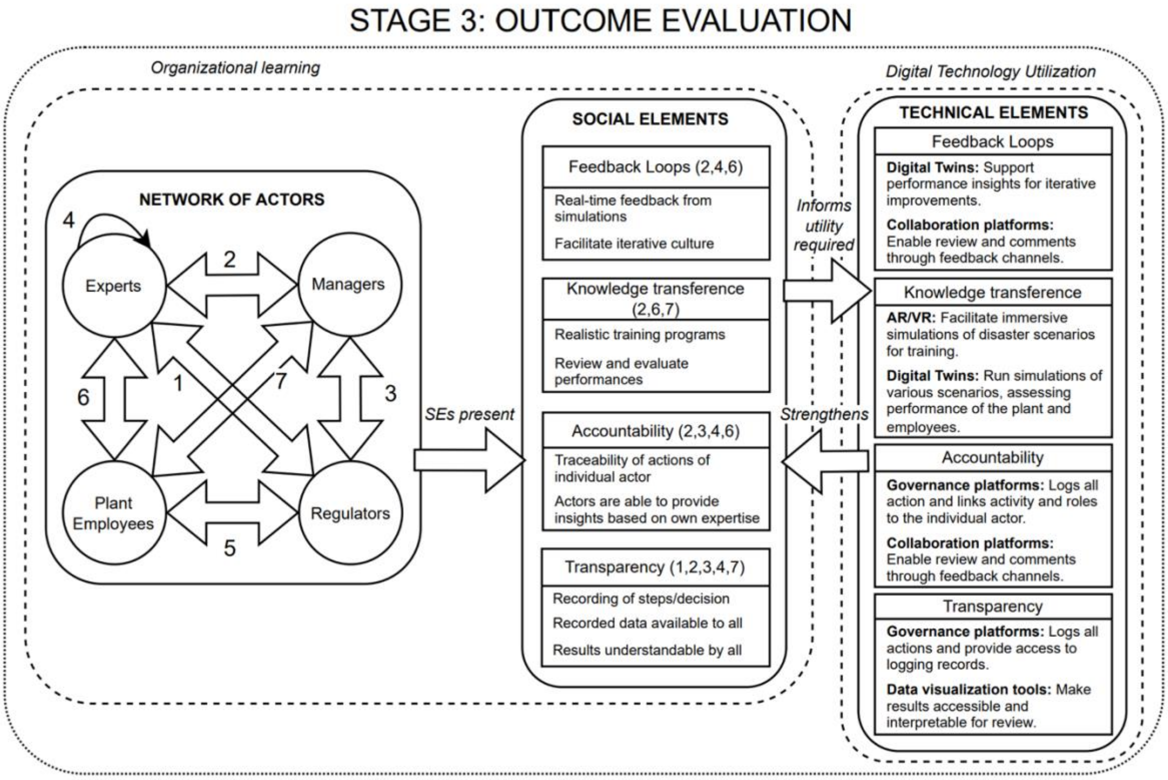

Figure 11: Stage 3: outcome evaluation

Demonstration

Building on the insight derived from analysing the collected data, the outcome evaluation commences, illustrated in Figure 11. Regarding the Fukushima case, these insights could include, the cascading failures caused by flooding, power loss resulting is cooling system breakdowns. Can now be validated using scenario simulation and performance evaluation. The model's approach supports the development of realistic and verified disaster scenarios as part of the enhanced learning process. Which can help NPPs to evaluate their own resilience performance and disaster preparedness. By replicating the conditions of historical events, such as the Fukushima disaster, NPPs can test how their own systems would perform under similar circumstances in a realistic simulated environment. Analysing the data on the Fukushima case, a scenario could be devised where a magnitude 9.0 earthquake, triggering a tsunami wave which exceeds the existing seawall height. Resulting in the flooding of critical energy and redundancy systems, causing a power loss resulting in reactor cooling failure. Leveraging Digital Twins (Brucherseifer et al., 2021), allows NPPs to model disaster scenarios in a virtual environment next to the physical and computational models already in use. And evaluate how the systems' infrastructure, such as seawalls or emergency power systems and

emergency operational protocols respond in the event of a disaster. Helping the NPP to understand its' vulnerabilities and limitations and identify where their preparedness or recovery strategies may fall short. This activity not only helps the plant evaluate the insight from stage 2 but also supports the NPP in building awareness of their vulnerabilities and refining their resilience mechanisms. Laying the basis for scenario-based learning.
Building on this, the ELP-model shows how the integration of simulation-based personnel training can enhance learning. Through enhanced knowledge transfer between disastrous scenarios, emergency procedures and plant staff. Relating to the case of Fukushima, delays in the venting of hydrogen, contributed to the eventual reactor explosions. Highlighting inadequate operational response from the plant. Based on this situation, where excess of substances needs to be removed to stop a potential explosion. Can be recreated through immersive training tools such as AR or VR (Zhu & Li, 2020)., to recreate such conditions in a controlled, virtual environment. Thus, the actors inside the plant, can use these technologies to practice their emergency responses in high-pressure situations. Thereby mitigating the change of human errors, through enhanced awareness and experience with emergency procedures. Continuous simulation of scenarios can help NPPs to not only be aware of historical disasters but also to respond effectively to similar situations in the future.

Additionally, these simulation technologies, coupled with governance & compliance platforms, help establish feedback loops, and create an outcome evaluation process that is transparent and enables actors to be accountable. Performance data of the simulations and training are logged, shared and review among actors, such as managers, engineers and data scientists, regulators and plant personnel. This feedback mechanism supports that the evaluation process itself becomes a learning opportunity. For example, if through simulation, it becomes evident that there are significant delays in the activation of back-up systems in the event of an emergency. The feedback enabled by the digital technologies, can be used to refine the emergency protocols and in turn iterate the training program. By utilizing governance platforms and visualization tools during outcome evaluation, any decision, and results of simulation or training and feedback is documented and made accessible. And making it possible for actors to review the process and assess the effectiveness of the learning process itself overtime. For example, the plants performance during the simulation and personnels ability to execute procedures successfully can be tracked over time. Thereby the improvement of the NPPs resilience and the plants' enhanced ability to turn insights into lessons and iterate accordingly, ergo the NPPs absorptive capacity, can become clear.

To summarize, stage 3 of the ELP-model demonstrates how NPPs can validate their insights gathered during stage 2. And support existing scenario-based learning by verifying the assumptions made to develop disaster scenarios. As well as evaluate plant and staff performance during simulations of potential disaster scenarios. Enabling the transition of data-driven lessons into actionable steps. Application to the Fukushima disaster shows that systematic and continuous outcome evaluation not only helps to validate findings from past events but also provides learning opportunities to refine NPP hazard and emergency procedure awareness. Improving the preparedness. For example, improve response times and mitigate human errors. The use of digital technologies such as Digital Twins, AR/VR enabled training, governance & compliance platforms. Transforms the learning process into a dynamic, continuous and iterative cycle. Ensuring that lessons learned are tried and tested, understood throughout the plant and possibly integrated into strategies.

Stage 4: Strategy Development

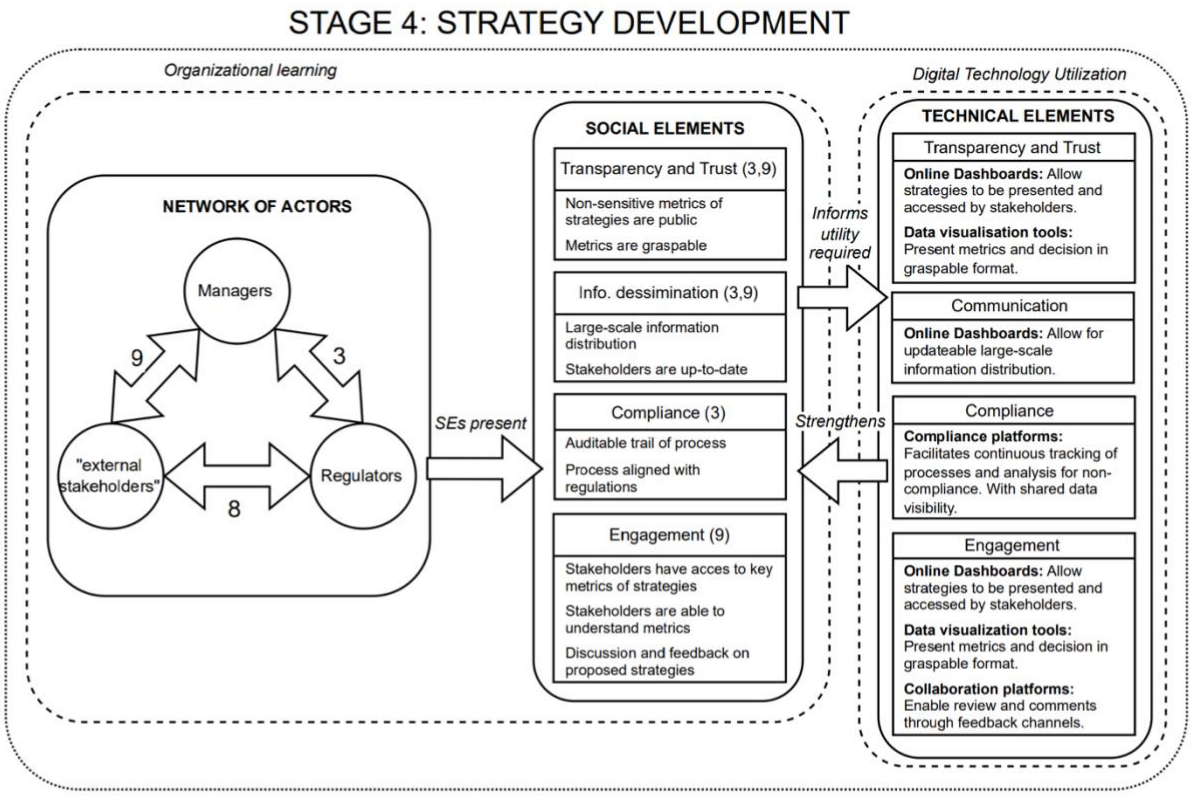

Figure 12: Stage 4: Strategy Development

Demonstration

The last stage, illustrated by Figure 12, begins with turning the lessons generated, from historical events, in earlier stages into resilience strategies. In regard to the Fukushima disaster, these insights can include lessons surrounding underestimated tsunami risks, missed opportunities in back-up energy systems or inadequate emergency protocol awareness or preparedness. Supported by the ELP-model, the NPP is able to inform their resilience strategies based on lessons learned in previous stages, in a structured manner.

Stage 4 is focused on communicating developed strategies, based on lessons learned, with external stakeholders, as well as the general public. Disseminating information on the strategies and resilience status the outside world in an automated manner. Reflecting on the Fukushima disaster, the plant operators failed to share critical information of emergency protocols, thereby hindering coordinated emergency services response. By utilizing online dashboards coupled with visualization tools to support the sharing non-sensitive metrics of developed strategies in a graspable manner. For example, progress on seawall improvements or coordinated emergency evacuation protocols. A transparent approach to strategy development enabled by digital technology capabilities, helps foster trust and demonstrates accountability to resilience from the NPPs to its surroundings.

Building on this, stakeholder engagement, can support the strengthening of the learning process. By incorporating various perspectives and requirements of stakeholders to further iterate the strategies based on their expertise and feedback. To ensure that stakeholders are well-informed on the strategies and are able to contribute and give feedback in a meaningful way. The capabilities of online dashboards and data visualization tools (Zscaler, 2024) can be utilized to present the plans for resilience in a clear and comprehensible manner. And integrate governance & compliance platforms, to allow feedback-mechanisms to occur through review and commenting by relevant external stakeholders on the presented strategies. And refine them accordingly. Regarding the Fukushima case, the lack of external stakeholder engagement, left the emergency strategies and natural hazard risk assessment largely uninformed by contextual stakeholder expertise. For example, these communication technologies support feedback channels, enabling experts to give input on natural hazard risks, evacuation planning or seawall design. To maintain alignment with regulations, governance & compliance platforms (Gartner, 2024) can be utilized to support the continuous monitoring for regulatory inspectors. By documenting the strategy development process. For example, updated risk assessment models or proposed infrastructure improvements can be tracked and validated to make sure they meet compliance and safety standards.

In conclusion, the fourth stage of the ELP-model, is aimed at enhancing learning through the formalizing of lessons generated from historical disaster data into resilience strategies that are data-driven, inclusive and adaptive. The Fukushima case demonstrated gaps in communication with actors and stakeholders and regulatory compliance. Where lessons were not effectively shared and adopted into the plant. The ELP-model addresses these opportunities by promoting the utilization of digital technologies for automated data sharing. So, the strategies are able to become not only developed through validated insights, but also through stakeholder engagement. Enabling the strategies to be supported, trusted and continuously iterated upon. For NPPs, this stage visualizes how a structured and engaging approach to strategy development can enhance the learning process and the resilience against potential natural hazards.

5.1.4 Key insights and areas of improvement for the learning process based on the case

This sub-chapter consists of two sections. First, the key insights from the application of the ELP-model to the Fukushima Daiichi disaster case. As a historical, real-world event for other NPPs to learn from. Secondly discussion is held on how the case application helps highlight areas of improvement for the learning process. Together with a discussion on how the ELP-model supports the strengthening of the learning from the past capabilities of NPPs.

The application of the ELP-model to the Fukushima Daiichi disaster highlights several areas where the learning from the past process can be enhanced. For starters, it became evident that there was a lack of historical data integration at Fukushima. Resulting in vulnerabilities in their risk management and natural hazard preparedness. Data analytics tools, such as AI-tools (e.g. ML models or Big Data analytics) can be utilized to process both historical and real-time disaster data, supporting a more aggregated data analysis process. Here the ELP-model promotes aggregated historical data processing. To generate lessons where insights from data is systematically evaluated and integrated into resilience enhancement strategies. Thereby showing promise in strengthening risk assessments and disaster preparedness Moreover, the absence of feedback mechanisms and lack of accountability, which led to cascading mistakes and unresolved safety concerns. Contrary to this, the ELP-model promotes the implementation of continuous review, traceable actions and feedback loops through the utility of governance and collaboration platforms. Therefore, supporting transparency in the learning process and upholding of actors' accountability. Creating a more safeguarded learning process. Lack of communication during the Fukushima disaster also underscored the need for internal and external communication and coordination. The ELP-model emphasizes strengthening communication through digital platform utilization, where information sharing is streamlined. As well as keeping the environment surrounding the plant informed through online dashboards, and visualization tools. The Fukushima case revealed limitations in plant and employee preparedness for disastrous scenarios due to the lack of emergency procedure planning and awareness with actors. By utilizing Digital Twins and simulation technologies such as AR and VR, NPPs can model various disaster scenarios, enabling them to evaluate plant and employee performance, training programs and refine strategies. The existent organizational culture further hindered learning and natural hazard preparedness at Fukushima. The ELP-model emphasizes the importance of establishing a pro-active learning culture. Focussed on transparency, accountability, and continuous improvement throughout the process. Insights from the Fukushima disaster highlight the need for a resilience enhancement approach that takes a shift towards a more pro-active stance to learning from the past, to ensure natural hazards preparedness and ability to withstand and recover from a disastrous event.

Moving on to the discussion on how the ELP-model visualizes a theoretical potential enhanced learning process. Therefore, bolstering the ability of NPPs to systematically learn from past event, like the Fukushima disaster. The four stages of the model, visualizes what a structured DT-integrated and STS backed, learning process could look like. Serving as an addition to existent learning processes. Where NPPs pro-actively analyse historical data, address their vulnerabilities, improve their natural hazard preparedness and iterate their resilience strategies. Strengthening the activities within the learning process, through STS theory informed digital technology utilization. Thereby aligning social and technical dimensions of the learning process. The case application has identified several areas of improvement for the learning process. Synthesizing these insights resulted in the following discussion on where the learning process can be strengthened.

First is integrating structured data management within resilience engineering. Meaning systematic data collection, aggregation and subsequent analysis, should be prioritized when developing resilience strategies. To avoid missing opportunities for risk identification. Regarding structuring data management, the ELP-model promotes data accessibility, traceability of actions and the effective integration of data for decision-making in resilience engineering. Additionally, it incorporates a collaborative and transparent learning approach. With feedback loops, collaborative and governance platforms as suggested in the ELP-model. Thus, fostering shared understanding and learning across all relevant stakeholders. Mitigating interpretation bias and knowledge gaps, whilst supporting a collective accountability among stakeholders throughout resilience strategy development. Furthermore, realistic disaster scenario creation and utilization. Disaster scenarios, based on data of historical events and real-time plant data. Not only serve to replicate past events but also evaluate the capabilities and vulnerabilities of the individual NPP. Integrating disaster scenarios in resilience engineering, as suggested in the ELP-model. Helps anticipate and understand cascading failures and address them in a structured manner. Lastly, promoting a continuously iterative approach to learning. The ELP-model emphasizes the importance of continuous iteration. Meaning that insights throughout the process are reviewed. Lessons are revisited, strategies are refined and adapted depending on the evolving risk assessments and organizational context.

To conclude, the application of the Fukushima case to the ELP-model, helps validate the model’s visualization of a structured learning process and ability to identify and address gaps within the existing learning from the past process. With its’ emphasis on utilizing digital technologies to enhances this process in a systematic and continuous manner. The case study has demonstrated the integration of digital tools with an socio-technical approach has the potential to improve the ability to learn from past disaster and inform the development of sophisticated and adaptive strategies. Through enhanced data collection and analysis, collaborative and iterative operations and scenario-based learning. The model supports the enhancement of organizational learning by structuring this process. Building the foundations for a learning process in the form of a technical guideline. For NPPs to strengthen their resilience practices. The insights discussed in this sub-chapter underscore the validation of the general objective of the model to help transform historical events into actionable learning opportunities.

5.1.5 Value of the model

This sub-section discusses the theoretical value of the ELP-model within the context of resilience learning from the past, particularly compared to existing studies on the Fukushima disaster and traditional learning processes. And how the ELP-model helps extract insights from a historical event, in this case the Fukushima disaster, that go beyond other analyses on the case. Through a structured visualization of an iterative and transparent learning process, the model has unique contributions to offer, to a NPPs ability to extract lessons from past events. And shows how the ELP-model attempts to shift the current learning process to a more pro-active and rounded approach, through DT support and STS theory application. This section highlights its' value and how the model's structure, based in socio-technical alignment and digital technology utilization, lays a basis for a learning process guideline, for enhancing NPPs systemic resilience against natural hazards.

The ELP-model visualizes a comprehensive approach to learning from the past. Transitioning from reactive (Pęciłło, 2020), (Cantelmi et al., 2021), (Thomas et al., 2019), (Awad & Martín-Rojas, 2024) to pro-active learning mechanisms. Unlike such previous studies, that have emphasized on one specific component of resilience, such as technical or infrastructural resilience. Without regarding resilience and reflection on the past (i.e. learning) as a broad concept that can influence various parts of the NPP. Not only technical or infrastructural, but also on a procedural or organizational level. For example, post-Fukushima studies often focus on technical solutions, such as increasing seawall heights or back-up generator placement, without addressing cascading effects (Lipscy et al., 2013), (Moglen et al., 2024). Or investigate root-causes to the accident without considering factors of the broader context as demonstrated by Hollnagel & Fujita, (2013). Without the consideration of socio-technical dimensions. The ELP-model emphasizes the importance of structured learning when attempting to enhance resilience. And focusses on the integration of historical data, both data on natural disaster properties as well as back-up system vulnerabilities and disaster reports, to increase the knowledge base onto which lessons are learnt from. And attempts to overcome data quality and organizational barriers to learning (Fanelli et al., 2022), (Wang et al., 2018), (Tabesh et al., 2019). Thereby supporting the creation of multi-faceted strategies that cover all aspects of resilience engineering as understood by Petrenj et al. (2018) and Mottahedi et al. (2021).

The model advocates for the integration of both real-time monitoring and historical data analysis, for a dynamic learning approach. By utilizing the capabilities that IoT devices, AI-driven tools, digital platforms coupled with simulation technologies have to offer in a consolidated synthesized approach to address learning. Allowing a NPP to contextualize disaster scenarios, specific to each plant and its' environment. Overcome points of improvements for data interpretation and knowledge-sharing. Enhancing the applicability of lessons to inform resilience strategies. The model enables the simulation of scenarios to identify cascading failures. When looking at those observed before and during the hydrogen explosion at Fukushima, providing insights into the weaknesses of the plant, going beyond investigating the inadequacy of existing risk assessment in the form of seawall height or back-up generator placement (Murakami et al, 2021). Thereby helping the NPP to identify weak spots in their own operations, when running these verified simulations enabling scenario-based learning, that otherwise would not be uncovered by merely adjusting the seawall height for example, as a reactive measure.

Furthermore, as iterative and continuous improvement is a central part of the ELP-model. Through DT-enabled review and feedback mechanisms. Thus, allowing for continuous refinement of resilience strategies. Contrarily to a more static analysis approach of other studies, emphasizing revisiting lessons and refining strategies where other case analysis approaches offer a "one-time" critical analysis of the event and identify missed opportunities on a particular facet of the disaster (Yamashita & Takamura, 2015), (Lipscy et al., 2013), (Murakami et al, 2021). The model promotes the continuation of the cycle after a strategy has been developed and to go back to the data collection stage. As continuous iteration is an important part of resilience building (Hollnagel & Fujita, 2013). And the model understands that the industry itself benefits from compliance governance, where effective developed strategies can in turn inform sector-wide policy or regulations.

Also, the ELP-model uniquely adopts an STS perspective to the learning process itself. By integrating digital technology capabilities with social dimension objectives. Such as stakeholder engagement, accountability among actors and transparent practice. Other studies have also emphasized on the importance of integrating both human and organizational factors within nuclear safety (Schöbel et al., 2022 + (Dainoff et al., 2023), (Thomas, 2017), (Azadeh et al., 2015), (Tabesh et al., 2019). And other studies have explored the advantage of digital technology integration when aiming to enhance resilience of NPPs (Kropaczek et al., 2023), (Argyroudis et al., 2022), (Yan et al., 2023), (Gohel et al., 2020). However, the ELP-model uniquely bridges the connection of human/organizational factors with digital technology utilization to address enhanced learning for resilience enhancement against natural hazards within NPPs.

Additionally, when compared to existing analyses of the Fukushima Daiichi disaster, highlights the lack of a holistic approach, incorporating an STS perspective to resilience learning. Lipscy et al. (2013), (Hollnagel & Fujita, 2013) or Murakami et al., (2021), highlight vulnerabilities in generator placement and seawall heights. Girgin et al. assessing the cascading failures that occurred during the disaster. Advocating for the inclusion of a NATECH risk assessment on national level, however, does not integrate socio-technical aspects in doing so. Similar to Misuri & Cozzani, 2024, proposing a resilience strategies framework, without considering socio-technical dimensions. And Kawane et al. (2024), focus on disaster risk reduction from a social systems perspective, even considering the advantages of digital technologies, without systematically integrating them into a learning process, like the ELP-model does. Or such as, Yamashita & Takamura, (2015), analyzing root-causes of the hydrogen explosion at Fukushima, however omitting the analysis of contextual factors leading up to the explosion. Comparatively, the ELP-model incorporates such findings, from an STS perspective, into a structured iterative theoretical learning process. Through the leveraging of digital technologies, enhancing plant and employee resilience learning through simulated scenario-based learning, documentation of results for review and refinement. Thereby enabling insights to be shared among actors, turned into lessons and transformed into effective resilience strategies.

Furthermore, the comparison of the ELP-model analysis of the case with other works, has shown that traditional resilience learning focusses on static reports and disaster evaluation. Whilst the ELP-model promotes the importance of continuous learning and iteration through digital technology supported enhanced data processing and insight generation. Giving NPPs the guidance to adapt based on various disaster scenarios and to learn from them in a holistic manner. Supporting the actors within to make data-driven decisions on resilience strategy enhancement. Moreover, it became evident that standard frameworks compared to this study, often overlook the integration between human and technological factors. Whereas the ELP-model is grounded in social and technical dimensions alignment. Which enables the improvement of the overall learning process. Additionally, if compared to a DT-supported, traditional learning process without the perspective of STS theory, certain differences arise. Highlighting that simply adding DTs to the learning process is not enough, and warrant the adaptation of a integration framework, such as STS theory. For example, AI-capabilities offer the analysis of past tsunami events, and can predict risks based on historical data. Simulation technology such as a Digital Twin can simulate plant behavior during seismic events. Without STS integration, as done in the ELP-model. Decision-making may remain top-down and learning based on risk assessment static. Where human factors such as organizational culture, collaboration and emergency coordination may not be fully adjusted and integrated into the resilience enhancement. Where the strategies may not be adequately improved due to the lack of feedback mechanisms. The ELP-model ensures that the resilience learning process becomes data-driven, human-centered and continuously iterative. Supporting the efficient adoption and integration of DTs into the learning process through alignment of social and organizational elements with these technology.

In conclusion, the ELP-model demonstrates its' potential to enhance traditional learning and form the basis for an enhanced learning process guideline, by addressing gaps within current learning from past disasters and resilience practices. Taking a novel STS perspective to align social facets with the utilization of digital technology capabilities within the realm of resilience learning from past disasters within NPPs. Supporting a plants ability to reflect and extract lessons from past events, such as Fukushima. Thereby facilitating improved organizational absorptive capacity. Through a structured, iterative approach to enhance the learning capabilities of the NPP to prepare, withstand and recover from future natural hazards. Supporting the enhancement of NPP resilience.

5.2 Expert consultation

This subsection represents a consolidation of the expert consultation session performed. To verify and validate findings and results of this research. Where the main take-aways and insights generated from the literature synthesis, in Chapter 3. And the ELP-model, in Chapter 4. Were reviewed by the expert. Additionally, the propositions developed in this study, which will be discussed in Chapter 6.2, were reviewed by the expert and discussed during the consultation. The session provided valuable additional insights on top of the literature synthesis and the case-based evaluation. Adding to the strength of the research and its' outcomes.

The consultation was conducted with an experienced and expert in incident learning, risk assessment and crisis management within the nuclear industry. Providing a valuable external perspective and input from practice regarding the results of this research and the proposed theoretical learning process model.

Expert verification

The consultations main focus was on verifying of the research findings and validation of the outcomes, and whether they aligned with real-world practices and challenges. Serving as an important part of the validation process, the practical applicability of the outlined theoretical learning process. The expert's feedback confirmed several theoretical insights generated in this study. Particularly regarding the (systematic) resilience learning processes, the integration of digital tools, and data-driven decision-making in the nuclear industry. Moreover, the consultation session reinforced this research's stance on the value of structured learning mechanisms. Highlighting both strengths and potential points of improvements for the industries learning practices.

The session also gave feedback that underscored the value of systematic learning processes and the utility of digital technology adoption. In strengthening the effectiveness of historical incident-based learning. While current practice involves some form of structured safety and risk assessments, they are still largely reliant on periodic check-ins and human intervention on the reporting of an incident. And rely on manual filtering and expert judgement in evaluating the relevancy of historical event data. This was mentioned as a point of improvement, where digital technology has value to add. The expert confirmed that digital platforms, such as those discussed in Chapter 3 and 4, could support systematic and automated information exchange. As well as other digital tools, such as AI-driven technologies, to support pattern recognition, and data accessibility. Fostering cross-organizational learning and data exchange, ultimately strengthening NPP resilience.

Another valuable feedback was the recognition of the use of simulation tools already in use within the nuclear industry. Through the use of probabilistic failure models and physical training simulation. However yet, the validation of scenarios onto which these simulations are based, remains an area for improvement. The expert discussed the need for addressing the front-end of scenario-based learning, particularly to verify whether assumptions made on failure point inside the NPP. And the particular impact/consequences of a (natural) hazard, and to what extent they align with real-world disaster scenarios. For example, current simulations are done on the assumption that if for instance a tsunami wave of x height strikes the plant, system 1 and 2 or a particular building is damaged. However, the verification of the assumption that in fact system 1 or 2 fail, or damage to a particular infrastructure happens, is lacking. Additionally, the back-end evaluation of the simulation outcomes could benefit from further digital technology utilization. To further extract lessons and uncover actionable insight on performance to strengthen the learning process. Lastly, the expert recognized the value of automated resilience strategy metrics distribution with external stakeholders and underscored that the current process does not include status boards and automated information distribution.

Practical application of ELP-model

An important outcome of the expert consultation on the validation of this research, revolves around the recognition that the ELP-model, has real-world applicability. And it was discussed that the practicality of the ELP-model is viable and has value to add to the existing learning processes. As it should be positioned as an addition but not a replacement. Noting that the industry is quite sophisticated in their learning processes and operate under strict regulatory frameworks. Meaning that any new system or mechanism should integrate into, rather than replace existing mechanisms. Presenting the model as an augmentation or addition to gain traction and mitigate resistance to adoption. The model holds real-world value, if further developed, and could serve as a technical guideline to improve systematic learning capabilities of NPPs. And can be offered as a structured approach for NPPs to implement at their discretion, aligning it with their internal resilience strategies and compliance requirements. It was also noted that to develop the model effectively, it should be developed together with experts on the technical level who have experience with the learning process. Since they have a clear overview of what needs further addressment. And who'll be able to collaborate with data experts to construct the model as a technical guideline in such a way that it is able fit within existing processes.

Propositions

The discussion regarding the validation of the propositions and their practical applicability and value to explore them further, confirmed several insights. Digital technologies indeed show potential to enhance learning processes, by adding to the usability of data and strengthening the learning capabilities. However, digital adoption should not replace current practices. Especially expert judgement. The expert supported the idea of digital technology adoption and that digital tools can help with pattern recognition, enhanced data accessibility and facilitate knowledge transfer. However, the need for human oversight remains. The expert confirmed the importance of supporting the actors within learning processes to work under a common language. Emphasizing the importance of a shared-knowledge base between actors for effective collaboration. And recognized that a digital platform that enables this is desirable. Furthermore, confirming that data quality and complexity are limiting factors. Acknowledging that the effectiveness of digital tools is highly dependent on the accuracy, completeness and categorization of incident data. It was also mentioned the exploration within the industry on the AI-capabilities to overcome poor data quality, by aggregating data analysis and pattern recognition where AI-tools can still extract lessons and actionable insights. Additionally, the expert recognized and confirmed that a structured learning mechanism, according to STS theory principles, where social factors influence digital tool utility supports the strengthening of the learning culture and the learning process itself.

In conclusion, the expert consultation provided valuable feedback into verification of the research findings and outcomes. Confirming that the resilience learning environment as laid out by this research is indeed close to reality. And helped validate this research, the model and its' propositions and recognize the practical applicability of the ELP-model, as the foundation for a technical learning process guideline document.

Chapter 6: Discussion

This research is aimed at addressing the resilience enhancement learning process within nuclear power plants, in the face of natural hazards. Through a comprehensive and systematic review of the literature, three main knowledge gaps emerged regarding the main objective of this study. Firstly, the lack of systematic and holistic learning-from-the-past mechanisms to enhance resilience within NPPs. The underutilization of digital technologies to support the learning process. And the integration of a socio-technical systems perspective on the resilience learning process within NPPs. To address these identified gaps, this study has aimed to lay the groundwork for a learning process for resilience enhancement guideline. In the form of an enhanced learning process (ELP-model) approach for resilience enhancement within NPPs. Integrating an STS perspective to construct the model, integrate digital technologies and align them with social dimensions within the learning process. To assess the feasibility of application of the proposed approach, a case-based evaluation was conducted on the Fukushima Daiichi nuclear disaster, as a historical event, which NPPs learn from. Serving as the bridge between theoretical foundation and application. By demonstrating the ELP-model using the case. Coupled with an expert consultation, to verify the findings on areas of improvements for the resilience learning process within NPPs. And further validate the practical feasibility of the devised model, to serve as the foundation for a technical guideline.

This chapter discusses the insight, findings and outcomes generated throughout this study, reflecting on the research objectives and questions posed in Chapter 1. Additionally, the theoretical and practical implications of the results of this study are discussed within the broader context of this research. Moreover, reflection on the employed methodology is done, acknowledging limitations. Lastly, propositions for further studies are laid out. As well as recommendations for the continued development of a learning process guideline for natural hazard resilience engineering within NPPs.

Addressing the research questions

The development of the ELP-model required the answering of the sub-questions as outlined in Chapter 1.6. The SLR and subsequent literature synthesis provided this research with the knowledge foundation to develop the theoretical potential enhanced learning process approach in this study. The research was designed to answer the sub-research questions through a combination of literature synthesis, case-study and expert consultation.

SRQ 1: *What gaps exist in current resilience engineering learning processes within NPPs and what are the barriers to learning from the past?*

This question is primarily answered through extensive investigation of the literature surrounding resilience engineering and organizational learning. To gain an understanding of resilience learning processes within NPPs. Through the SLR, the study explored and identified existing resilience learning practices. And analyzed their shortcomings. This included the review of resilience engineering frameworks, organizational learning practices and regulatory policies relevant to this study. By categorizing the findings from the literature into key themes. As delineated in Chapter 2.2 and Appendices A.2 and A.3. Through the review and subsequent synthesis, this study was able to highlight recurring challenges in learning from past disasters. Such as fragmented learning and knowledge management, underutilization of digital tools, insufficient feedback mechanisms and stakeholder engagement. Comparing existent resilience frameworks, the research was able to assess to what extent structured learning occurs within current practices, to evaluate the present knowledge gaps in the resilience engineering and barriers that hinder effective learning from the past. To understand what needs to be addressed by the proposed enhanced learning process. Furthermore, the case-study was in part performed to validate the identified points of improvement for the traditional resilience learning process. By comparing existing works and analyses of the Fukushima case, to the ELP-model. To validate how this model moves away from contemporary frameworks and takes a comprehensive and pro-active approach to resilience learning from past disasters. Lastly, to verify the findings from the literature synthesis, the consulted expert provided feedback on the learning process as outlined by this study.

SRQ 2: *Which digital technologies can be utilized to address these challenges and enhance historical disaster data processing and improve resilience strategies?*

This question was addressed by reviewing the literature on digital technology utilization in the context of resilience engineering within NPPs or CIs with transferable insight to the realities of an NPP. This study and its' SLR contained an extensive exploration of digital technologies with potential applications within resilience learning. Such as, AI-driven tools, Digital Twin technology, and collaborative and governance platforms. By integrating findings from SRQ 1, the study assessed which digital tools could specifically address or mitigate identified learning barriers. Aided by STS theory to align technology with learning needs. Thereby creating an understanding how the ELP-model can be developed. By aiming to improve historical data processing, and absorptive capacity for resilience strategy enhancement. Additionally, the case-based evaluation aided in the demonstration how DTs could enhance resilience learning from past disasters. By analyzing the Fukushima Daiichi disaster. Lastly, the expert consultation provided feedback on the applicability of digital technologies in resilience learning within the nuclear industry. Verifying the utility of the identified technologies and how they are applied in the ELP-model.

SRQ 3: *How can digital technologies be integrated into a learning mechanism to strengthen learning capabilities through enhanced historical data-driven decision-making, and inform resilience strategies?*

Was answered by drawing on the insights gained from the literature synthesis. To develop a theoretical potential enhanced learning process. This ELP-model was conceptualized as a multi-stage process that systematically integrated DTs for the strengthening of resilience learning. Based in STS theory, to ensure that technology adoption is in line with organizational and social factors. Meaning that digital tool integration is not isolated but embedded within organizational processes. The four stages of the model (Data Collection, Data Analysis, Outcome Evaluation and Strategy Development) were designed to visualize the resilience learning cycle. Ensuring lessons generation and extraction from historical data by systematically integrating digital tools. These DTs were mapped to specific stages in the model and it was described how they are able to facilitate enhanced data processing and learning, as well as data-driven collaboration and decision-making. Furthermore, to demonstrate the model's application the Fukushima disaster was used as an illustrative case study. And subsequent evaluation demonstrated how DTs have the potential to improve resilience learning if integrated into a learning mechanism according to STS principles. The expert consultation feedback helped verify that the proposed integration of DTs and enhanced learning process is in line with practice. And recognized the model's alignment with industry needs.

Literature synthesis

From the extensive review of the literature, performed in this study and synthesized in this report in Chapter 3. To answer the two sub-questions mentioned above. Multiple insights were generated on the current status of resilience engineering and learning processes within NPPs and knowledge gaps within. Together with limitations and barriers to learning from the past and strategy adoption. The SLR revealed that current resilience engineering practices mainly revolve around reactive, event-driven learning. And the notion of iterative and continuous learning, as part of resilience engineering is still sparsely touched upon within the literature. Regulatory frameworks and policy directives recognized the importance of learning from the past but where they lack is in the adoption of structured, continuous and systemic mechanisms for learning for historical disaster data. These insights encompass the answer to SQR 1. The gaps and barriers identified will be further synthesized later in this discussion. Furthermore, while digital technologies have been explored widely in the literature, their utilization within policy and practice remains underrepresented. Therefore, this study has investigated the digital technologies that show potential for utilization within resilience enhancement, as considered by the literature. Which are extensively discussed in Chapter 3.5 with an overview of the identified digital technologies given in Appendix B.2. Thus, answering SQR

2. This imbalance highlights a gap between research literature and practical implementation. Where several opportunities to integrate digital tools to support resilience learning-from-the-past processes, within NPPs in the face of natural hazards were identified. To bridge this gap, this study has attempted to lay the groundwork for the development of a structured learning guideline. Leveraging digital technologies to strengthen social and organizational dimensions within learning, and support actors within the process for resilience strategy development.

As mentioned before a distinct and systematic learning process guideline aimed at learning from historical disaster data taken from various NATECH events and other disasters. To enhance the natural hazards resilience of NPP systems leveraging digital tools has not been addressed in the published directives and guidelines. Additionally, the perspective of nuclear energy differs a lot between nations in the EU. Which might hinder progress in terms of safety and resilience. Where fostering trust, through transparency and publicizing developed resilience enhancement strategies might help generate traction for support of nuclear energy. The resilience engineering landscape suffers from the variability within its' practices and approaches (Mehvar et al., 2021). Highlighting the importance of systematic, semi-formalized approach to resilience enhancement learning. As underscored by the expert. These inconsistencies can cause problems in areas prone to natural hazards such as earthquakes and tsunamis, where the disastrous effects are high (Sänger et al., 2021). Building on the rationale for a systematic learning mechanism. The literature emphasized that the complexity CIs interdependencies. Leading to vulnerabilities that are not immediately apparent. Where a disruption could create cascading effects in other CIs and society (Mottahedi et al., 2021). Therefore, informing outside stakeholders on risk and resilience development, allowing them to provide input, ensures that the broader grid of CIs and society is better safeguarded. The ELP-model addresses this by underlining the importance of resilience strategy information dissemination. So that the NPP and its' surroundings may become coordinated with each other, fostering collective resilience.

Stakeholder engagement

Exploring the stakeholders surrounding the plant helped understand their involvement with the learning process and the importance of their engagement for effective strategy development and adoption. Where a collaborative approach to the learning process can lead to greater operational efficiency. When every actor present is able to communicate on the same level and with a shared knowledgebase. An interesting insight emerged regarding resilience learning enhancement from the stakeholder analysis. Stakeholder with a high-level of influence, such as regulators, may hinder the learning process in some degree. Due to them imposing stringent regulatory frameworks. Regulations are an essential part of the safeguarding of the industry and its operations. However, due to their potential rigid structure, may also delay adoption of new strategies thus reducing flexibility within resilience learning enhancement. Contrasting, lower-power stakeholders such as plant staff, despite them possessing less formal authority, are able to provide invaluable insights on resilience and the learning process, due to their hands-on experience and direct engagement with strategies or resilience practices. Which highlights the importance of engaging with actors on all levels of the operation. And supporting systematic feedback mechanisms, allowing actor to provide their input, regardless of formal authority. Thereby opening the door to adaptive learning which can improve the resilience strategies. Which the ELP-model aims to address to integrating the capabilities of digital technologies for facilitating feedback mechanisms. The literature synthesis (Aitsi-Selma et al., 2016) and the expert consultation have highlighted the importance of compliance with regulators on best practices, when aiming to learn from the past. From this a crucial distinction emerges and shows a multi-layered learning process. On the one hand there are regulators who operate at an industry level, driving safe and resilient practice compliance and learning from outside of the plant. To ensure that lessons from the past are integrated on industry wide. An on the other hand there are plant staff, on a system-level, driving experience-based learning, which enhances the adaptability and alignment of strategies with the realities of the plant. It needs to be understood that these should not work as opposing forces, and a balance should be struck between the two. While high-level stakeholders mandate safe practices and learning, there should be a space to improve the individual plants' adaptability and preparedness to hazards most relevant for the particular plant. Where lower-level stakeholders actualize these imposed practices. The resilience learning process should facilitate an interaction between these stakeholders, where they are able to inform each other, further developing the sophistication of resilience strategies.

Barriers

By synthesizing the literature of organizational learning (from the past) and resilience engineering in NPPs, various barriers to effective learning from the past emerged. This was done to directly answer SRQ 1. The complexity of NATECH events, play a large role in hindering learning. The unpredictable and multi-layered nature of these events complicates structured learning from these events. This goes hand-in-hand with another barrier identified, poor data quality and management. Due to the complexities and disastrous nature of these events, data gathered and reports on these incidents can be fragmented. The literature highlighted the lack of systematic approaches to capture, process and evaluate disaster data. The ELP-model developed, aims to address this by proposing a systematic approach to learning from the past. And even though poor data quality might hinder the utility the DTs might have to offer. AI-driven data analytics have to ability to aggregate data analysis and overcome gaps in datasets. Having the ability to recognize patterns and extract insights from fragmented data. Enabling lesson generation informing resilience strategies.

Another important barrier identified is the limiting role that organizational inertia plays in learning from the past and strategy adoption. The resistance to adoption of new practices or technologies within an organization slows down the integration of effective learning approaches. Highlighting the importance of a continuous learning and iterative organizational culture. And it is up to leadership to facilitate such a culture. The ELP-model aims to overcome this by facilitating continuous iterations and this study regards learning as a continuous process, which is reflected by the way the model is visualized. Furthermore, to support a culture of learning, the model integrates feedback mechanisms, to ensure results are review, and learnt from, facilitating iterative input. Helping to inform well-informed data-driven resilience strategies. New strategies, process or technology implementation may require a large amount or resources (knowledge, time, financial etc.). So increased complexity, especially DTs can cause significant barriers to adoption. Therefore, it is imperative to develop a learning process guideline that does not change current practices but is able to build on top of it. And it is important that it is understood as an addition not a re-arrangement of the learning process. This resistance mindset comes from several factors; reluctance to acknowledge past failures, resource cost of implementing a new approach, (over)confidence in existing strategies and systemic commitment (Moradi et al, 2021), (Moniz et al. 2023). The expert consultation underlined this.

Lastly, a main barrier to learning was identified as cognitive bias. Human-actor interpretation bias and judgement can hinder learning. Highlighted by the expert, current resilience learning practices, and historical disaster data analysis is reliant on expert judgement and manual labour. Which introduces the possibility of biases, where critical data or pattern may be overlooked. The ELP-model incorporates AI-driven data analytics, to support actors in their data analysis processes. And can serve to verify or support human insights and assumptions. Furthermore, to ensure the actors collaborate with a shared-knowledge base, mitigating individual interpretation bias, the ELP-model proposes the integration of digital platforms to support collaborative efforts. Serving as a means for ensuring data accessibility and visibility, coupled with data visualization tools. To ensure the data, and analysis results are graspable and interpretable by actors of varying expertise.

Additional insights

Another interesting insight from this research is the trade-off dynamic between transparency and knowledge or access control. It became evident that transparency and accountable operations is supportive of trust building, fosters collaborative decision-making and ensures that insights and results from historical data processing are effectively shared and integrated. However, due to the nature of the nuclear industry, regarding sensitive information and safeguarding operations. Full transparency is not always feasible, and some hierarchy and sensitive data access control is warranted. However, as underlined by the expert, knowledge and data sharing are vital to an effective learning process. Where varying experts need to collaborate using a common language during resilience strategy decision-making. Creating the challenge, where too much transparency may pose security issues, and too much restriction causing hindered collaboration and learning. The ELP-model enables this by proposing the integration of digital governance platforms, that allow for role and task division, with accompanying data access, depending on tasks and level of clearance.

Another interesting insight revolves around the counter-intuitive aspect of learning in resilience engineering. Is the role of individual human interpretation and accompanying bias. Bias can hinder the learning process. When set beliefs and subjective judgement may lead to important insights overlook. And when reliant on manual labour for data analysis, insights generated may focus on expected outcomes. Here, digital technologies offer a way to overcome these biases, through AI-driven data analytics, to provide objective, aggregated, data-driven insights. Highlighting trends or pattern, that may be overlooked by actors. These digital tools such as ML models, support an automated and systematic data processing approach to learning from historical disaster data, where areas of improvement within the plant may be highlighted. However, as highlighted by the expert, human expert judgement remains a vital part of the resilience learning process. Due to their expertise and contextual understanding and providing oversights. Therefore, a DT-integrated learning approach should facilitate the collaboration between human actors and digital systems. And allow for the combination of data-driven and human insights. The ELP-model facilitates this by making the data and results accessible to actors via digital platforms for them to interact and collaborate with the data.

Additionally, it was found that compared to other DTs, digital platforms, specifically governance & compliance platforms are less considered in literature. Even though from considering the STS perspective and expert input, have value to add. Since they address many social and organizational facets. And enable an important part of resilience learning as highlighted by the expert, efficient collaboration with shared knowledge, data security and result review for lesson generations. As well as automated systematic compliance. Coupled with the challenges identified existing within the NPP resilience learning processes. And the social factors influencing learning. The potentials of leveraging of governance & compliance platforms emerged as a strong way to address those. Since we are looking at the learning process on a systems level, with the STS perspective, the study appreciates the human and social dimensions side of the learning process, and digital tool adoption. They have been addressed in literature, as more streamlining information exchange is important. But not integrated into the literature as extensively as the other DTs. Showing how considering socio technical factors is very valuable when aiming to address resilience.

The STS theory application approach

The application of the STS approach to resilience learning is two-fold**.** First, analyzing the literature from an STS perspective, secondly by developing the ELP-model that aligns with the theoretical framework.

STS theory is used to analyze the synthesized literature. By exploring and identifying the sub-systems of the learning process. Including the actors, social and organizational dimension, combined with the technical elements (i.e. the digital technologies). Which play an influential role in shaping learning capabilities. Thus, building a theoretical knowledge foundation that informed the development of the ELP-model. Ensuring digital technologies are integrated in such a way that they support the social elements present in the learning process.

Additionally, analyzing the literature from an STS perspective has shown that its' application within resilience engineering and learning literature remains underrepresented. Where the resilience learning process is not yet considered as an STS. Furthermore, as mentioned before in Chapter 2.3, a clear consensus on what is considered as a socio-technical system is lacking. Leading to varied interpretations. Making the application of the theory dependent on the perspective utilized**.** Without a well-defined scope, the lack of clear definition can hinder practical application of STS theory within resilience learning literature. This study aims to address this gap by explicitly defining the socio-technical boundaries of the learning process. And aims to add to the literature by taking the STS perspective to the learning process and utilizing it to outline the learning process, and its' subsystems. Delineating the key subsystems (actors, social and organizational structures and digital technologies) within the resilience learning process. One of the key contributions of this study is demonstrating how STS theory can be utilized to structure a resilience learning process and integrate digital tools within effectively. Thereby addressing SRQ 3.

By employing the STS theory framework, as outlined in Chapter 2.3. This study was able to develop a structured learning process model, that facilitates the systematic integration of DTs into resilience learning. Structuring learning as an interconnected system composed of actors, social and organizational dimensions and digital technologies. Furthermore, the application of STS helped underscore the importance of aligning technology adoption with social and organizational factors and dynamics, rather than isolated technology addition.

The literature synthesis has shown that current resilience learning literature lacks a formal STS-integrated model. Existing studies often address technical aspects of resilience or social-organizational dynamics of learning. But their interaction as a holistic system is rarely considered. This study shows how STS theory can contribute to resilience by ensuring technology adoption aligns with social and organization factors. Thereby supporting the effective integration of digital tools. Moreover, STS theory has helped to develop the model in such a way that digital tools are able to enhance learning and decision-making rather than override human actors. By strengthening relationships between social and technical sub-systems, in accordance with STS theory. It can help improve the decision-making process, by addressing the dynamic between human actors and the learning process itself. Supported by digital technologies, collaboration and communication between actors is enhanced. And encouraging feedback mechanisms. By allowing them to work under a shared-knowledge base, making data accessible and visible. Enhancing the knowledge generation and retention capabilities. Thus, ensuring that actors are able to review data, insights and results and interact with it. To shape and inform the NPPs resilience strategies.

STS theory was particularly useful in identifying the subsystems from the literature synthesis. And within the ELP-model the mapping of the relationships between the social and technical elements. Making it clear that successful integration of digital technologies in resilience learning relies on the joint optimization of both social and technical sub-systems. This perspective helped build the ELP-model by ensuring that the digital tools proposed do not offer standalone solutions but as embedded components that serve to strengthen learning.

The ELP-model

The ELP-model was designed to address the gaps identified in resilience learning by proposing a structured learning mechanism that integrates digital technologies in alignment with socio-organizational dimensions.

Theoretical foundation

The model is developed based on the theoretical foundation, obtained throughout the literature synthesis. On existing literature surrounding resilience engineering, learning from the past and digital technology utilization, coupled with STS theory as a framework to analyze the literature and dissect the learning process in STS subsystems. The model structures the theoretical learning process into four stages, Data collection, Data analysis, Outcome evaluation and Strategy development. To ensure that learning from the past and digital technology integration occurs systematically. Contributing to the continuous integration of lessons and iteration of resilience strategies.

Digital technology integration

A key pillar that of this study and the ELP-model, is the utilization of digital technologies for a strengthened resilience learning process. This includes AI-driven data analytics for aggregated historical dataset processing. And the identification of patterns and insights within the datasets. That may be overlooked by manual analysis and interpretation bias. As the expert indicated that current data analysis practices are reliant on manual practice and expert judgement. To support the development of disaster scenarios based on the historical events, that are in line with the situation and capabilities of the plant. Which addresses an area of improvement highlighted by the expert. Where assumptions made on the impact a natural hazard has on the NPP, is not verified. Enabling sophisticated scenario building helps overcome these challenges. Serving as a steppingstone to the next phase of the model. Outcome evaluation, where the results of the data analysis are reviewed through simulated scenario-based learning, using AR or VR to train and assess staff performance in the event of an emergency. And support their awareness of emergency protocols and disaster preparedness. Coupled with a digital twin of the plant, helps evaluate plant performance on these simulated scenarios. These technologies can serve as an addition to the existent simulation practices within NPP resilience learning processes. Furthermore, as the expert highlighted another area of improvement, the ELP-model support the review of the performances and results based on the simulations. Through the use of digital platforms, to allow actors to access and collaborate performance data, coupled with data visualization tools to present the data in a graspable manner. Enabling actors to work with a shared knowledgebase, regardless of expertise. The importance of a shared knowledgebase was recognized by the expert and acknowledged that it is an integral part to resilience learning. Important to note, the ELP-model proposes that these digital platforms should be integrated throughout the learning process, to support efficient and streamlined data accessibility, accountability and transparency. Furthermore, to support compliance with regulators throughout the process, supporting the dynamic interaction between the plant and regulators, the ELP-model proposes the integration of governance and compliance platforms, enabling automated and systemic compliance, which was also indicated as a valuable addition to the learning process by the expert. Lastly, stage four, represents strategy development, where metrics of the developed strategies are shared with outside stakeholders through digital platforms and online dashboards, depending on their role and influence. To support trust and support for the strategies. Allowing the stakeholders to provide their input and feedback depending on their expertise, to further refine the strategies. Underlining the notion that the model supports feedback mechanisms throughout the process, therefore fostering enhanced learning. These developed strategies on innovative practices, may in turn inform the wider industry and CI-grid. Therefore, enhancing the resilience of the industry as a whole.

The model emphasizes a continuous and iterative learning approach, where insights and lessons generated, based on historical data, are continuously reviewed and refined the model therefore supports a shift from reactive learning, as in typically the case in contemporary resilience frameworks, to a more pro-active approach. Strengthening the NPP systems' absorptive capacity.

Validation process

Case-based evaluation

Applying the ELP-model to the Fukushima Daiichi disaster case as a historical event to learn from, demonstrated the models' practical value, and highlighted areas of improvement for the resilience learning process. Illustrating the models' ability to structure historical data processing, in the learning from the past process. By comparing the findings from the case study to existing analysis of the disaster case. Helped highlight the model's value in providing a unique and holistic approach to resilience learning. By application of the STS perspective to the learning process, to align digital technologies with social factors.

Expert consultation

The expert consultation session, coupled with the case-based evaluation, has helped strengthen the research outcomes. By verifying findings and results of this study. Allowed for the recognition of the feasibility of the ELP-model to serve as the foundation for a enhanced learning process guideline document, to be published by regulatory agencies. To be adopted by NPPs at their discretion. Important to note, as the expert highlighted, the guideline must serve as an addition to current practices, not a replacement. To ensure support and traction for the proposed approach. Also, it was mentioned that, if to be further developed, should be done in collaboration with technical experts of the regulatory agencies, who have experience with resilience learning and the technical capabilities of the NPP and can further refine the model, based on more in-depth knowledge on areas for improvement. Ensure that the guideline provides practical value.

Regarding the ELP-model itself, the expert consultation, has verified the importance of a shared knowledgebase among actors, current data analysis is reliant on manual labour and expert judgement, compliance monitoring happens periodically and is not automated. Furthermore, there is value to be gained on the front-end and back-end of scenario-based training practices. Ensuring that lessons learnt are contextually relevant to the plant. Verifying assumption made on the simulated scenarios and supported enhanced review of simulation performance.

Evolution of the traditional resilience learning process into the ELP-model

This section discusses a comparative summary of the transformation of traditional learning processes in NPPs towards the DT-integrated and STS perspective of the ELP-model. Which proposes the transformation of the learning process into a structured, data-driven and continuously iterative approach.

Considering the synthesized literature and the feedback from the expert consultation. The standard learning process is mainly focused on post-event learning with a reactive approach. Even though lessons are extracted from past disasters or incidents, learning mechanisms as part of regulations and inside the plant may lack systematic integration into resilience enhancement strategies. Reports and evaluations of past events (e.g., Fukushima Daiichi disasters) primarily rely on document-based assessments that lack iterative and comprehensive learning processes. Where assumptions are made on the effects of a disastrous scenario for the plant and its' operations. Without regarding possible cascading effects, after being struck by a natural hazard. Moreover, regulatory bodies impose resilience directives, without proposing formalized and structured guidelines to reflect on the past. Where traditional data collection is heavily depended on available datasets with varying data quality. With the analysis of the historical data is done through manual analysis and relies on expert judgement. To extract insights, discover patterns in the data and relevance to the realities of an NPP. Making the process subjective to individual interpretation. Where vital insights might become overlooked. Moreover, collaboration and engagement with historical data, the outcomes of analysis and reviews of simulation-based learning and performances is fragmented, non-automated and relies on expert judgement. Regarding upholding of compliance during the learning process, the communication with regulatory stakeholders is periodic and reliant on human intervention for reporting. Additionally, it became evident that regarding the dissemination of information on natural hazard risk assessments and developed resilience strategies between outside stakeholders and the NPP is fragmented, where feedback mechanisms to improve strategies is underrepresented. Thereby allowing the NPP to become vulnerable to natural hazards when underestimating risk or operating under outdated information. As well as in the event of a disaster, where outside stakeholders such as emergency responders are not fully aware of emergency protocols or the situation of the plant. They may be able to operate as adequately.

Enhancing the traditional learning process with DT utilization

Incorporating DTs into traditional resilience learning processes, introduces a data-driven and enhanced learning capabilities approach. Allowing NPPs to address various gaps in traditional learning processes. This study explores and demonstrates how the utilization of digital tools such as, AI-driven data analytics, digital twins, IoT monitoring, data visualization tools and governance and collaboration platforms can potentially improve the learning capabilities of an NPP. Enhancing the ability to identify patterns and generate insights form historical data processing. Turning them into lessons that inform resilience enhancement strategies. Allowing for a strengthened and adaptable learning from the past process within NPPs.

Key enhancements to the learning process provided by DT utilization encompass the following.

- Real-time data collection and enhanced historical data processing. Traditional learning is reliant on periodic logging and reporting, manual analysis and expert judgement. Allowing the process to become fragmented with varying quality of data with the possibility of interpretation bias. DT-utilization, such as IoT devices to enable monitoring for early warning signs of natural disasters or equipment failure. Enabling pro-active safety measures instead of reactive response based on incidents. Moreover, AI-driven data analytics such as ML-models or Big Data analytics. Have the ability to support human actors in learning. By processing large volumes of historical disaster data. Identifying patterns and cascading failure trends. Assessing the relevance of the data and disastrous scenario for the realities of the NPP. Supporting enhanced lessons generation and improving the predictive capabilities of the NPP. Refining risk assessments and inform resilience strategies.
- Automated compliance, enhanced communication and collaborative decision-making. Compliance monitoring happens on a periodic basis and is reliant on manual document sharing in the existent resilience learning process. Moreover, there is a need for a strong knowledgebase for actors within the NPP influencing the learning process. Data visibility and accessibility may be an issue, which leads to an inefficient learning process. Allowing them to work with a shared understanding of the data and analysis outcomes. Mitigates the actors' individual interpretations. Leveraging DTs can improve this part of the learning process. Integrating governance and collaboration platforms, enables real-time compliance monitoring and data-sharing between regulatory bodies, plant managers and experts at the plant. Utilizing these platform systems coupled with data visualization tools, allows the NPP and its' actors to collaborate and engage with the data. And retrieve

lessons learned from past disasters in an efficient manner. Supporting a well-informed, data-driven decision-making process on resilience enhancement. Additionally, these platforms facilitate clear role and task division, with role or action-based access control to sensitive data. Which is imperative due to the nature of the resilience learning process. Allowing for the resilience learning process to become accountable and transparent.

- Supporting existing simulation-based learning. As an addition to the traditional simulation-based learning practices. Where assumptions made to devise these simulated disaster scenarios, and its' impact on the plant remain unverified, and results of these simulations and performance reviews are reliant on manual reporting. The above-mentioned AI-driven analytics tools, support the development of disastrous scenarios. Together with Digital twin technology to verify the implications of such scenarios on the plant. And run simulations to enable operators to test alternative scenarios and responses in a controlled environment. Can improve the accuracy of the scenarios for simulation-based learning. Therefore, strengthening the ability to learn itself. Bolstering the largely physical simulation of traditional learning practices, with other simulation technologies. Such as AR or VR, can support the NPPs staff preparedness for a disastrous scenario and awareness of emergency protocols. Which was found to be lacking when the Fukushima disaster occurred.
- Strengthened feedback mechanisms. The standard learning process lacks structural feedback loops and mechanisms for continuous iteration. As mentioned above, a point of improvement for current resilience learning practices, is the review and analysis of scenario simulation performances. Moreover, learning may stagnate over time and patterns of recurring incidents may not be addressed. For example, AI-driven analytics may detect recurring failures in coolant systems, triggering an automated review of cooling system resilience strategies. Furthermore, governance and collaboration platforms support the engagement of actors with data and allow for them to provide input based on their expertise. Lastly, sharing metrics of developed resilience strategies with outside stakeholders, such as the public or industry partners. Through online dashboards. Support trust in the operations and resilience of the NPP and fosters support for strategies themselves. Also allowing the external stakeholders, once informed, to provide feedback on the strategies, based on their perspectives and expertise, to further refine the strategies and enhance the NPPs resilience.

To summarize, the utilization of DTs to support the resilience learning process has several key benefits. Transforming the standard learning process from a reactive to a pro-active approach. Enhancing incident reporting and historical data processing. To become better adaptable to risks posed by natural hazards. From fragmented and static to enhanced learning. Coupling various DTs to connect historical data with the realities of the plant and its' environment, into outcome and performance evaluation and strategy development. Furthermore, automating compliance monitoring and enabling seamless data sharing and knowledgebase. Supporting feedback mechanisms and data-driven refinement of resilience strategies.

DT-supported learning process compared to the Enhanced Learning Process

This comparison serves as the discussion of the importance and added value of considering the resilience learning process as an STS. Here STS theory application ensures that digital technology utilization is not a standalone solution but an integration into the resilience learning process. For effective adoption through alignment with social and organizational dynamics. Where these social elements inform the utility of the DTs and effective integration amplifies the impact of DTs on the learning process.

Whilst a DT-supported learning process introduces automatization, enhanced data processing and data-driven decision-making. It still lacks a structed, integrated and holistic approach. The ELP-model combines DT utilization to support learning with the STS perspective to strengthen the NPPs absorptive capacity and enhance its' resilience. Going beyond technical additions and improvements, facilitating a holistic, adaptive and embedded systemic structured continuous learning mechanism. Supporting the human and organizational dimensions of resilience learning with DT integration for resilience enhancement. Moving onto how the ELP-model extends beyond a isolated DT-supported learning process.

- Structured organizational learning and socio-technical integration. Taking the STS perspective to develop the ELP-model helps structure the learning process as delineated in this study. Used as a framework to help visualize, extract from the literature and assign the appropriate DTs to each of the stages of the learning process in the ELP-model where they have the most potential utility. Moreover, going beyond simply adding DTs to the learning process. Ensuring that DT utility is informed by the needs of the organization and ensure that the DTs are aligned with these social elements. To further support facets, such as accountability, transparency or knowledge transference, influencing the learning process. And help overcome the barriers to learning. Also, when comparing to a DT supported learning process, without the STS perspective. DT-driven insights are made possible however learning may not be systematically integrated into decision-making for strategy enhancement. The ELP-model addresses this by enabling learning outcomes to be integrated into organizational processes, through cross-functional knowledge sharing and continuous iteration.

- Stakeholder-centric learning process. The ELP-model proposes the transformation of the learning process, to ensure that stakeholder engagement is at the heart of learning. Supporting a shift from learning through technical insights with limited stakeholder engagement, towards human-technology integration in learning. Emphasizing cross-functional collaboration between managers, experts, staff and outside stakeholders. Facilitating that the learning process itself is well-informed, allowing for input from different perspectives and expertise that actors have to offer. And therefore, the development of resilience enhancement practices that are sophisticated, trusted and supported by the environment of the NPP.
- Continuous learning approach. Developing the ELP-model by applying the STS framework. Whereas if DTs are simply utilized to extract insights or perform simulations, providing historical data processing and performance outcomes. Without a structured mechanism to feed insights into organizational learning and resilience development. Then, learning may still not be enhanced. Therefore, STS theory helps embed feedback mechanisms between socio-technical elements, into the learning process. Thereby refining the resilience strategies. Ensured that the proposed learning mechanism is a cyclical process. The ELP-model support a continuously iterative learning approach, through the STS theory enabled feedback loops. Ensuring that organizational dynamics and procedures, evolve alongside technological improvements. Resulting in a rounded and comprehensive approach to learning. Where decision-making and resilience strategies are adaptive, data-driven and well-informed.

As shown, merely applying DTs to the learning process, without the STS perspective brings forth several pitfalls. Without STS, technical tools, may not align adequately with organizational needs, underlining a lack of human-technology alignment. As well as engagement with stakeholder may become underrepresented. Furthermore, DT utilization within the resilience learning process warrants a structured and adaptive mechanism. So that insights gained through leveraging DTs for data processing, communication or simulations, are adequately transformed into lessons and improve organizational procedures. STS theory ensures that the human, organizational and technical elements and in alignment and are leveraged in such a way that the DTs are informed by the social elements. And when integrated effectively are able to strengthen these social elements. Thereby amplifying the impact to learning the DTs may have. Without the application of STS theory as a framework to structure the learning process, digital technologies remain tools, but do not actively shape a continuously iterative learning culture for resilience enhancement.

In conclusion, this comparative discussion outlines the evolution of the traditional learning process of the nuclear industry towards a DT-integrated and STS structured resilience learning process. Representing a shift in how NPPs can approach resilience learning. Where current learning processes provide a method for post-event learning, that is reactive in nature, is reliant on manual reporting and analysis, and subject to expert judgement for lesson extraction with limited feedback mechanisms and DT utilization. Making NPPs vulnerable to underlying weaknesses, inadequate risk assessments and preparedness. The introduction of DTs strengthens this process by allowing for aggregated data collection and predictive analysis, data-driven decision-making and enhanced scenario-based simulations. However, while technologies provide the potential to improve the above. It does not automatically translate into systematic learning. Where effectiveness of DTs is dependent on adequate adoption into the learning process. This is where the ELP-model, developed through STS theory application, provides a holistic analysis of the learning process, allowing NPPs to gain an in-depth understanding of the intricacies of organizational learning and influencing factors. Integrated into the ELP-model to align social and technical elements to transforming traditional learning into a comprehensive resilience learning approach. By ensuring that technology utilization is informed by the needs of the organization and is specified to strengthen learning capabilities. Allowing for the utilized DTs to be adopted effectively into the learning process. Embedding systematic feedback mechanism, structural stakeholder engagement and enhanced knowledge transference. The ELP-model proposes an approach to learning that is not just reactive or a single operation. Based on technological insights. But a pro-active and continuous process where human-technology integration and collaboration are harmonious and supportive of each other. Presenting a shift towards dynamic and adaptable resilience, where lessons learned from historical events enhance the resilience of NPPs. Making them not just better at responding to disasters, but also enable them to pro-actively learning, prepare, adapt and withstand future natural hazards.

Theoretical and practical implications

Theoretical contribution

This study advances the theoretical landscape of resilience engineering, organizational learning and digital technology utilization with NPPs for natural hazard resilience enhancement. By adopting a STS theory perspective to the resilience learning process. This study introduces the ELP-model, representing a theoretical potential enhanced resilience learning approach. In the form of a structured, continuously iterative resilience learning process. That extend beyond traditional resilience engineering and reactive learning mechanisms. The theoretical contribution of this work covers several literature domains.

The work done in this study contributes to the literature of resilience engineering through structured learning. Resilience engineering has traditionally prioritized withstanding impacts and system recovery. Often overlooking the importance of structured learning mechanisms. This research addresses this limitation by introducing and structured and continuously iterative resilience learning process. That allows NPPs to enhance their lessons generation from historical disaster data and integrate them effectively into their organizational processes. By refining their resilience practices. Furthermore, supporting well-informed data-driven decision-making and preparation of actors and the plant. Through enhanced disaster data processing and predictive analysis to learn and uncover vulnerabilities in the resilience of the plant using digital tools . Thereby strengthening the absorptive capacity of NPPs by visualizing the steps to extracting, processing and implementing of lessons from historical disaster and inform resilience strategy development. Even though STS theory has been widely applied, it has not been systematically integrated into resilience learning. This study extends the application of STS theory in a novel manner, by regarding the resilience learning process as a socio-technical system Enabling the proposed technological adoption to be aligned with human and organizational factors, rather than isolated utilization. By structuring the ELP-model from an STS perspective. Has helped map the interaction between human actors, social and organizational elements and digital technologies within NPP resilience learning. Providing an STS framework visualization that can be transformed and adapted for use in other critical infrastructures. Ensuring that digital technologies are effectively adopted and supports rather than replace resilience learning practices. Showing that simply adding DTs to the learning process, may improve data processing and insight extracting. However, STS integration, as done in the ELP-model helps turn DT utilization into enhanced learning capabilities. And help translate lessons into enhanced resilience. Thereby the model makes resilience learning an adaptive, continuously evolving process, through human, social and organizational and technical learning. Where DTs are not simply tools for data processing or sharing, but amplifiers of organizational learning capabilities and NPP resilience. Additionally, this study contributes to organizational learning literature, by consolidating and explicitly defining digital technologies that have potential to support resilience learning processes. Previous studies either discuss the various digital technologies and their potential or examine a digital technology in isolation rather than integrated into a structured resilience learning model. By introducing and visualizing a structured technology integrated learning process, shows how DT utility can contribute to the refinement of resilience strategies.

This study presents a shift in traditional learning and resilience engineering. Emphasizing learning as a pro-active, structured and technology supported process, rather than a reactive and event-driven one. The structured learning approach in the ELP-model is able to not only enhance nuclear resilience, but if further developed and adapted can provide transferable insights on resilience learning applicable to other CIs.

Practical application

The ELP-model proposed in this research was aimed at laying the groundwork for a resilience learning guideline document, to be issued by policymakers and applied and adopted by NPP operators. Offering actionable and structured approach for improving organizational learning for the enhancement of resilience practices. That supports data-driven and informed decision-making and the development of sophisticated resilience strategies. Strengthening plant and employee preparedness and regulatory compliance within the industry.

The way the model has been devised, emphasizes on the utilization of digital tools. Offering practical recommendation to improve data-drive pattern recognition and decision-making. Continuous, real-time data exchange and learning. And automated compliance tracking. Through its' structured approach, allows NPPs and its' operators to systematically evaluate their resilience performance, uncover vulnerabilities, and enhancing their preparedness, by refining resilience strategies over time. Allowing the plant to be adaptive to evolving and complex risks and environmental conditions. Also, the model proposes automated compliance tracking, reducing regulatory deviations and ensuring standardization across the industry. Further supporting the existing learning processes by enabling enhanced scenario-based learning assessments, ensuring ongoing evaluation of performance and vulnerabilities, and lessons learning. Applying STS theory to the resilience learning process, ensures that NPPs adopt a data-driven from a shared-knowledge base, human-centered and scenario-based learning approach. The ELP-model also shows promise in application in other CIs, where DT utilization and STS application is not exclusive to the nuclear industry. By adjusting the model to suit the realities of other industries, their resilience learning processes can become strengthened as well. Strengthening cross-industry knowledge-sharing, facilitating collaborative disaster preparedness between NPPs and other CIs. If further developed with resilience and learning experts within regulatory bodies. The ELP-model possesses the feasibility to be developed into a learning guideline. To be adopted by NPPs and support their existing learning practices. Part of the ELP-model is the knowledge exchange with outside stakeholders, this includes informing policymakers on the developed strategies. Which in turn may inform the development of policy and enhance the resilience on an industry-wide level. Presenting a step forward in the supporting a safer, supported and more resilient nuclear industry.

Methodology

The method employed involved a comprehensive literature review, the SLR provided the basis for a rigorous literature synthesis, combining resilience engineering, organizational learning from the past and digital technology integration. Gave the developed model a strong theoretical foundation and through the STS theory application was able to delineate the sub-systems from the literature, according to STS principles with ease. The application of the STS perspective helped provide a holistic view and analysis of the literature and the learning process. Supporting the adaptation of digital tools by informing the utility based on social dimensions. Therefore, the digital tools have the capacity to strengthen the social dimensions in return. The application of the model on the Fukushima Daiichi case, demonstrated the model, and illustrated the applicability in a real-world scenario. The integration of expert consultation provided invaluable feedback from the industry, cross-validated findings and confirmed insight made from the literature and recognized the model's practical feasibility for serving as a basis for a learning process guideline. As well as highlighting areas of improvement within the resilience learning process of NPPs.

Limitations

Despite its' strengths, the methodology of this research does have limitations. Employing a systematic literature review, meant that the literature sources needed to be carefully assessed and evaluation on their quality and relevance to the study. The information varied greatly across the various types of sources. Therefore, the collected data needed to be scrutinized on relevance and credibility before consideration into the research. Furthermore, in this quickly evolving environment, certain policies or other documents might get updated making the sources used in this study less relevant and do not reflect the current direction of the field. Another limitation is the lack of empirical testing, since the model has not been implemented in practice such as an actual nuclear power plant. Furthermore, while the model was validated through a case study, it remains a single case. Such that findings may not be generalizable through other disasters. Additionally, the limited sample size of expert consultation, leaving the possibility of personal bias in the feedback given by the expert.

Recommendations for future research

The recommendations for future research, in this section revolve around the further development of the ELP-model. To provide the basis for a learning process guideline.

Even though the Fukushima Daiichi Disaster case provide valuable validation and allowed this study to demonstrate its' application to a real-world scenario. Expanding the case studies to ensure the model's applicability across various NATECH events. By examining different disaster scenarios and contexts.

Furthermore, the model should integrate more stakeholder perspectives and collaborate with industry experts to further the development and refinement of the model. As the expert consultation has highlighted. To ensure its practical application, the model should be developed in collaboration with regulatory, technical experts. Ideally on an international level. Since that is the level at which the guideline should be implemented, and the model provides the most value. These experts have the ability to develop the model based on their technical expertise, and experience with the learning processes of NPPs and their capabilities. To ensure that the guideline provides a valuable addition onto the existing resilience learning practices within NPPs. To ensure traction and support for the adoption of the learning process guideline, the model should not aim to alter or change existing practices, as highlighted by the expert. And be developed with the right people. Developing the model on a too high-level within the regulatory authorities, will result in resistance to adoption.

Furthermore, to further evaluate and refine the model's practical application. Future research should pilot the model in a real-world NPP. And integrate it into its' operations. To assess the practical feasibility, assess its effectiveness. Starting with conducting small-scale implementation, within selected facilities, would provide valuable insights into real-world challenges and refinements needed. To further develop the model, and potentially re-apply it to another facility to assess its' effect on learning capabilities again. Another important part of digital technology integration, and adaption revolves around a cost/benefit analysis of the recommended digital technologies. To assess which technology serves the most value to the learning process. This will help with adoption and integration of the guideline, as NPPs will have a greater picture of the possibility of integration, and feasibility of application. Before they make any decisions.

Employing the proposed adjusted STS framework, found in Appendix D, the Socio-Technical-Contextual framework, allows for a greater understanding of the interplay of different systems within the organization as well as surrounding it. Integrating this framework in future studies on resilience enhancement engineering of critical infrastructures allows for a customized approach, tailored to the landscape of such a study.

Propositions for further research

Based on the literature synthesis, discussed in Chapter 3 of this research. Several propositions have been devised, revolving around several gaps identified within the literature surrounding resilience engineering, organizational learning and digital technology utilization. These propositions will be expanded upon in the coming section. Calling for further research and investigation on the relationship between digital technology utilization and improved organizational learning capabilities. These propositions aim to explore the influence digital technologies have on enhancing resilience by improving organizational learning. To help validate the outcomes of the literature review performed in this study in an empirical manner. Highlighting relationships between concepts and gaps that warrant further research. The first proposition is developed on the direct relationship between utilization of digital technologies and strengthening organizational learning capabilities.

P1: The utilization of digital technologies enhances organizational learning by improving the collection, analysis and integration of historical data, thereby strengthening the absorptive capacity of NPPs to develop enhanced resilience strategies.

The integration of various digital technologies, such as AI, ML, IoT devices, Digital Twins or cloud-based platforms, as introduced in Chapter 3.5 and outlined in the various stages of the ELP-model in Chapter 4. Can enable NPP organizations to systematically collect and analyze historical disaster data, enhancing their abilities to recognize, generate and apply new knowledge, thereby improving their learning process. This proposition aligns with the overarching theme of this study and the stages of the ELP-model. Where the focus lies on utilizing the advantages that digital tools have to offer, to improve the absorption and processing of critical information, related to historical disasters and NPP resilience. The findings from Chapter 3 highlight the gap within the literature on systematic reflection on the past, i.e. lack of integrated learning mechanisms. Which these technologies can help overcome and improve organizational learning. As well the lack of integration of digital tools within resilience learning processes.

Proposed validation method

Conduct a longitudinal study, across multiple NPPs adopting digital technologies for resilience enhancement. Compare organizational performance through indicators of absorptive capacity, before and after the adoption of digital technologies. Include a control group of NPPs that do not integrate these technologies during the time period of the study, isolating the effect of digital technology utilization.

Measure the improvements in absorptive capacity through various indicators, such as:

- Number of insights generated: Insight generated from historical data analysis with the help of digital technologies
- Speed of knowledge assimilation: Time taken to integrate lessons from historical data.
- Organizational adaptability: Changes in procedures or resilience strategies, based on insights generated through digital technology, such as AI, ML utilization.

Using statistical analysis to compare the situation before and after digital technology implementation with the control group. Thereby isolating the impact that the adoption of digital technologies to enhance learning from the past, has on resilience enhancement. And over the period of the study, at intervals, observe the rate of change in the indicators.

Theoretical contribution

Investigating this proposition contributes to the organizational learning and resilience literature by highlighting how digital technologies can influence learning. With the integration of absorptive capacity indicators (insights generated, speed of assimilation and adaptability) to test learning capabilities. Further contributing to the theoretical knowledge how digital tools can influence learning mechanisms. Demonstrating the importance of leveraging the advantages that digital technologies such as ML-models, IoT devices, digital twins, AR/VR have to offer. Within resilience enhancement engineering practices in a NPP context. Providing evidence for their role in strengthening organizational learning. Thus, exploring this proposition will support the further development of a learning process guideline.

The rest of the propositions are constructed in such a way that they are built upon the direct effect of proposition 1. Exploring on various specific digital technologies and moderating effects that influence the relation outlaid in the first proposition. Based on identified challenges in Chapter 3, and concepts that influence learning. Specifically, the effect data quality has on the performance of ML-models to enhance learning. How perceived complexity of digital twins can hinder the influence it has on learning. And the amplifying effect a strong learning culture on the application of digital twins to enhance learning. Lastly, the importance of STS alignment within utilizing digital technologies for organizational learning enhancement is explored.

P2: Data quality positively moderates the relationship between digital technology utilization and enhanced learning capabilities. Having access to reliable and accurate data increasing the effectiveness of ML-models in generating actionable insights from historical data for resilience strategy development.

This proposition addresses a key challenge identified in Chapter 3. The availability and quality of data, from past NATECH events. Where poor data management and quality cause barriers for effective digital technology utilization. And the capabilities of digital tools such as ML-models and Data Analytics can become less effective. Additionally, this proposition is directly linked to the stage 2 of the ELP-model, concerned about data analysis.

Proposed validation method

Quantitative validation by conducting a controlled experimental study. Develop scenarios with datasets of varying quality based on established criteria (e.g, completeness, accuracy, consistency, noise). Reflecting the available data and complexities surrounding NATECH events. And process the various datasets by applying ML-models to assess the effectiveness of the technology. Measuring the outcomes of the analysis:

- Number and quality of actionable insights generated.
- Accuracy of outcomes, percentage of accurate outcomes based on different dataset qualities.
- Time taken to process the varying datasets and produce useable results.

Then using a statistical test, to determine the effect that data quality has on the outcomes of the analysis. Lastly, conducting comparisons between the varying datasets to identify specific differences in outcomes. Thereby identifying the effect data quality has on the performance of the digital technology.

Theoretical contribution

Investigating this proposition advances the understanding of data management's role in enhancing organizational learning and resilience. Emphasizing on the effect data quality has as an important factor on the effective adoption and utilization of digital technologies. Demonstrates the importance of (historical) data as a resource for resilience engineering and effective learning. Providing insights into the conditions required for the digital tools to be most impactful. Addresses the gaps within the literature between data quality difficulties in learning from the past and digital technology utilization. Bridging resilience engineering, data management and learning from past disasters.

P3: Perceived complexity of the Digital Twin technology can negatively moderate the impact that Digital Twin utilization has on enhancing organizational learning capabilities.

As discussed in Chapter 3, the deployment of digital technologies, in this case digital twins, with its inherent complexities, require a certain level of technological expertise. Digital Twins have the possibility to enhance learning through simulated scenario-based learning. However, perceived complexity of the technology moderates the impact it has, where high complexity creates barriers for effective integration and use, reducing the overall impact on enhancing learning. Furthermore, related to stage 3 of the ELP-model, where simulated scenario-based learning play an important role in evaluating the NPPs performance in such disaster scenarios, helping to shape resilience strategies and in enhancing the employee and organizations' disaster preparedness.

Proposed validation method

Applying quantitative research, by conducting a numbered survey on the employees of a numerous amount of organization of varying sectors using digital twins, for generalizability. To assess whether perceived complexity significantly reduces the impact of digital twin utilization on organizational learning.

Design the survey in such a way to measure the utilization of digital twins (frequency, scope and depth of use in processes). Perceived complexity, to capture how users perceive the complexity of the technology (e.g., difficulty of use, expertise required, learning curve or other barriers). And to measure organizational learning, using validated indicators of learning.

Analyze the data gathered for insights on utilization, learning and complexity. To identify if there exists a correlation, between perceived complexity and the impact of digital twin utilization on absorptive capacity indicators. Thereby validating the moderating effect of perceived complexity on enhancing organizational learning.

Theoretical contribution

This proposition contributes to the literature of technology adoption, resilience engineering and organizational learning. By underscoring perceived complexity as a barrier to adoption of digital twins and effective learning. Therefore, building upon theory on how organizational and individual perceptions influence the effectiveness of a digital tools, like Digital Twins. Suggesting that perceived complexity must be managed to maximize learning capabilities. And provide adequate knowledge transference and training on the technology to ensure successful utilization. Going hand-in-hand with STS theory, by balancing integrating advanced digital technologies and capabilities of the organization and users.

P4: A strong learning culture within the organization can positively moderate the impact that digital twin utilization has on enhancing organizational learning capabilities.

As discussed in Chapter 3, organizational learning capabilities are impacted by the presence of a learning culture within the organization. Where Digital Twins have had a positive impact on resilience enhancement in other CIs (Brucherseifer et al. 2021), (Geihs, 2023), (Braik & Koliou, 2023), (Lin et al., 2021), (Kropaczek et al., 2023). And through simulated scenario-based learning shows potential to enhance learning. Therefore, there is merit to explore the combination of these two concepts and verifying whether having a strong culture of learning amplifies the impact that digital twin technologies have on organizational learning. This is directly linked to the ELP-model, which aims to promote a continuously iterative learning culture. Gaining more insights into the impact of a strong learning culture on the impact that a digital technology, in this case digital twins, have on learning capabilities. Can help shape and refine the ELP-model, to better promote such a culture.

Proposed validation method

Take a qualitative research approach by conducting case studies, to assess the moderation effect. By interpreting how the strength of a learning culture influences the impact of digital twin utilization on the learning process. Selecting organizations with varying levels of learning culture (strong, moderate, weak). Compare how digital twins are used and their influence on organizational learning processes. And examine whether a stronger learning culture amplifies the effectiveness of digital twins.

Conducting semi-structured interviews with stakeholders such as engineers, managers and employees. Focused on how digital twins are used for learning, and whether the organizational culture facilitates this use. Creating focus groups to facilitate discussion among stakeholders. And investigate collective perspectives on the role of learning culture in utilizing digital twins for learning. Lastly, observe how digital twins are integrated into organizational processes (day-to-day, training, decision-making). And note behaviors that are indicative of a strong learning culture (e.g., innovative and collaborative problem-solving and decision-making, knowledge-sharing).

Theoretical contribution

Validating this proposition adds to the resilience literature by demonstrating how a strong learning culture amplifies the influence digital technologies have on learning processes. Emphasizing the importance of human factors in resilience engineering practices. Also adding to the literature of organizational learning, underscoring the link between culture and technology adoption and performance. By highlighting a strong culture of learning as an important factor of leveraging digital technologies for resilience enhancement. Furthermore, adding to the theoretical basis for future studies on culture-technology interactions, exploring different technologies and their influence.

P5: Socio-technical alignment positively moderates the relationship between digital technology utilization and enhanced learning capabilities. Alignment of Socio and Technical elements supports an effective relationship between human actors, social factors and digital technologies. Resulting in productive technology adoption, strengthening the impact of digital technology integration on learning and resilience building.

As Socio-Technical alignment has shown to result in improved organizational performance, according to the principles of STS theory as outlined by Ottens et al. (2006) as discussed in Chapter 2 and 3. Together with this study's perspective of taking the learning process as a socio-technical system. And considering the notion of strengthening organizational learning to enhance resilience. This proposition combines the above and is aimed to explore the positive influence that STS dimension alignment has on the relation between digital technology utilization and improved organizational learning.

Proposed validation method

Using qualitative research by conducting case studies to validate the moderating role of STS alignment. Comparing cases with varying levels of STS alignment in their learning process to assess differences in outcomes. Investigating how alignment (or lack thereof) influences the effectiveness of digital technology utilization on organizational learning.

Setting up semi-structured interviews, with stakeholders such as managers, engineers and other end-users of digital technologies used for learning. To understand their perspectives on the role of technology in learning, perceived alignment of social and technical dimensions within the organization. And barriers and challenges experienced with digital technology utilization. Furthermore, observe learning processes, technology usage and interactions between staff and technology. Analyzing the gathered data to identify indicators of strong or weak STS alignment (e.g, communication gaps, data management gaps or lack of support for technology usage within the organization). Pattern in how the digital technology is used. And the impact of digital technologies on organizational learning.

Paying attention to outcomes regarding when STS alignment is strong, look for instances where technology adoption has led to significant learning improvements. And when STS alignment is weak, look for barriers that hinder the impact technology has on learning.

Theoretical contribution

This proposition furthers the application of STS theory in resilience literature. Demonstrating the role of the alignment of socio and technical aspects influence the learning from the past process. Demonstrating the interdependence between organizational factors, human actors and digital technologies. Underlining the importance of STS alignment for successful digital technology integration to enhance learning. Adding to the literature by regarding the role alignment plays in utilizing digital technologies for resilience enhancement. Offering practical insights into implementation. Regarding the learning process as a socio-technical system, advances the understanding of resilience as a socio-technical construct. Underlining the importance of a comprehensive approach to utilizing digital technologies into learning mechanisms.

Chapter 7: Conclusion

The aim of this thesis research was to lay the foundation for a learning process guideline to enhance the resilience of Nuclear Power Plants against natural disasters. Leveraging the capabilities that digital technologies, to enhance disaster data processing, simulated scenario-based learning, data-driven collaborative decision-making and information sharing. By developing a theoretical enhanced learning process, coined the Enhanced Learning Process-model. Based on the literature synthesis of resilience engineering, organizational learning from the past and digital technology utilization within the context of this study. Grounded in STS theory, to ensure that digital technology integration is informed by and in line with social and organizational dimensions. The research conducted, investigated and explored the literature, extracting the sub-systems of STS theory (actors, social and organizational elements, digital technologies) and the influence they have on the resilience enhancement learning process. Creating an in-depth comprehension of a digital technology-integrated systematic learning process guideline into NPP systems for resilience enhancement, supporting effective practical implementation.

The study employed a multi-method approach, combining a systematic literature review, case evaluation and expert consultation. To develop an in-depth understanding of resilience learning in NPPs. Identifying knowledge gaps and barriers to learning through the literature synthesis. And exploring DTs that have utility to strengthen the learning process and overcome these gaps and barriers. Analyzed from a socio-technical perspective, these insights informed the development of the ELP-model. Laying a theoretical foundation for a structured learning process that is aimed at enhancing resilience strategies in NPPs. By combining these approaches, this study demonstrated how digital technologies can be systematically integrated into a theoretical resilience learning mechanism. Synthesizing resilience engineering, organizational learning and digital technology utilization, to develop a theoretical model that serves as the foundation for a guideline to integrate historical data-driven learning and decision-making into resilience strategies.

Re-iterating the main research question of this study:

"How can a learning process guideline, using digital technologies, be developed and implemented in nuclear power plants to enhance their resilience against natural disasters?"

This study addresses the main research question by investigating the status quo resilience engineering practices and organizational learning. To gain an understanding of what constitutes resilience enhancement and learning from the past. Discussing the challenges existing within the current practices and barriers to learning from the past. Identify stakeholders surrounding the NPP and discuss the importance of stakeholder engagement. Exploring the role of digital technologies in supporting learning processes. To develop a structured learning approach, the ELP-model. Demonstrating and evaluating the model's applicability through a case-based evaluation. Coupled with expert consultation provided invaluable insight and feedback. To cross-validate findings and outcomes of the research. Refine the model where necessary. Verify the areas of improvement for the learning process within NPPs and validate the feasibility of the model's practical application and potential for further development into an enhanced learning approach technical guideline. For adoption by the industry and NPPs, at their discretion. To serve as an addition to their existing practices.

The ELP-model represents a novel and integrative approach to learning from the past to enhance resilience of NPPs. By aligning social and organizational dimensions with digital technology utilization, according to STS theory. The model offers a structured approach for systematically enhancing resilience against natural disasters through learning from the past. The key contributions of the ELP-model are as follows:

Structured visualization of the learning process: The ELP-model establishes a systematic process for learning from past disasters, transforming historical data into actionable insights. This approach addresses the lack of structured learning mechanisms in traditional resilience frameworks. The model's iterative nature ensures that resilience strategies are continuously refined and improved, fostering a culture of ongoing learning and adaptation within organizations.

Digital technology utilization: The integration of advanced digital tools supports enhanced data analysis, collaborative data-driven decision-making, and simulated scenario-based learning, enabling organizations to anticipate and mitigate potential vulnerabilities. Supporting resilience and staff performance evaluation to strengthen disaster preparedness. And enables actors to collaborate and learn lessons from historical data analysis under a shared knowledge base.

Socio-Technical Integration: This thesis incorporated STS theory in a unique way, by taking the learning process to strengthen systemic resilience itself as a Socio-Technical system. By aligning actors, social and organizational dimensions with technical elements, the model aims to strengthen the organizational absorptive capacity and facilitates effective collaboration among actors and enhance the systemic resilience of NPPs.

While the ELP-model shows practical potential, its' successful implementation requires addressing several challenges, including ensuring adequate data management, overcoming resistance to technological integration, and managing the complexity of socio-technical interactions and the nuclear industry. Future research should explore these challenges in depth. Integrating more perspectives from experts in the industry for the development of the model. And evaluating the impact of the ELP-model on resilience outcomes in a real-world setting.

In conclusion, the ELP-model sets the foundation for a proactive and adaptive learning process guideline to strengthen NPPs resilience engineering. Transforming the traditional learning processes and ensuring that NPPs are better equipped to prepare for, withstand, and recover from natural disasters. Its’ contextual contribution goes beyond individual NPPs, offering insights that can inform policy development and enhance resilience practices across the industry and other CIs. This work thus represents a step forward in safer and more resilient nuclear energy production.

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Appendix A.1 Literature Matrix

Table 3 is an indexation of the literature reviewed during the SLR. The table provides an overview of the characteristics of the sources, in order of citation within the report. Covering; the Title of the source, Authors, Year of publishing, area of focus of the article, report or paper, key findings taken from reviewing the source, the methodology of the research conducted is mentioned or if the source is non-scholarly, lastly, the relevance of the source to this thesis research. (NPP system research context and stakeholder engagement, Socio-Technical systems perspective, Current practices and challenges in NPP resilience engineering/risk management, learning from past disasters, utilization of digital technologies for resilience learning)

Source Title	*Authors*	*Year*	*Focus area*	*Key findings*	*Methodology*	*Relevance*
NPP system research context						
The Fukushima Daiichi accident	IAEA	2015	Nuclear Accident Analysis	Comprehensive analysis of the Fukushima Daiichi nuclear disaster. Highlights the causes, consequences, and lessons learned from the disaster. Discusses the safety measures, emergency responses, and the long-term implications for nuclear safety globally.	Non-scholarly article: Report on accident analysis	Direct insights for nuclear disaster response and resilience. Highlighting nuclear safety, infrastructure resilience, and disaster response in the context of nuclear power.
Ten years of lessons learned from operating experience in nuclear power plants	Manna et al.	2021	Nuclear power plant management	Emphasizes the importance of operating experience in improving nuclear safety, identifying recurring contributing factors such as design, maintenance, and management issues. Highlights the need for better use of international operating feedback, design deficiency mitigation, and improved safety culture.	Retrospective and comparative analysis	Study aims to enhance nuclear safety through improved experience feedback systems and lessons learned from past operational events.
Site survey and site selection for nuclear installations	IAEA	2015	Site selection for nuclear infrastructure	Provides guidelines for site selection and survey methodologies to ensure nuclear safety and risk mitigation.	Non-scholarly: Policy guidelines & case examples	Important for understanding nuclear infrastructure site selection and risk assessment.

Sendai Framework for disaster risk reduction 2015-2030	UNDRR	2015	Disaster Risk Reduction Framework	Established guidelines for disaster risk reduction across critical infrastructures, including nuclear power plants. Focused on reducing disaster risk at national and local levels.	Policy Framework	Relevant for understanding resilience and disaster preparedness in critical infrastructures, particularly nuclear power plants, aligning with NATECH event preparedness strategies.
World Association of Nuclear Operators: Guideline GL 2018-01 Independent Oversight	Selting	2018	Nuclear safety management	Establishment of an independent oversight function to assess safety performance and identify areas for improvement in nuclear operations. Discusses structures, reporting lines, and the importance of independence to prevent conflicts of interest.	Non-scholarly article. Revision of guidelines	Insight into guidelines of governing bodies, implementing independent safety oversight programs in nuclear facilities to ensure safe operations and continual performance improvement
Nuclear energy - The solution to climate change?	Muellner et al.	2021	Nuclear energy and climate change	Nuclear energy's role in mitigating climate change is limited by technical and resource constraints. Highlights the importance of safety governance.	Literature review and policy analysis	Provides context on the broader challenges of nuclear energy, indirectly affecting long-term NPP resilience planning.
Council Directive on European Critical Infrastructures	EU Commissio n	2008	European Policy on Critical Infrastructures	Directive for identification and protection of European critical infrastructures. By establishing requirements for identifying and designating European Critical Infrastructures and laying out safety measures.	Non-scholarly article: Policy Directive document.	European perspective on critical infrastructure protection. Foundational for policy development and risk management strategies concerning CIs.
Operating Experience Feedback for Nuclear Installations	IAEA	2018	Feedback systems for nuclear plants	Highlights the importance of establishing programs to collect and analyze operational experience across the lifetime of nuclear installations, covering design to decommissioning. Discusses safety culture, corrective actions, and the role of the regulatory body in maintaining operational safety.	Non-scholarly article. Review and update of IAEA safety standards	Provides foundational guidelines for nuclear power plants to enhance safety through structured operating experience feedback systems. By using lessons learned from past incidents and operational data to prevent future risks.
Update on the use of International Operating Experience Feedback for improving nuclear safety	NEA	2015	Nuclear power plant safety	The report identifies weaknesses in the current operation experience feedback systems, including insufficient strategic oversight, inadequate international coordination, and lack of web-based systems for data management. It also emphasizes the need for better integration of national and international systems.	Non-scholarly article. Advisory guideline on nuclear safety	Study highlights weaknesses in NPP system safety management. Lacking strategic oversight, coordination and web-bassed systems.

Ensuring the Safety of Nuclear Installations: Lessons Learned from the Fukushima Daiichi Accident.	Willis	2021	Nuclear safety and disaster preparedness.	This paper discusses the critical lessons learned from the Fukushima Daiichi nuclear disaster, particularly the need for robust safety protocols, early warning systems, and emergency preparedness. Highlights structural vulnerabilities in nuclear infrastructure and the importance of safety culture to prevent future accidents.	Case study analysis	Call for for NPPs to reflect on past nuclear safety failures and ihow past disasters inform future safety practices.
International nuclear energy legal regulation: comparing the experience of the EU and the CIS countries	Nukusheva et al.	2021	Legal regulations on nuclear energy	Identifies differences in regulatory approaches, safety standards, and international cooperation frameworks. The EU is found to have stricter regulations and more robust safety protocols than the CIs.	Comparative Analysis	Highlights the legal frameworks critical to implementing resilience strategies in NPPs.
Bulletin: Nuclear Power and the Clean Energy Transition	IAEA	2020	Role of nuclear energy in achieving clean energy goals.	Emphasizes that nuclear energy is a key player in reducing carbon emissions and transitioning to a clean energy future. It discusses how nuclear power has contributed to preventing 74 gigatons of CO_2 emissions since 1971. Nuclear energy is considered essential for achieving global energy sustainability.	Systematic data analysis	Essential for discussions on decarbonization strategies, particularly in integrating nuclear power into clean energy systems.
Building low-carbon resilient electricity infrastructures with nuclear energy in the post-COVID-19 era	OECD	2020	Low-carbon energy resilience with nuclear power	Explores how nuclear energy contributes to resilient electricity infrastructures in a post-COVID-19 economic landscape.	Non-scholarly: Policy analysis & economic modeling	Discusses resilience policies within nuclear industry
Securing the Resilience of Nuclear Infrastructure against Natural Disasters	Murakami et al.	2021	Nuclear infrastructure resilience	Examines strategies for enhancing the resilience of nuclear infrastructure against natural disasters. Discusses policy interventions and engineering solutions.	Policy analysis & case studies	Useful for research on critical infrastructure resilience and risk mitigation in high-risk environments.
eNatech Database	eNATECH	n.d.	Natech Events Data Repository	Provides a repository of data on past Natech events, including their impact on critical infrastructures. Useful for understanding historical data on Natech events.	Non-scholarly article. Data analysis repository	Offers empirical data critical for evaluating and understanding the impacts of Natech events on nuclear power plants and other infrastructures.

Natech Risk Assessment and Management	Krausmann et al.	2016	Natech Risk Management	Comprehensive review of risk assessment and management strategies for Natech events. Emphasizes the need for integrating natural disaster risks with technological vulnerability assessments.	Risk Management Framework	For implementing resilience strategies that account for Natech risks in nuclear power plants.
The Chernobyl Disaster and Beyond: Implications of the Sendai Framework for Disaster Risk Reduction	Aitsi-Selmi et al.	2016	Disaster Risk Governance	Reflection on the Chernobyl disaster and its implications for the Sendai Framework. Lessons from Chernobyl highlight the need for better disaster preparedness in nuclear facilities.	Case study and review	Informs how lessons from past nuclear disasters can improve learning processes for NPP resilience.
Lessons from Fukushima disaster 10 years later	StanfordReport	2021	Lessons learned from Fukushima disaster	Analyzes key lessons from the Fukushima nuclear disaster a decade later. Focuses on policy changes, disaster preparedness, and infrastructure resilience.	Non-scholarly article: Policy review & expert analysis	Important for understanding long-term impacts and improvements in disaster management and resilience strategies.
Ten years after Fukushima: The experts examine lessons learned and forgotten	Ahmad et al.	2021	Safety management in nuclear industry	The impact the Fukushima nuclear disaster had on the industry. Emphasizing lessons that have been learned and forgotten. Include the inadequacy of quantitative metrics in assessing nuclear accidents, the importance of intangible factors like safety culture, leadership, and memory, and the need for shared accountability mechanisms. It stresses the global implications of nuclear accidents and calls for collective engagement in nuclear safety.	Non-scholarly article with expert commentary	Reflection on a past nuclear disaster, focusing on safety culture, organizational practices, and the global need for coordinated safety efforts.
The Fukushima Disaster – Systemic Failures as the Lack of Resilience	Hollnagel & Fujita, 2013	2013	Systemic failures in Fukushima disaster	Identifies systemic failures that contributed to the Fukushima nuclear disaster, emphasizing the importance of resilience in high-risk industries.	Systemic analysis & resilience modeling	Crucial for understanding how systemic failures impact disaster resilience and infrastructure safety.

Dealing with cascading multi-hazard risks in national risk assessment: The case of Natech accidents.	Girgin et al.	2019	Multi-hazard risk management.	Examines Natech (Natural Hazard Triggering Technological) accidents, which involve cascading natural and technological events. It highlights the importance of including Natech risks in National Risk Assessments (NRA) and proposes methodologies for assessing these risks. The research calls for comprehensive frameworks that include multi-hazard scenarios to prevent cascading effects in critical infrastructures.	Case study and risk management framework proposal.	Shows how NPP can manage cascading multi-hazard risks, particularly Natech-related accidents.
The Fukushima Disaster and Japan's Nuclear Plant Vulnerability in Comparative Perspective	Lipscy et al.	2013	Comparative vulnerability of nuclear plants	Compares the vulnerability of Japan's nuclear infrastructure with global standards. Identifies policy and engineering gaps.	Comparative policy analysis	Relevant for analyzing nuclear infrastructure risks and disaster preparedness policies.
Social innovation and disaster risk reduction in Japan: challenges and opportunities	Kawane et al., 2024	2024	Social innovation in disaster risk reduction	Explores the role of social innovation in disaster risk reduction in Japan. Highlights community-driven strategies for resilience.	Case studies & policy analysis	Useful for integrating social innovation in disaster resilience frameworks.
Post-crisis efforts towards recovery and resilience after the Fukushima Daiichi Nuclear Power Plant accident	Yamashita & Takamura	2015	Post-crisis resilience and recovery	Examines post-crisis recovery efforts after the Fukushima nuclear disaster, highlighting health, social, and policy responses. Emphasizes resilience-building strategies.	Case study & policy analysis	Relevant for understanding resilience and recovery mechanisms post-disaster, applicable to critical infrastructure resilience research.
Fukushima Daiichi Accident - World Nuclear Association	WNA	2024 b	Analysis of the Fukushima Daiichi nuclear accident	Provides a comprehensive review of the Fukushima nuclear accident, including causes, responses, and lessons learned.	Non-scholarly article: Case study & historical review	Discusses the events of the Fukushima disaster
Earthquakes and Seismic Protection for Japanese Nuclear Power Plants - World Nuclear Association	WNA	2017	Seismic protection for nuclear power plants	Discusses earthquake risk and seismic protection measures for Japanese nuclear power plants.	Non-scholarly article: Risk assessment & engineering analysis	Discusses the events of the Fukushima disaster and seismic resilience in nuclear industry.

A Roadmap for The Comprehensive Assessment Of Natech Risk	Misuri & Cozzani	2024	Natech Events Risk Assessment	Proposes a roadmap for assessing natural-technological disaster events affecting critical infrastructures. Provides a framework for systematically evaluating Natech risks and their cascading impacts.	Risk Assessment Framework	Supports understanding of managing Natech risks in nuclear power plants and enhancing resilience strategies.
Stakeholder engagement						
Stakeholder management in complex projects	Nguyen & Mohamed	2018	Stakeholder management in project environments	Explores best practices for managing stakeholders in complex projects. Emphasizes the need for communication, risk mitigation, and stakeholder engagement to improve project outcomes.	Empirical study & stakeholder analysis	Essential for research on managing multiple stakeholders in large-scale projects, particularly in infrastructure and safety contexts.
The role of culture in stakeholder engagement: Its implication for open innovation	Osobajo et al.	2023	Cultural influence on stakeholder engagement	Explores how cultural differences shape stakeholder engagement in open innovation. Highlights best practices for managing diverse stakeholders.	Qualitative study & case analysis	Relevant for understanding cultural influences in infrastructure projects and stakeholder engagement.
Examining the association between stakeholder culture, stakeholder salience and stakeholder engagement activities	Boesso & Kumar	2016	Stakeholder management	Finds that stakeholder culture influences engagement strategies. Proposes a framework for effective stakeholder interaction.	Quantitative study & statistical modeling	Important for designing stakeholder management strategies in critical projects.
Infrastructure delivered through networks: engagement of stakeholders	Beach	2014	Stakeholder Engagement in Nuclear Energy Development	Analyzes the effectiveness of stakeholder communication strategies in nuclear energy projects and how they affect project success.	Mixed-method approach using surveys and interviews	Provides insight into stakeholder communication practices essential for project success.

Mediation Effect of Stakeholder Management between Stakeholder Characteristics and Project Performance	Nguyen & Mohamed	2021	Stakeholder Management in Projects	Effective stakeholder management improves project performance by mediating risk management strategies.	Structural Equation Modeling (SEM)	Offers insights into how stakeholder management can enhance resilience in NPP projects.
Stakeholder salience in global projects	Aaltonen et al.	2008	Stakeholder Influence in Global Projects	Stakeholder salience is determined by power, legitimacy, and urgency, with strategies like withholding and indirect pressure.	Case study	Provides understanding of stakeholder influence management in large-scale NPP projects.
Understanding stakeholders' approaches to sustainability in building projects	Herazo & Lizarralde	2016	Stakeholder Approaches to Sustainability	Stakeholders have varying approaches to sustainability, which create tensions impacting project outcomes.	Case study	Relevant for understanding how varying approaches can impact sustainability goals in NPP projects.
Stakeholder engagement in nuclear programmes	International Atomic Energy Agency	2021	Stakeholder Engagement in nuclear industry	Emphasizes the role of stakeholder involvement in ensuring the safety, security, and sustainability of nuclear energy programs.	Comparative analysis	Relevant for designing engagement protocols for NPP resilience and safety.
Ethical considerations on stakeholder engagement in radiological risk governance	Meskens	2020	Ethical Stakeholder Engagement in Risk Governance	Highlights ethical considerations in engaging stakeholders in radiological risk governance, focusing on justice and fairness in decision-making.	Literature review	Offers ethical guidelines for stakeholder engagement in NPP risk management.
Socio-Technical systems perspective						

Modelling infrastructures as socio-technical systems	Ottens et al.	2006	Socio-technical system modelling for infrastructures	Infrastructure systems should be modelled as socio-technical systems due to their complexity and interactions between social and technical elements. Traditional engineering models fail to capture social dependencies and institutional factors. Traditional engineering models fail to capture social dependencies and institutional factors.	Conceptual analysis & literature review	Relevant for understanding CI development from a socio-technical perspective. Helps in modelling the learning process. As a Socio-Technical System.
Human resilience and development in coupled socio-technical systems: A holistic approach to critical infrastructure resilience	Thomas	2017	Holistic resilience approach in critical infrastructure	Focuses on integrating human, organizational, and technological factors to enhance resilience in critical infrastructures like nuclear power plants.	Case studies, theoretical frameworks	Highlights the need for a socio-technical approach to resilience, emphasizing the importance of both social and technical factors in nuclear resilience strategies.
Assessing organizational culture in complex sociotechnical systems	Reiman	2007	Organizational culture in nuclear power plant maintenance	Highlights how organizational psychology contributes to safety and resilience in nuclear facilities through maintenance organizations.	Empirical study of organizational behavior in maintenance	Demonstrates the interaction of social elements with technical aspects in ensuring resilience, key to understanding socio-technical systems in nuclear resilience.
Addressing Human and Organizational Factors in Nuclear Industry Modernization: A Sociotechnically Based Strategic Framework.	Dainoff et al.	2023	Socio-technical frameworks for nuclear modernization	Proposes a socio-technical strategy for nuclear power plant modernization, focusing on the integration of human systems, resilience engineering, and technological updates.	Case analysis, strategic framework development	Demonstrates how both organizational (social) and technical factors contribute to resilience in nuclear power plant management.
A resilience engineering approach to integrating human and socio-technical system capacities and processes for national infrastructure resilience	Thomas et al.	2019	Resilience engineering in national infrastructure	Proposes a resilience engineering framework that integrates human and socio-technical capacities for improving national infrastructure resilience. Highlights adaptive capabilities and risk management.	Resilience engineering & case study analysis	Essential for understanding how engineering and human factors contribute to resilient infrastructure systems.

Interplay of human factors and safety culture in nuclear safety for enhanced organisational and individual performance: A comprehensive review	Orikpete & Ewim	2023	Human factors and safety culture in nuclear safety	Explores how human factors and safety culture influence nuclear safety performance at organizational and individual levels. Highlights best practices for improving safety culture.	Comprehensive literature review	Essential for understanding human factors in nuclear infrastructure resilience and safety management.
Socio-technical systems and interaction design – 21st century relevance	Trucco & Petrenj	2017	Critical infrastructure resilience	Reviews emerging resilience practices at the local level, discussing challenges in implementation.	Case study & policy analysis	Useful for local governance and infrastructure resilience programs.
Current practices within NPP resilience engineering and risk management						
Resilience Framework for Critical Infrastructures: An Empirical Study in a Nuclear Plant	Labaka et al.	2015	Nuclear Plant Resilience Framework	A resilience framework based on the ability of nuclear infrastructures to withstand, respond, and recover from disruptions.	Case Study	Applying resilience framework in NPPs and creates understanding on the improvement of resilience strategies within NPPs and other CIs.
Resilience of critical infrastructures: Review and analysis of current approaches	Curt & Tacnet	2018	Resilience Assessment	Reviews current approaches to infrastructure resilience, providing an analysis of methodologies used in assessing and improving resilience in various sectors, including energy and transport.	Literature Review	Analysis of existing resilience frameworks applicable to nuclear sector. Useful for enhancing resilience strategies across critical infrastructures and can be translated to nuclear safety.
International Project Risk Management for Nuclear Power Plant (NPP) Construction	Kim et al.	2017	NPP Construction Risk Management	Compares risk management in nuclear power plant projects with fossil and gas power plants, emphasizing unique risks and mitigation strategies for nuclear projects.	Comparative Analysis	Insights into risk assessment and project management in nuclear projects.

Development of a Quantitative Resilience Model for Nuclear Power Plants	Kim et al.	2018	Nuclear Power Plant Resilience	Developed a quantitative resilience model for NPPs. Emphasizing the ability to recover from disruptions.	Quantitative Modelling	Quantitative approach to resilience assessment in NPPs. Useful for improving resilience and safety management.
Risk analysis in Natech events: State of the art	Mesa-Gómez et al.	2020	Natech Risk Analysis	Reviews the current state of risk analysis for Natech events and provides insights into best practices for assessing and managing these risks.	Literature Review	Provides a comprehensive overview of current Natech risk assessment methods applicable to nuclear power plants.
Resilience and Stability of Ecological Systems	Holling	1973	Ecological Resilience	Introduced the concept of ecological resilience, focusing on the ability of ecosystems to absorb disturbances and reorganize while undergoing change.	Theoretical Framework Development	Supports understanding resilience in various systems, including its application to technological and infrastructure resilience.
The Resilience of Critical Infrastructure Systems: A Systematic Literature Review	Mottahedi et al.	2021	Critical Infrastructure Resilience	Identification of key resilience factors such as robustness, redundancy, and adaptability. It emphasizes the importance of system interdependencies and suggests that future research should focus on dynamic resilience metrics and real-time monitoring.	Systematic Literature Review	Creates comprehensive understanding of the concept of resilience in critical infrastructures by proposing a framework for assessing the resilience offering a basis for the development of resilience strategies.
Critical Infrastructures, Protection and Resilience	Setola et al.	2016	Overview of critical infrastructure protection and resilience strategies.	Outlines a multidisciplinary approach to infrastructure protection, integrating both technical and organizational measures. It highlights the increasing reliance on cyber-physical systems and the need for coordinated international efforts in resilience planning.	Broader strategies for critical infrastructure resilience	Broader strategies for critical infrastructure resilience
Strengthening Resilience in Critical Infrastructure Systems: A Deep Learning Approach for Smart Early Warning of Critical States.	Möhrle et al.	2021	Critical Infrastructure Resilience	Deep learning model for early warning of critical states in infrastructure systems.	Development of a Deep Learning Model	Innovative approach to enhancing predictive resilience strategies

Quantitative resilience evaluation on recovery from emergency situations in nuclear power plants.	Kim et al.	2021	Nuclear Power Plant Emergency Response	Quantitative assessment of resilience during NPP emergencies.	Quantitative Analysis	Enhances understanding of NPP resilience in emergencies
A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities	Bruneau et al.	2003	Community Seismic Resilience	Framework for assessing and enhancing community resilience to seismic events.	Conceptual Framework Development	Community-focused resilience, potentially applicable to NPP communities
Resilience Index Development for the Manufacturing Industry based on Robustness, Resourcefulness, Redundancy, and Rapidity	Sambowo & Hidayatno	2021	Resilience in manufacturing industry	Proposes a resilience index based on four key factors: robustness, resourcefulness, redundancy, and rapidity. The index helps assess the capacity of manufacturing systems to withstand and recover from disruptions.	Theoretical framework development and case study research	Useful for evaluating and enhancing resilience in manufacturing industries, especially in sectors highly vulnerable to operational disruptions.
Resilience capacities assessment for critical infrastructures disruption: the READ framework	Petrenj et al.	2018	Critical Infrastructure Resilience Assessment	Presented the READ framework for resilience capacity assessment in CIs.	Framework Development	Framework for assessing and enhancing resilience capacities in CIs
Resilience of critical infrastructure elements and its main factors	Rehak et al.	2018	Critical infrastructure resilience	Identifies key factors influencing the resilience of critical infrastructure. Develops a framework for assessing and improving resilience.	Theoretical framework & empirical validation	Crucial for understanding how infrastructure systems maintain function under disruption.
Understanding Resilience – a Conceptual Framework	Bucovetchi et al.	2024	Resilience conceptualization	Proposes a new conceptual framework for resilience applicable across multiple domains. Emphasizes adaptability, robustness, and recovery capacity.	Conceptual analysis & theoretical synthesis	Helps define resilience in various contexts, including critical infrastructure.

Identification of gaps in safety management systems from the resilience engineering perspective in upper and lower-tier enterprise	Pęciłło	2020	Safety management and resilience engineering	Exploration of main gaps in safety management. When applying to NPP safety, it emphasizes the importance of responsiveness, monitoring, learning and anticipation of adverse events.	Survey study	Shows importance of various dimensions of safety management with regards to resilience engineering. Highlighting weaknesses within resilience engineering practices.
Systemic resilience model	Lundberg & Johansson	2015	Resilience modeling	Develops a systemic model for analyzing resilience, integrating technical, social, and organizational factors.	Mathematical modeling & case study	Provides a structured model for assessing resilience in complex systems.
Reviewing qualitative research approaches in the context of critical infrastructure resilience	Cantelmi et al.	2021	Qualitative research in critical infrastructure resilience	Analyzes qualitative research methods used in studying critical infrastructure resilience. Identifies key gaps and suggests improvements for future studies.	Systematic literature review	Relevant for evaluating and refining research methodologies in infrastructure resilience studies.
Resilience of Critical Infrastructures: Benefits and Challenges from Emerging Practices and Programmes at Local Level	Albu & Flyverbom	2016	Organizational transparency	Explores different conceptualizations of organizational transparency, its enablers, and its effects on governance.	Theoretical framework & empirical study	Important for accountability and transparency research in infrastructure management.
Integration of Level 3 probabilistic risk assessment for nuclear power plants with transportation simulation considering earthquake hazards	Shimada et al.	2024	Probabilistic risk assessment (PRA) for nuclear power plants (NPPs).	Digital technology integration by Level 3 PRA model for NPPs by incorporating transportation simulation. This improves evacuation modeling during disasters, reducing reliance on subjective expert judgment.	Model development	Relevant for developing more accurate disaster preparedness strategies for NPPs by improving evacuation simulations during earthquake scenarios.

Optimal restoration of power infrastructure following a disaster with environmental hazards.	Moglen et al.	2024	Management of nuclear-contaminated water discharge for marine environment protection.	The paper discusses the emergency management and regulatory measures taken to control the discharge of nuclear-contaminated water from the Fukushima disaster into the ocean. It highlights the risks to marine life,	Literature review and analysis	Relevant for assessing nuclear safety measures in NPP operations, especially concerning environmental contamination and disaster response.
Emergency management of nuclear-contaminated water discharged into the ocean for marine environment security.	Shan and Ding	2024	Nuclear water contamination management	Discusses emergency management measures for discharging nuclear-contaminated water, focusing on the risks posed to marine life.	Literature review and post-disaster management strategy	Highlights nuclear safety measures and environmental impact mitigation in NPPs.
Resilience in Infrastructure Systems: A Comprehensive review	Liu et al.	2022	Critical Infrastructure Resilience	Literature review on infrastructure resilience, identifying five key research streams: assessment, improvement, conceptualization, influencing factors, and prediction of resilience.	Systematic literature review	Relevant for NPP resilience in improving and predicting critical infrastructure resilience under different conditions.
Assessing Resilience of Urban Critical Infrastructure Networks: A Case Study of Ahvaz, Iran	Alizadeh & Sharifi	2020	Urban infrastructure resilience	Assesses the resilience of water, electricity, and gas infrastructure in Ahvaz, showing poor performance in key regions due to centralized infrastructure and high population density.	Spatial analysis based on Delphi survey	Relevant for improving urban resilience strategies in NPPs, focusing on infrastructure robustness and redundancy
Building urban and infrastructure resilience through connectivity: An institutional perspective on disaster risk management in Christchurch, New Zealand	Huck et al.	2020	Institutional connectivity in urban resilience	Emphasizes the role of institutional connectivity in improving urban resilience, highlighting the complexities and trade-offs involved in institutional reforms for disaster risk management.	Case study and institutional analysis	Useful for understanding institutional reforms in infrastructure systems and NPP management to strengthen disaster resilience.

A framework for the resilience analysis of electric infrastructure systems including temporary generation systems	Toroghi & Thomas	2020	Electric power infrastructure resilience	Develops a quantitative framework to assess resilience in electric infrastructure systems, considering the contributions of temporary distributed generation (DG) technologies.	Quantitative framework based analysis	Evaluates critical infrastructure resilience, HelpsNPPs, particularly in disaster recovery scenarios where temporary generation systems are critical.
Power system resilience and strategies for a sustainable infrastructure: A review.	Mohanty et al.	2024	Power system resilience and sustainability	Reviews on resilience strategies for power systems, focusing on localized generation, diversification of energy resources, and recovery measures, with emphasis on integrating renewable energy sources into power grids.	Literature review	Review on developing resilience strategies in power generation systems, especially in integrating renewable energy and recovering from disruptions.
Probabilistic assessment of climate-related impacts and risks in ports	Lucio et al.	2024	Climate-related risks in port infrastructure	Introduction on a probabilistic risk assessment framework for ports exposed to climate hazards, integrating wave propagation simulations, climate hazard modeling, and failure mode assessments.	Probabilistic risk assessment with climate hazard modeling	Provides insights into managing climate-related risks for coastal NPP infrastructures, emphasizing the need for robust, long-term resilience planning.
Robustness-based evaluation of hydropower infrastructure design under climate change.	Taner et al.	2017	Hydropower infrastructure design under climate change	Application of a decision-scaling framework to assess the robustness of hydropower designs under climate change, showing that robustness-based designs perform better under uncertain future climates than traditional approaches.	Critical evaluation and building of decision-scaling framework	Relevant for NPP infrastructure design, especially in evaluating resilience under uncertain climate conditions.
A Petri net model-based resilience analysis of nuclear power plants under the threat of natural hazards	Yan et al.	2023	Resilience analysis for NPPs under natural hazards	Utilization of Petri net models to simulate the impact of extreme events on NPPs, covering design, operation, maintenance, and recovery. The method assesses the resilience of a single-unit pressurized heavy water reactor under multiple external event scenarios.		Provides a quantitative method for evaluating NPP resilience against natural hazards, essential for disaster preparedness and recovery.

Resilient critical infrastructures: An innovative methodological perspective for critical infrastructure (CI) integrated assessment models by inducing digital technologies during multi-hazard incidents.	El-Maissi et al.	2024	Methodological approaches for critical infrastructure resilience.	Proposing an innovative methodological framework for evaluating the vulnerability and accessibility of critical infrastructures during multi-hazard events. It emphasizes the use of digital technologies, including virtual reality, and big data to create an integrated system for disaster management.	Integrated assessment model	Relevant for enhancing the resilience of critical infrastructures, including NPPs, by integrating digital tools and spatial data for disaster preparedness
Hazard identification risk assessment and determining control for seismic aspects on site evaluation the nuclear power plant in West Kalimantan	Widjanarko et al.	2024	Seismic risk assessment for NPPs	Identifies hazards related to seismic activities for NPP sites and assesses risks at the regional, near-region, and site-specific levels. Establishes controls to mitigate occupational safety risks during NPP construction in seismic zones.	Risk Assessment Framework	Comprehension on evaluating and controlling seismic risks at NPPs, particularly in seismic zones.
Towards resilient vital infrastructure systems – challenges, opportunities, and future research agenda.	Mehvar et al.	2021	Critical Infrastructure Resilience	Identifies key challenges and opportunities in designing resilient infrastructure systems, proposing a conceptual framework for integrating social, ecological, and technical resilience, with attention to cascading effects and dependencies across systems.	Systematic literature review and conceptual framework	Useful for NPP system resilience by integrating social, ecological, and technical dimensions, and addressing cascading effects in complex systems.
Advancing Resilience of Critical Health Infrastructures to Cascading Impacts of Water Supply Outages—Insights from a Systematic Literature Review.	Sänger et al.	2021	Resilience in healthcare infrastructure and water supply.	The study highlights the vulnerability of healthcare infrastructures to cascading impacts caused by water supply failures, emphasizing the need for targeted organizational strategies to address these challenges. Lessons from past failures underline the importance of multi-disciplinary resilience strategies for future disruptions.	Systematic literature review	Relevant for improving the resilience of critical infrastructure in NPPs, especially for cascading impacts related to water or power supply failures, and organizational preparedness strategies.

Resilience assessment framework for critical infrastructure in a multi-hazard environment	Argyroudis et al.	2020	Multi-hazard resilience in critical infrastructure.	The paper proposes a novel framework for quantitative resilience assessment of critical infrastructures subjected to multiple hazards. It considers the vulnerability of infrastructure to various hazard actions and recovery strategies.	Quantitative resilience assessment with multiple hazard scenarios.	Supports NPP systems to develop multi-hazard resilience strategies, considering sequential hazards and varying recovery strategies.
Nuclear and renewables in multipurpose integrated energy systems: A critical review.	El-Enam et al.	2024	Integrated nuclear-renewable energy systems	Reviews integrated nuclear-renewable systems for multipurpose applications, discussing operational flexibility, cost reduction, and safety challenges. Emphasizes regulatory challenges and social acceptance.	Critical literature review	Integrated systems inmplementation into NPP systems
Reassessing the safety of nuclear power.	Wheatley et al.	2016	Nuclear power safety	Provides a statistical analysis of nuclear accidents, suggesting that while their frequency has decreased, severity has increased.	Statistical analysis of nuclear incidents	Highlighting the need for continued safety reforms in NPPs to prevent future catastrophic events.
Digital Twin conceptual framework for improving critical infrastructure resilience.	Brucherseifer et al.	2021	Digital Twin technology for infrastructure resilience	Proposes a conceptual framework for using Digital Twin technology to monitor, analyze, and predict infrastructure vulnerabilities in real-time. Integrates sensor data with virtual models for improved decision-making.	Conceptual Framework Development	Leveraging Digital Twin technology for real-time monitoring, prediction, and resilience improvements.
User Intervention in Disaster Management Systems for Resilient Smart Cities	Geihs	2023	Disaster management in smart cities	Proposes integrating Digital Twin technology with chatbots to enable real-time user intervention in disaster management systems. Aims to improve resilience and disaster response in smart city environments.	Case study and framework proposal	Integrating user-based interactions into disaster management protocols for enhancing disaster response capabilities.
Digitization, Cybersecurity and Risk Management in the Oil and Gas Sector in the post COVID world: A Systematic Literature Review.	Imran et al.	2024	Cybersecurity in digitized infrastructures	Explores the challenges of digitization and cybersecurity threats in critical infrastructures, especially in the oil and gas sector. Highlights the evolving threat landscape and the need for robust cybersecurity strategies.	Systematic literature review	Integration of digital technologies, particularly for managing cybersecurity risks in digitized operations.

Bridging gaps: Developing sustainable intergenerational decision making in radioactive waste management	Mayer et al.	2016	Intergenerational Collaboration in Radioactive Waste Management	Discusses sustainable decision-making processes that involve both current and future generations in managing radioactive waste.	Case study	Supports collaborative approaches for decision-making in NPP resilience and waste management.
Organizational learning from the past, for resilience enhancemnt						
Barriers to learning from incidents and accidents	ESReDa	2015	Barriers to learning from incidents and accidents	Identifies common barriers to learning from past incidents in high-risk industries. Discusses cultural, organizational, and systemic obstacles that prevent effective learning and improvement in safety management.	Non-scholarly article: Case study analysis & expert consultation	Crucial for understanding why organizations fail to learn from accidents and how systemic changes can improve learning and safety practices.
Passive and active training approaches for critical infrastructure protection	Franchina et al.	2021	Training for critical infrastructure security	Compares passive and active training methods in critical infrastructure protection. Concludes that blended training approaches enhance resilience and responsiveness.	Comparative study & empirical analysis	Essential for designing security training programs for infrastructure resilience.
Sustainable evaluation and verification in supply chains	Gualandris et al.	2015	Sustainability in supply chains	Examines how firms evaluate and verify sustainability in supply chains. Aligning accountability with stakeholder expectations improves performance.	Empirical study & stakeholder analysis	Relevant for research on sustainability and accountability in large infrastructure projects.
Transparency	Farrell	2016	Transparency in organizations	Explores transparency as a key factor in organizational trust and accountability. Discusses strategies for improving transparency.	Theoretical analysis & case studies	Essential for understanding how transparency affects governance and risk management.
The complexity of the antecedents influencing accountability in organisations	Pearson & Sutherland	2017	Organizational accountability	Identifies factors influencing accountability in organizations. Proposes a complexity-based model for improving accountability practices.	Empirical study & theoretical framework	Important for governance and accountability research in infrastructure projects.

Beyond compliance: evaluating the role of ESG disclosures in enhancing firm value and performance	Tamasiga et al.	2024	ESG disclosures and corporate performance	Finds that robust ESG disclosures improve firm value and stakeholder trust. Highlights challenges in ESG reporting.	Empirical study & regression analysis	Useful for sustainability and transparency discussions in business and infrastructure resilience.
Measuring organizational resilience as a performance outcome	Ilseven & Puranam	2021	Organizational resilience	Develops a methodology for measuring resilience as a performance indicator. Demonstrates how resilience contributes to organizational success.	Empirical study & resilience modeling	Useful for quantifying resilience in business and infrastructure settings.
No Longer Out of Sight, No Longer Out of Mind? How Organizations Engage with Process Mining-Induced Transparency	Eggers et al.	2021	Process mining and transparency	Explores how process mining increases transparency in organizations. Highlights potential risks and benefits.	Case study & theoretical analysis	Relevant for understanding digital transparency in infrastructure management.
Exploring transparency: A new framework for responsible business management	Parris et al.	2016	Corporate transparency	Proposes a new framework for business transparency, integrating ethical and regulatory aspects.	Conceptual framework & empirical testing	Relevant for accountability and transparency in large projects.
Trust and risk perception of natural hazards: implications for risk preparedness in Chile	Bronfman et al.	2016	Risk perception and preparedness	Analyzes the relationship between public trust, risk perception, and preparedness for natural hazards in Chile. Finds that trust in institutions influences risk mitigation behavior.	Empirical study & survey analysis	Relevant for understanding the role of trust and perception in disaster preparedness and policy implementation.
Corporate sustainability, organizational resilience, and corporate purpose: a review of the academic traditions connecting them	Florez-Jimenez et al.	2024	Corporate sustainability and resilience	Explores academic traditions connecting corporate sustainability, resilience, and purpose. Highlights best practices for integrating sustainability into corporate strategy.	Systematic literature review	Useful for understanding the intersection of corporate sustainability and resilience strategies.

Resilience metrics for improved process-risk decision making: Survey, analysis and application.	Jain et al.	2018	Process-risk decision making through resilience metrics.	The paper proposes the Process Resilience Analysis Framework (PRAF) to assess risk through three phases: avoidance, survival, and recovery. It provides a comprehensive survey of resilience metrics and their application in chemical process systems, enhancing risk assessment with a structured resilience approach.	Survey and application of framework	elevant for NPPs focusing on resilience-based risk assessment in process safety and decision-making frameworks.
Digital transformation influence on organisational resilience through organisational learning and innovation	Awad & Martín-Rojas	2019	Resilience engineering in national infrastructure	Proposes a resilience engineering framework that integrates human and socio-technical capacities for improving national infrastructure resilience. Highlights adaptive capabilities and risk management.	Resilience engineering & case study analysis	Essential for understanding how engineering and human factors contribute to resilient infrastructure systems.
Data for Disaster Management: Mind the Gap.	van den Hornberg	2016	Data management in disaster risk reduction.	Significant gaps in the collection, management, and use of disaster-related data, calling for improved data governance in disaster management frameworks. It discusses the challenges in accessing real-time, reliable data during crises, and the importance of community participation. The lack of coordination between various stakeholders leads to suboptimal disaster preparedness and response. The study proposes a multi-stakeholder approach to bridge the gap.	Literature review	Relevant for improving data management strategies in NPPs to enhance disaster preparedness and response systems. Proposes a multi-stakeholder approach.
Impact of organizational inertia on business model innovation, open innovation and corporate performance.	Moradi et al.	2021	Organizational inertia in innovation processes.	The study explores how organizational inertia acts as a significant barrier to business model innovation (BMI) and open innovation (OI), thus organizational performance. It highlights that overcoming inertia requires changes in organizational structures, management practices, and external collaborations to improve innovation performance and corporate outcomes.	Emperical analysis and case study research	Important for addressing organizational resistance to change, ability to innovate and enhance operational efficiency.

Identification of managerial shaping factors in a petrochemical plant by resilience engineering and data envelopment analysis.	Azadeh et al.	2015	Managerial factors influencing resilience in petrochemical plants.	Focus on how managerial shaping factors can influence resilience in petrochemical plants through resilience engineering principles.Factors such as leadership, decision-making, and organizational culture can impact the plant's ability to handle disruptions and recover from incidents.	Resilience engineering framework with data envelopment analysis	Helps understanding how managerial practices influence operational resilience and safety.
Knowledge sharing in heterogeneous teams through collaboration and cooperation	Grösser et al.	2017	Long-life asset management	Examines the lifecycle dynamics of long-life assets, emphasizing sustainability, resilience, and maintenance strategies.	Systems dynamics & case study analysis	Essential for understanding asset management and long-term infrastructure resilience.
Understanding Collaboration in Integrated Forms of Project Delivery by Taking a Risk-Uncertainty Based Perspective	Nissen et al.	2014	Knowledge sharing in innovation partnerships	Explores how knowledge sharing mechanisms in heterogeneous teams impact collaboration in public-private innovation partnerships.	Empirical study & case analysis	Important for fostering innovation and collaboration in infrastructure projects.
Organizational Structure, Information Processing, and Decision-Making: A Retrospective and Road Map for research	Walker & Lloyd-Walker	2016	Project collaboration and risk management	Examines collaboration in integrated project delivery, focusing on managing risks and uncertainties.	Case study & risk analysis	Useful for understanding risk management in collaborative infrastructure projects.
Developing shared understanding through online interdisciplinary collaboration	Joseph & Gaba	2019	Organizational decision-making	Reviews research on organizational structure, information processing, and decision-making, proposing a roadmap for future studies.	Systematic literature review	Important for decision-making frameworks in infrastructure and resilience planning.
Human and organizational factors in European nuclear safety	Hasan et al.	2023	Interdisciplinary collaboration in urban development	Examines how online collaboration enhances shared understanding in research projects focused on urban health integration.	Qualitative research & case study	Relevant for research on interdisciplinary approaches to infrastructure planning.

Collaborative Traceability Management: Challenges and Opportunities	Schöbel et al.	2021	Human and organizational factors in nuclear safety	Analyzes how human and organizational factors have shaped European nuclear safety over 50 years.	Historical review & policy analysis	Useful for understanding nuclear safety governance and human factors in resilience.
Organizational transparency: conceptualizations, conditions, and consequences	Wohlrab et al.	2016	Traceability in collaborative projects	Examines challenges and best practices for collaborative traceability management in engineering projects.	Case study & theoretical framework	Essential for traceability management in complex infrastructure systems.
Knowledge sharing in heterogeneous teams through collaboration and cooperation	He et al.	2022	Digital transformation and resilience	Analyzes how digital transformation strategies enhance organizational resilience, focusing on adaptability and risk management.	Empirical study & digital resilience framework	Useful for integrating digital tools in infrastructure resilience strategies.
Project governance and its role in enabling organizational strategy implementation: A systematic literature review	Musawir et al.	2019	Project governance and strategy implementation	Reviews project governance structures and their role in facilitating organizational strategy execution.	Systematic literature review	Crucial for governance in infrastructure and large-scale projects.
On inscription and bias: data, actor network theory, and the social problems of text-to-image AI models	Morton	2024	Bias and AI models in text-to-image generation	Examines how bias is embedded in text-to-image AI models using actor network theory. Discusses ethical implications and possible mitigation strategies.	Theoretical analysis	Important for understanding bias in AI applications related to digital transformation and infrastructure monitoring.
Linking knowledge management, organizational learning and memory	Antunes & Pinheiro	2019	Knowledge management and organizational learning	Examines how organizations integrate knowledge management, learning, and memory to improve decision-making and performance.	Theoretical analysis & empirical case studies	Important for fostering learning and adaptability in infrastructure organizations.

The Role of Leadership in Changing Organizational Culture.	Jerab & Mabrouk	2023	Leadership and organizational culture change.	Leadership shapes organizational culture by defining values, fostering innovation, and managing resistance to change. Ethical leadership and adaptability are emphasized as crucial for successful cultural transformation.	Literature review and empirical study	Leverage of leadership for cultural transformation, promoting innovation and adaptability.
Effects of perceived role clarity on innovative work behavior: a multiple mediation model	Kundu et al.	2019	Role clarity and innovative work behavior	Explores how perceived role clarity influences innovative work behavior through multiple mediation effects.	Empirical study & mediation modeling	Relevant for understanding factors driving innovation in organizational settings.
The role of organizational learning in the Opportunity–Recognition process	Lumpkin & Lichtenstein	2005	Organizational learning and opportunity recognition	Analyzes the role of organizational learning in recognizing and seizing entrepreneurial opportunities.	Conceptual framework & empirical validation	Useful for integrating learning processes into innovation and strategy development.
Fair, transparent, and accountable algorithmic decision-making processes	Lepri et al.	2017	Algorithmic decision-making and accountability	Discusses principles for fair, transparent, and accountable AI-driven decision-making processes.	Theoretical analysis	Important discussion on AI usage in decision-making and governance.
Accountable privacy-preserving attribute-based access control for cloud services enforced using blockchain	Ghorbel et al.	2021	Privacy and security in cloud computing	Proposes a blockchain-enforced attribute-based access control model to enhance accountability and privacy in cloud services.	Technical framework & empirical validation	Discusses components of secure and accountable data management in cloud computing and infrastructure resilience.
From transparency to accountability of intelligent systems: Moving beyond aspirations	Williams et al.	2022	Transparency and accountability in AI systems	Explores challenges in shifting from AI transparency to accountability and proposes actionable solutions.	Theoretical framework & empirical review	Essential for ensuring responsible AI deployment in critical infrastructure and decision-making.
Towards a standard for identifying and managing bias in artificial intelligence	Schwartz et al.	2022	AI bias management and standardization	Proposes a standardized framework for detecting and mitigating bias in AI systems.	Policy analysis & technical framework	Important for fairness, transparency, and accountability in AI applications.

Four reference models for transparency requirements in information systems	Hosseini et al.	2017	Transparency in information systems	Proposes four reference models for designing transparency requirements in information systems.	Conceptual framework & empirical validation	Important for ensuring transparency in digital infrastructure systems.
New Information Technology and Implicit Bias	Elsbach & Stigliani	2018	Implicit bias in new information technology	Explores how new IT can reinforce or mitigate implicit biases in organizational decision-making.	Theoretical framework & empirical analysis	Relevant for addressing biases in AI-driven decision-making and infrastructure management.
Strategic alignment: A missing link in the relationship between strategic consensus and organizational performance	Walter et al.	2013	Strategic alignment in organizations	Investigates how strategic alignment acts as a mediator between strategic consensus and organizational performance.	Empirical study & structural equation modeling	Useful for understanding how strategic alignment influences resilience in organizations.
Separation of duties for access control enforcement in workflow environments	Botha & Eloff	2001	Access control and security enforcement	Analyzes separation of duties in access control enforcement to enhance security in workflow environments.	Security modeling & empirical validation	Relevant for cybersecurity and access control strategies in infrastructure systems.
Extending business process management for regulatory transparency	Kiesel & Grünewald	2024	Business process management and transparency	Proposes extensions to business process management frameworks to improve regulatory transparency and compliance.	Conceptual framework & case study	Useful for integrating regulatory transparency in infrastructure governance.
Absorptive Capacity: A New Perspective on Learning and Innovation.	Cohen & Levinthal	1990	Organizational learning and innovation	Introduction of absorptive capacity, defined as an organization's ability to recognize the value of external knowledge, assimilate it, and apply it to commercial ends. It argues that a firm's innovative capacity is not only determined by its own R&D efforts but also by its ability to learn from external knowledge sources. Prior knowledge plays a critical role in building absorptive capacity.	Theoretical and conceptual framework development.	Explores how organisations can improve their capacity to learn and innovate from external sources. Underlines that external knowledge integration leads to operational improvements.

Intervening role of realized absorptive capacity in organizational culture–open innovation relationship.	Naqshbandi & Kamel	2017	Absorptive capacity, organizational culture, and open innovation.	Investigation on different types of organizational culture, influencing open innovation and the mediating role of absorptive capacity. Highlights how integrative organizational culture positively influence open innovation, by enhancing absorptive capacity.	Empirical study	Shows importance of an organizational culture that enhances absoprtive capacity. Resultign in enhanced knowledge integration.
Investigating the Impact of Information Technology, Absorptive Capacity, and Dynamic Capabilities on Firm Performance: An Empirical Study	Ma et al.	2021	Information technology, absorptive capacity, and dynamic capabilities.	Dynamic capabilities and absorptive capacity enhance firm performance by improving innovation, sensing opportunities, and adapting to environmental changes. Information technology supports these capabilities, leading to increased financial performance and competitive advantage.	Empirical study	Shows that leveraging IT and dynamic capabilities improves operational efficiency and innovation.
Utilization of Digital Technologies						
Digital technologies can enhance climate resilience of critical infrastructure	Argyroudis et al.	2022	Climate Resilience in Critical Infrastructures	IoT, AI and digital tools can improve infrastructure resilience but lacks full integration	Literature review	Relevant for integrating IoT and AI into resilience strategies for NPP disaster management.
A resilient Internet of Things architecture for smart cities.	Abreu et al.	2016	IoT and Smart Cities Resilience	IoT architecture improves fault recovery in smart systems without human intervention.	Proposal for IoT architecture design	Useful for designing resilient IoT systems for NPPs to handle faults and disasters automatically.
Predictive maintenance architecture development for nuclear infrastructure using machine learning.	Gohel et al.	2020	Predictive Maintenance for Nuclear Infrastructure	Machine learning improves predictive maintenance in nuclear infrastructure by focusing on rare events.	Development of machine learning model	Supports the use of predictive analytics in enhancing NPP resilience to disruptive events.

Towards Disaster Resilient Smart Cities: Can Internet of Things and Big Data Analytics Be the Game Changers?	Shah et al.	2019	Disaster resilience in smart cities using IoT and big data.	The paper proposes a novel reference architecture for disaster-resilient smart cities (DRSC) through the integration of IoT and big data analytics (BDA). It discusses how these technologies can enhance disaster preparedness and management by providing real-time data and insights for effective decision-making during crises.	Design science approach and case study research.	Implementation of advanced technology solutions for enhancing resilience.
Big data analytics: Understanding its capabilities and potential benefits for healthcare organizations.	Wang et al.	2018	Big data in decision-making for safety and risk management.	This study presents a conceptual framework for safety decision-making (SDM) based on big data. It outlines the process of data collection, analysis, and decision-making, identifying six general types of analytics and five specific types for safety management. The framework helps in understanding how big data influences safety strategies and risk mitigation.	Conceptual framework for big-data-driven safety decision-making (SDM).	Levaraging big data for improving safety strategies and risk management in critical operations.
Implementing big data strategies: A managerial perspective	Tabesh et al.	2019	Big data strategy implementation.	The paper lays out the steps necessary for successfully implementing big data strategies, highlighting managerial responsibilities such as commitment, coordination, and communication. It also identifies common challenges in using big data and offers strategies for overcoming these challenges, with recommendations for developing knowledge and expertise in big data analytics.	Managerial perspective and case study analysis.	Implementation of big data strategies for decision-making, enhancing their operational efficiency and risk management.
Big data analysis for decision-making processes: challenges and opportunities for the management of health-care organizations.	Fanelli et al.	2022	Big data in healthcare management	Big data can revolutionize decision-making processes in healthcare organizations, focusing on the challenges and opportunities it presents. Highlighting issues such as data integration, privacy, and the need for skilled professionals to interpret data. T	Systematic literature review and empirical analysis.	Considers big data analytics for operational decision-making and managing complex systems.
A Cost Stabilization Facility for Kickstarting the Commercialization of Small Modular Reactors.	Moniz et al.	2023	Commercialization of Small Modular Reactors and cost risk management	The study suggests that risk-sharing mechanisms and government-backed financial support are essential to stabilize costs, reduce risks, and attract private investment for SMR deployment.	Policy analysis and framework development	Important for NPPs and policymakers on resilience engineering, considering financial barriers.

Building organizational resilience with digital transformation	Maguire	2013	Socio-technical systems and interaction design	Explores the relevance of socio-technical systems thinking in modern interaction design.	Conceptual framework & empirical validation	Important for designing resilient socio-technical infrastructure systems.
Advances in Computer Vision-Based Civil Infrastructure Inspection and Monitoring.	Spencer et al.	2019	Digital technology integration in CIs	Highlights the use of AI, machine learning, and UAVs for automating defect detection, monitoring structural displacements. Emphasizes challenges such as data quality and environmental impacts.	Literature review and case study analysis	Implementation of advanced monitoring and inspection techniques using computer vision for infrastructure maintenance.
Video Data Analysis: A Methodological frame for a novel research trend	Nassauer & Legewie	2018	Video data analysis in social research	Proposes a methodological framework for video data analysis in social research, highlighting its advantages and limitations.	Methodological analysis & case study	Useful for integrating video analysis techniques into resilience and infrastructure research.
Industry 4.0, Disaster Risk Management and Infrastructure Resilience: A Systematic Review and Bibliometric Analysis	Rad et al.	2021	Industry 4.0, disaster risk management (DRM), and infrastructure resilience.	The paper systematically reviews the integration of Industry 4.0 technologies—such as AI, IoT, and big data analytics—into DRM. Identification of six research clusters: AI, big data, IoT, prefabrication and modularization, robotics, and cyber-physical systems. These technologies support improvement of the resilience against natural disasters.	Systematic literature review	Highlights adoption of Industry 4.0 technologies to improve disaster preparedness, response, and infrastructure resilience.
Use of personal health records during and after a disaster including a nuclear accident: A scoping review.	Oikawa et al.	2024	Data management of nuclear disaster	Public health records play a crucial role in managing patient care, tracking survivors, and improving healthcare access during disasters. However, challenges such as data quality, privacy, and cost need to be addressed. Integration with national database to enhance effectiveness in future disaster scenarios.	Scoping review	Shows the challenges of data management during and post nuclear accident.
The expected contribution of Industry 4.0 technologies for industrial performance.	Dalenogare et al.	2018	Contribution of Industry 4.0 technologies to industrial performance	Industry 4.0 technologies such as integrated engineering systems, additive manufacturing, and digital automation can significantly enhance product development, operational efficiency, and sustainability. The study uses data from Brazilian industries and highlights challenges specific to emerging markets.	Regression analysis using survey data	Shows how Industry 4.0 technologies can improve operational performance.

Guest Editorial Industry 4.0–Prerequisites and Visions	Vogel-Heuser en Hess	2016	Industry 4.0 technology implementation	Outline of design principles for Cyber-Physical Production Systems in Industry 4.0, including modularity, interoperability, real-time data processing, and cross-disciplinary integration. It emphasizes the need for cooperation between academia and industry to fully realize the benefits of Industry 4.0.	Conceptual framework	Helps understanding the prerequisites and design principles needed to implement Industry 4.0 technologies for improved operational efficiency and adaptability.
Strategic energy management in industry 4.0 environment.	Javied et al.	2018	Strategic energy management in Industry 4.0.	Explores cloud-based energy monitoring systems in Industry 4.0 environments, emphasizing the importance of energy management for reducing costs, increasing energy efficiency, and maintaining competitiveness. It also presents an integrated energy management solution that enables real-time monitoring, energy flexibility, and load management.	Conceptual framework and case study research	Implementation of cloud-based digital technologies to improve operational performance
An empirical analysis of critical factors of Industry 4.0: a contingency theory perspective.	Bhatia & Kumar	2023	Industry 4.0 adoption in manufacturing.	Identifies six categories of critical factors: organizational, workforce management, external support, technological infrastructure, usage of data, and regulations. Examines contingency effects of firm size and industry sector on I4 adoption.	Emperical analysis and case study research	Implemention of industry 4.0 technologies by identifying key factors influencing adoption and success.
Industry 4.0 Solutions Impacts on Critical Infrastructure Safety and Protection–A Systematic Literature Review	Wisniewski et al.	2022	Impact of Industry 4.0 solutions on critical infrastructure safety and protection.	Industry 4.0 technologies, such as CPS, IIoT, and big data, offer improvements in decision-making, forecasting, and system resilience for critical infrastructures. However, they also introduce cybersecurity risks and integration challenges.	Systematic literature review	Integration of Industry 4.0 technologies while managing cybersecurity risks and enhancing infrastructure safety.
Industry 4.0 ten years on: A bibliometric and systematic review of concepts, sustainability value drivers, and success determinants	Ghobakhloo et al.	2021	Industry 4.0 concepts, sustainability drivers, and success factors over ten years.	Identifies technologies such as IoT and AI as key drivers. Emphasizes sustainability benefits, including enhanced resource efficiency and environmental impact reduction. Success factors for adoption include technological readiness, financial resources, and strong organizational support.	systematic literature review.	Integration Industry 4.0 technologies for enhanced operational performance

Making Smart Cities Resilient to Climate Change by Mitigating Natural Hazard Impacts	Ragia & Antoniou	2020	Smart cities resilience to climate change	GIS-based tools are critical for risk mapping, real-time hazard monitoring, and urban planning to increase resilience against climate-induced hazards.	Case study research	Integrating technological solutions to enhance resilience against natural hazards.
Impact of Digital Transformation on the Energy Sector: A Review.	Nazari & Musilek,	2023	Digital transformation in the energy sector.	Digital technologies like IoT, Big Data, and AI improve operational efficiency, cost reduction, and the integration of renewable energy sources.	Systematic literature review.	Explores the role of digital transformation in optimizing energy management and integrating renewables.
The impact of Industry 4.0 technologies on the resilience of established cross-border supply chains.	Brookbanks & Parry	2024	Impact of Industry 4.0 technologies on cross-border supply chain resilience.	Industry 4.0 technologies like IoT and blockchain enhance supply chain visibility, collaboration, and trust, improving resilience and reducing disruptions in cross-border logistics.	Systematic review and case study analysis	Impact of Industry 4.0 technologies adoption on resilience and organizational performance
Artificial Intelligence in Disaster Risk Communication: A Systematic Literature Review	Ogie et al.	2018	AI in disaster risk communication	Reviews AI applications in disaster risk communication, identifying key trends, challenges, and future research directions.	Systematic literature review	Important for understanding AI's role in enhancing disaster response and resilience.
The role of IT-enabled collaborative decision making in inter-organizational information integration to improve customer service performance	Wong et al.	2014	IT-enabled collaborative decision making	Explores how IT-enabled decision-making enhances information integration and customer service performance in inter-organizational networks.	Empirical study & statistical modeling	Useful for understanding the role of IT in decision-making and collaboration.
Machine learning applications in the resilience of interdependent critical infrastructure systems—A systematic literature review.	Alkhaleel	2024	Machine learning applications in the resilience of CIs	Highlights ML technologies used to model and enhance resilience in CIs, addressing gaps in failure prediction and resource optimization.	Systematic literature review	Relevant for enhancing NPPs resilience through advanced machine learning applications.

A novel digital twin framework of electric power infrastructure systems subjected to hurricanes.	Braik & Koliou	2023	Digital Twin integration for CI resilience against natural hazards	Proposes a Digital Twin framework integrating real-time data and predictive models to enhance decision-making for hurricane impact mitigation on electric power networks.	Case study research	Adopting Digital Twin technology for real-time monitoring and decision support systems for infrastructure resilience during natural hazards.
Enhancing the Operational Resilience of Advanced Reactors with Digital Twins by Recurrent Neural Networks.	Lin et al.	2021	Digital Twin utilization for enhancing resilience of nuclear plants using	Discussion on the application of diagnosis and prognosis digital twins to improve state awareness and operational flexibility in reactors. The implementation enhances real-time monitoring and predictive control during anomaly or accident scenarios.	Conceptual model development	Relevant for integrating digital twin technology in nuclear plant management to ensure operational resilience, safety, and optimized decision-making.
Smart Cities with Digital Twin Systems for Disaster Management	Ford & Wolf	2020	Digital twin application in smart cities for disaster management	Proposes a conceptual model integrating smart city technologies and digital twins to manage disasters by enhancing community resilience. Highlights the role of real-time data and simulation for improved decision-making across disaster phases.	Development of a conceptual model based on literature review and analysis of smart city and digital twin case studies.	Employing digital twin systems for proactive disaster mitigation, preparation, response, and recovery
Digital Twins for Nuclear Power Plants and Facilities.	Kropaczek et al.	2023	Digital Twin utilization in nuclear plants	Emphasis on application and advancements of digital twin technologies in enhancing the operational efficiency, safety, and maintenance of nuclear power plants.	Systematic literature review	Provides an in-depth analysis of how digital twins can be integrated into nuclear energy systems for real-time monitoring, predictive maintenance, and operational efficiency.
Big Data Analytics: an emerging technology	Kumar	2021	Big data analytics	Examination of the evolution of BDA from a niche area to a critical technology, with widespread applications across military, medical, educational, and business domains. Highlights the integration of AI-driven machine learning, IoT, and cloud computing in predictive, prescriptive, and descriptive analytics.	Systematic literature review	Relevant for understanding the penetration of big data analytics, focusing on how it drives digital transformation and decision-making processes.

Disaster resilience through big data: Way to environmental sustainability.	Sarker et al.	2020	Big data applications in disaster resilience and environmental sustainability.	Investigation on how big data technologies such as remote sensing data can enhance resilience by improving disaster management in areas like early warning, response, and recovery. It highlights the role of open data, strong infrastructure, and local skill development in ensuring effective use of big data.	Systematic literature review	Leveraging big data for more efficient and sustainable disaster response systems.
Virtual and augmented reality technologies for emergency management in the built environments: A state-of-the-art review.	Zhu & Li	2020	Virtual and augmented reality (VR/AR) technologies for emergency management in the built environment.	VR/AR technologies are increasingly adopted for pre-emergency preparedness, real-time emergency response, and post-emergency recovery. The paper highlights their potential for hazard recognition, safety training, evacuation, and damage assessment.	Systematic literature review	Application of VR and AR for improving emergency management, to simulate scenarios for training, planning and disaster response.
Defining Mutual Awareness: Results of Reactor Operator Surveys on the Emergence of Digital Technology in Main Control Rooms	Medema et al.	2018	Human behaviour related to digital technolgy application	Reactor operators face challenges in maintaining mutual awareness due to the increasing use of digital technology in control rooms. Surveys revealed a gap in communication and awareness in high-tech environments, emphasizing the need for better human-machine interfaces.	Survey study	Incorporating digital technologies in safety-critical environments, such as nuclear power plants (NPPs). Investigating where human error can have significant consequences
Unifying technologies in industry 4.0.	Logeswaran et al.	2024	Integration of industry 4.0 technologies	Discusses unification of various technological innovations such as IoT, AI, and cyber-physical systems to enhance industrial processes. The study highlights challenges and opportunities in merging these technologies to improve resilience, productivity, and automation.	Systematic literature review	Understanding the role of integrated technologies in modern industries, particularly in automation, supply chain management, and disaster resilience contexts.
Agile IoT for Critical Infrastructure Resilience: Cross-Modal Sensing As Part of a Situational Awareness Approach	Russell et al.	2018	IoT solutions for enhancing resilience of CIs	Proposes a model for utilization of agile IoT-based systems to improve situational awareness in critical infrastructure. By repurposing existing sensors in critical infrastructures to sense additional parameters, improving resilience without needing new hardware.	Model development	Study shows the potential of leveraging existing IoT devices in improving the resilience and adaptive capacity of critical infrastructures, especially in disaster management and real-time monitoring.

Table 3: Characteristics of the reviewed literature

Appendix A.2 SLR search strategy

Adding to the scope discussed in Chapter 2.2 relating the objectives of this study to the scope by narrowing down the literature to be reviewed;

- Evaluate the status quo of resilience engineering and risk management – In relevant critical infrastructures
- Identify challenges within the process of organizational learning – From past disasters
- Implementation of digital technologies in organizational learning– For enhanced resilience in nuclear power plants

The full criteria for selection are shown below in Table 4. This approach ensures that the review is comprehensive and captures the most relevant research within the context of this study. By setting a clear scope, the review focuses on adequate and relevant literature. Make sure that studies reviewed are relevant to the nuclear industry and resilience learning. The emphasis on natural disasters and critical infrastructures, specifically nuclear power plants. Ensures that the findings are directly applicable to the primary objective of enhancing NPP resilience against such events. This detailed scope aided the screening process by making sure the studies selected, and its' contents were relevant or translatable to nuclear power plants and resilience enhancement learning. Several older papers, seven, were added to the literature as they provided concept definitions, adding to the clarity of discussion. To complement the insights derived from the scholarly literature on existing resilience learning practices and investigate the integration of learning process guidelines and digital technology capabilities. Grey literature was systematically included as part of the SLR and literature synthesis. Consisting of policy documents, regulatory frameworks and industry reports. Targeted searches were conducted on the websites of the IAEA, the European commission and the UN office for disaster risk reduction (UNDRR). The selection of these documents was based on the relevance to NPP resilience, governance and policy directives or regulatory frameworks. For example, the Directive 2014/87/EURATOM was included due to direct implications on nuclear safety protocols following the Fukushima Daiichi disaster. Regarding the grey literature, the screening and selection process were similar. The selection and relevance of industry reports and policy or regulatory documents was assessed based on established authorities within the industry. And done through targeted searches on “nuclear safety and resilience” within the IAEA publication database and European Commission websites.

Criteria	Inclusion	Exclusion
Year of publication	2011-2024	<2011
Type	Articles, Conference papers, book chapters and reviews Reports from authority sources (IAEA, EU commission, UNDRR).	(Lecture) notes, editorials, , short surveys. Books, unless they present a systematic framework relevant to resilience engineering/learning. Grey Literature: Except for policy directives, regulatory frameworks, and industry reports from authority institutions.
Language	English	Non-English, due to accessibility and interpretation limits.
Focus of research	Studies that specifically address: - Resilience engineering and risk management in NPPs or similar critical infrastructures. - Organizational learning and absorptive capacity in resilience engineering. - Integrating digital technologies for disaster data analysis, resilience enhancement and learning process development. - Exploring barriers to learning, from past disasters, strategy adoption - Stakeholders, disaster response strategies and regulatory frameworks that influence resilience learning in NPPs.	- Focus on supply/value chains. - Focus on disasters not related to natural hazards. - Sole focus on cyber-security or research from economics perspective. - Unclear methodology for data collection. - Generic safety management. - Critical Infrastructures not relatable to NPPs (e.g., hospitals, telecommunication, transport). And non-transferable insights to NPPs.

Table 4: Inclusion and Exclusion criteria for the literature selection process

Search queries used

	Queries	Results WOS	WOS: Exclusion on Year of publication, Type, Language	Results Scopus	Scopus: Exclusion on Year of publication, Type, Language
1	(nuclear power plant OR critical infrastructure) AND (resilience engineering OR risk management) AND (natural hazards OR natural disaster)	57	Year: 5 Type: 2 Language: 0 Records after filters N=50	129	Year: 20 Type: 1 Language: 4 Records after filters N=104

2	(nuclear power plant OR critical infrastructure) AND (challenges OR barriers) AND (resilience engineering)	10	Year: 0 Type: 0 Language: 0 Records after filters N=10	15	Year: 0 Type: 0 Language: 0 Records after filters N=15
3	Socio technical systems AND nuclear power plants	38	Year: 3 Type: 0 Language: 0 Records after filters N=35	68	Year: 12 Type: 0 Language: 1 Records after filters N=55
4	Learning AND resilience engineering AND (critical infrastructures OR nuclear power plants)	12	Year: 1 Type: 0 Language: 0 Records after filters N=11	40	Year: 1 Type: 0 Language: 3 Records after filters N=36
5	Organizational learning AND absorptive capacity AND resilience)	19	Year: 3 Type: 4 Language: 0 Records after filters N=12	7	Year: 1 Type: 0 Language: 0 Records after filters N=6
6	(Absorptive capacity AND resilience engineering)	76	Year: 1 Type: 2 Language: 0 Records after filters N=73	13	Year: 0 Type: 0 Language: 0 Records after filters N=13
7	Learning from past AND nuclear power plants	79	Year: 20 Type: 1 Language: 0 Records after filters N=58	67	Year: 18 Type: 1 Language: 3 Records after filters N=45
8	Learning from past AND critical infrastructure	171	Year: 23 Type: 5 Language: 1 Records after filters N=142	231	Year: 23 Type: 9 Language: 6 Records after filters N=193
9	Digital technology OR digitalization) AND resilience AND nuclear power plants	10	Year: 0 Type: 0 Language: 0 Records after filters N=10	11	Year: 0 Type: 1 Language: 0 Records after filters N=10
10	Digital technology OR industry 4.0" AND resilience engineering AND (critical infrastructures OR nuclear power plants)	82	Year: 2 Type: 4 Language: 0 Records after filters N=64	91	Year: 1 Type: 4 Language: 1 Records after filters N=85
11	Digital technologies AND natural hazards AND	12	Year: 0 Type: 0	2	Year: 0 Type: 0

	(critical infrastructures OR nuclear power plants)		Language: 0 Records after filters N=12		Language: 0 Records after filters N=2
12	Learning AND resilience AND nuclear power plants	30	Year: 1 Type: 0 Language: 0 Records after filters N=29	25	Year: 5 Type: 2 Language: 0 Records after filters N=18

Table 5: Search queries and initial results obtained after filtering

Thematic clusters

From the SLR data processing, several, sub-topics emerged, which were grouped into thematic clusters. Each cluster represents a key area of the focus of this study and presents a pillar for developing the theoretical learning process (ELP-model). Through these thematic clusters, this study was able to structure a comprehensive synthesis of the existing literature, identifying interrelations, trends and gaps to inform an integrated learning process guideline.

NPP system context and Stakeholders:

- Gain a comprehensive understanding of the surroundings of the nuclear power plant and this study. Examining policy, regulatory landscape regarding resilience and learning from the past.
- Evaluation of stakeholders surrounding the NPP system, and their roles in resilience practices and learning processes.
- Identification of key stakeholders and their roles in NPP resilience.

Socio-Technical systems perspective

- Identify interdependencies between social and technical subsystems. Understanding the relation between technology integration and social dimension that inform successful and effective adoption.

Current Practices and Challenges in NPP Resilience:

- Assessment of current resilience engineering and risk management
- Identify barriers and challenges in implementing these strategies.

Learning from Past Disasters:

- Explore what it takes to learn, and how to enhance the learning processes within NPPs
- Frameworks and models for improving learning processes.

Utilization of Digital Technologies:

- Research on digital technologies that can enhance learning through strengthened data collection and analysis, scenario-based learning or decision-making and data interpretation.
- Case studies and literature reviews on integration of these technologies within resilience learning processes.

By organizing the literature into these thematic clusters, the review provides a structured and comprehensive understanding of the key areas relevant to enhancing NPP resilience. This thematic synthesis allows for the identification of interconnections, trends and gaps between different areas, informing the development of an integrated learning process guideline.

Appendix A.3 Consolidation of literature synthesis

The literature synthesis has revealed several key gaps in current resilience learning practices:

Key findings

Reactive rather than pro-active learning mechanisms

Current resilience strategies are predominantly reactive, event-driven, and lack iterative learning mechanisms. While post-event assessments exist, a continuous, structured learning process that systematically extracts insights from historical disaster data is missing.

Underutilization of DTs

Despite the recognized potential of digital tools (e.g., AI-driven predictive analytics, digital twins, cloud-platforms etc.), their application in resilience learning remains underdeveloped. Existing studies acknowledge their benefits but do not provide a structured framework for their systematic integration into resilience strategies.

Lack of systematic learning mechanisms in policy and regulation documents

Regulatory and policy documents emphasize resilience but lack structured learning mechanisms that incorporate digital technologies into learning practices. This presents an opportunity for research to develop a structured learning guideline that leverages digital tools to enhance data collection, analysis, and decision-making.

Barriers to learning from the past

Complexity of NATECH: The unpredictable and multi-layered characteristic of NATECH events complicates structured learning.

Complexity of DTs: While digital tools can enhance learning, their complexity can hinder adoption, requiring structured integration strategies.

Organizational inertia: Resistance to adopting new practices and technologies within organizations slows down the implementation of effective learning mechanisms. Highlighting the need for a culture of continuous learning and iteration.

Poor data quality and management: There is a lack of systematic approaches to capturing, processing and evaluating disaster-related data. Hindering the utility that DT have to offer in historical data analysis and lesson generation.

Cognitive bias: Human-actor interpretation bias and judgement can hinder learning. If solely reliant on human interpretation, critical data or patterns may be overlooked.

Stakeholder engagement in learning processes

Engaging stakeholders such as, regulatory bodies, plant operators, and external organizations can support enhanced learning and foster trust. Through feedback mechanism and allowing stakeholder to provide input based on their expertise. However, resilience engineering literature does not fully address how to systematically integrate stakeholder perspectives into resilience learning.

Application of STS perspective in resilience learning practices

STS theory provides a holistic perspective on system analysis. And thus, the learning process, emphasizing the importance of alignment between human, organizational, and technological dimensions. However, its' application within resilience learning frameworks and literature remain underexplored, leading to gaps in effectively strengthening technical and social factors of learning processes.

How the ELP-Model addresses these insights

The ELP-Model is designed to address these findings and bridge these gaps by proposing a structured, systematic and iterative learning approach that integrates digital tools from an STS perspective. It addresses the key findings in the following ways.

Supporting proactive learning

The ELP-model introduces a continuous and iterative learning cycle, ensuring that learning is not just event-driven but an ongoing process. By systematically analysing historical data and integrating insights into resilience strategies, the model supports pro-active resilience enhancement.

Systematic DT-integration

Incorporates AI-driven analytics, digital twins, AR/VR, governance & compliance platforms coupled with data visualization tools to support effective lessons generation. Through enhanced disaster data collection, analysis and result evaluation. These tools enhance predictive capabilities, simulated scenario-based learning, and data-driven decision-making and review, reducing reliance on human interpretation.

Development of a learning process guideline

The ELP-model aims to serve as the foundation for a structured learning process guideline that aligns with regulatory and policy frameworks. By defining clear steps for capturing, analysing, and applying historical disaster data, the model proposes an addition to regulatory guidelines in resilience learning.

Addressing barriers to learning

The model proposes a structured process that integrates digital tools systematically. Highlighting practicality for resilience learning. Adopting learning into operational resilience practices and supporting iterative feedback mechanisms. The model supports a culture of continuous improvement. Incorporating data governance and accessibility tools, ensuring that historical data is systematically collected, shared and available for review. The ELP-model integrates a stakeholder engagement framework, ensuring that key actors (e.g., regulators, plant operators, external experts) contribute to and benefit from the learning process. This approach fosters trust, transparency, and collaborative resilience learning. Furthermore, the ELP-model support actors to work with a shared-knowledge base. Allowing them to communicate effectively, despite varying expertise. And through structured review practices, can overcome objective assessment of data.

Application of STS theory

By applying STS principles, the ELP model ensures that resilience learning is approached from a systems-level perspective, balancing technological advancements with organizational and human factors. It aligns digital tools with social (human and organizational) dimensions. Supporting a comprehensive, holistic approach to resilience enhancement learning.

To summarize, the findings from the literature highlight critical gaps in current resilience learning practices for NPPs, including the lack of structured learning mechanisms and underutilization of digital technologies. And underutilization of the STS perspective in resilience learning. The ELP-model aims to addresses these knowledge gaps and challenges emergent from learning-from-the-past by providing a structured, continuously iterative learning process approach that integrates digital tools with STS principles. Thus, can strengthens the ability of NPPs to continuously learn from historical disasters, enhance decision-making, and pro-actively improve resilience strategies.

Appendix B.1 The NPP physical infrastructure

The physical infrastructure of NPPs is to protect and support an optimal environment for the processes involved in nuclear power generation. The infrastructure must ensure the safe, reliable, and efficient operation of the plant whilst safeguarding against a variety of potential hazards, including natural disasters, operational defects or other external hazards.

Key Components of NPP Physical Infrastructure

"The physical infrastructure of a NPP system, based on the plant in Borssele, The Netherlands, comprises of a pressurized water reactor and can be categorized into several key components. Safely shielded by steel and concrete, the ***core [1]*** *lies at the heart of our plant. Here, heat is produced by the splitting of uranium or plutonium atoms – the reactor fuel. The heat is absorbed by water in the primary (nuclear) circuit, which circulates through the* ***reactor vessel [1]*** *under high pressure. The heat is used to produce steam in the secondary (non-nuclear) circuit, in the* ***steam generator [3]****. The steam drives a* ***turbine [6]*** *on an axle that drives a* ***generator [7]****. The power generated is fed into the electricity grid. The steam condenses back to water in a* ***condenser [8]****. It is cooled using cold surface water from the* ***Western Scheldt river [9]****, which is pumped through the condensers."* -Cited from (EPZ, 2024) on the production process of the plant at Borssele.

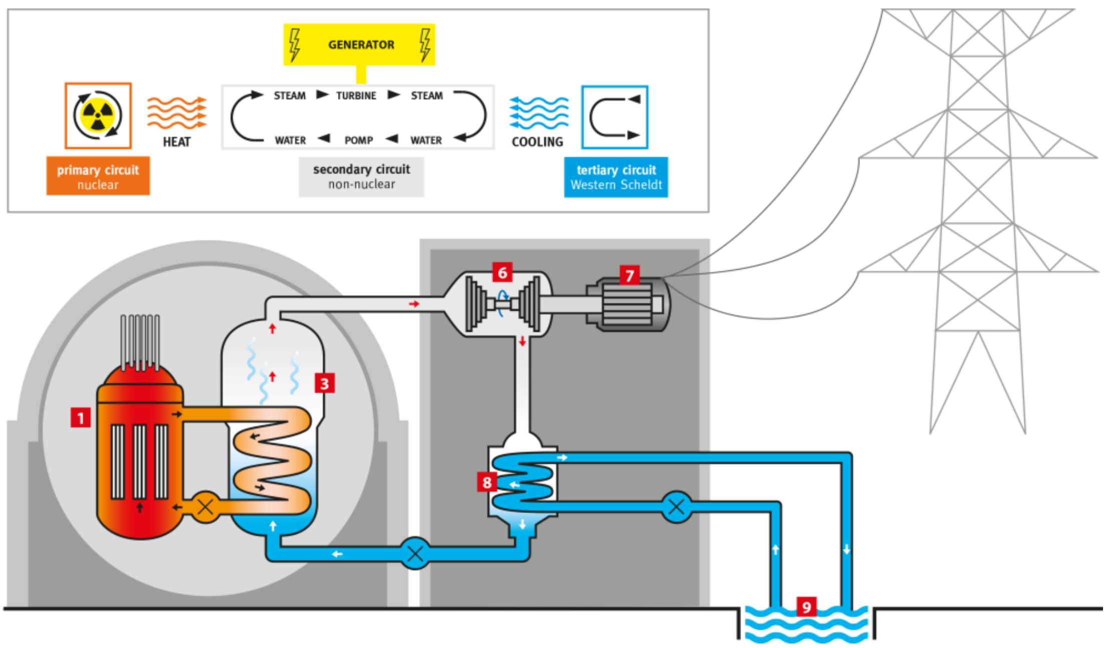

Figure 13: Schematic visualization of the production process at the Borssele plant. (EPZ, 2024)

Support Facilities

The control room is the centralized hub for monitoring and controlling the reactor and other plant systems, equipped with instrumentation and control (I&C) systems. The emergency response centre is a dedicated facility for coordinating emergency operations and communications during an incident. Maintenance and workshop areas are essential for the upkeep and repair of plant equipment and systems. In the case of an emergency where the control room is no longer available, the shutdown of the plant can be handled from an auxiliary control room. Where the automatic controls can be managed and safety is guarded.

Ensuring that the main reactor building, housing the nuclear core, is strong and robust is paramount. So that the infrastructure can withstand the impacts of natural hazards, protecting the core and guaranteeing safe shutdown operations.

Safety Features

NPPs incorporate multiple safety features to mitigate risks and ensure operational safety. Including multiple, independent systems designed to perform the same function, ensuring that a failure in one system does not compromise overall safety. Examples include multiple cooling systems, power supplies, and control systems.

Structural components of NPPs are engineered in such a way, that they are able to withstand earthquakes and other natural disasters. This includes reinforced foundations and shock absorbers to mitigate seismic impacts. Comprehensive detection and suppression systems are in place to protect critical areas of the plant, ensuring rapid response to any incidents. (EPZ, 2024), (Borssele, 2024)

Technological Integration

Real-time monitoring of conditions inside and surrounding the NPP system is achieved using sensors and digital instrumentation. These systems gather data on temperature, pressure, radiation levels, and other critical parameters continuously, enabling swift detection and response to any abnormal parameter levels. Digital controls and automated processes are used to manage reactor operations, enhancing safety and efficiency. These systems can automate tasks and instigate emergency protocols in case of an incident. These measures safeguard the plant’s operations and digital infrastructure. Working in parallel with human operators. (EPZ, 2024), (Borssele, 2024)

Appendix B.2 Overview of Digital Technologies

Several digital technologies were found to hold significant potential for enhancing the resilience of NPP systems, by integration into the learning processes. Below an overview of digital technologies is laid out.

Overview of Digital Technologies

Artificial Intelligence/Machine Learning Models

Within the risk management and resilience literature, two technologies often considered are Artificial Intelligence (Argyroudis et al., 2022), (Spencer et al., 2019), (Rad et al. 2021) and Machine Learning (ML) (Gohel et al., 2020), (Möhrle et al., 2021), (Alkhaleel, 2024). AI, is aimed at creating machines that are able to perform tasks for which human intelligence is usually needed, being able to mimic human behavior and decision-making. ML on the other hand is specifically focused on development of algorithms that allow for learning form data and make decisions based on that information. Together, Machine Learning and other AI technologies are able to analyze datasets from past disasters, operational data and ecological conditions and learn lessons from them and provide actionable insights. Thus, identifying patterns, predict hazards and optimize operations. Predicting potential future natural disasters based on historical data and indicators through real-time monitoring. Moreover, AI can aid in the assessment of quality of historical data and ML algorithms can be trained, using historical data, to recognize and identify early warning signs of an imminent natural hazards or potential system failures.

Role within learning process: By integrating AI and ML into a structured learning process within NPP systems, continuous learning and adaptation from past disasters is supported. Improving their knowledge extraction, therefore their absorptive capacity capability, as discussed in Chapter 3. Furthermore, improving their situational awareness, supporting the predictive capabilities, allowing for preemptive actions to be taken and prevent future potential escalating disruptions caused by natural hazards.

IoT devices

Essential for real-time data collection and monitoring, IoT devices refer to the network technological devices with sensors, processors, software and the ability to connect, collect and exchange data with other devices and a central system through the internet

(Rad et al., 2021). Relying on effective digital communication of networks, data processing and software. Implemented in NPP systems, IoT devices collect real-time data through sensors, constantly monitoring critical parameters (temperatures, radiation levels, pressure etc.) and comparing them to normal operational conditions. IoT sensors can provide NPP systems with early warning signs based on parameter levels and lessons learned, by recognizing similar levels experienced in past disastrous situations. Therefore, allowing for timely intervention before a similar disaster can occur, mitigating escalating effects. (Rad et al., 2021), (Russell et al., 2018), (Abreu et al. 2016), (Logeswaran et al., 2024)

Role within learning process: Integrating IoT devices, allowing for real-time data monitoring, together with patterns recognized and lessons learned through other DTs, ensures the ability to prevent similar scenarios that led to previous disruptions. Furthermore, real-time data validates lessons learned from the past and application of these lessons in current operations.

Big Data Analytics

Big data refers to large and complex datasets (Kumar, 2021). Big data analytics relies on digital tools to process and examine these large datasets from various sources. These specific tools are able to analyze these vast datasets, which traditional data-processing technologies cannot handle. By analyzing these big data datasets, hidden patterns, unknown correlations and trends or other valuable information can be uncovered and brought to light for NPP operators. Allowing them to make data-driven decisions and investigate root causes and escalating factors of disasters. (Kumar, 2021), (Rad et al. 2021), (Shah et al., 2019), (Wang et al., 2018), (Tabesh et al., 2019), (Sarker et al., 2020)

Role within learning process: Integrating big data analytics into the learning process guideline, provides NPP systems with tools to comb through and analyze the vast amounts of data arising from NATEH events, enabling these systems to learn from the past in an efficient manner. The enhanced capability to learn lessons from the past and understand root causes of disasters, allows for the development of more adequate resilience engineering strategies and more informed decision-making processes.

Governance & Compliance platforms, dashboards

Effective collaboration and governance can provide the coordination of data, results and actors throughout the learning process. These platforms facilitate collaboration among various stakeholders, ensuring that information flows efficiently during every stage of the learning process. Cloud-based collaborative platforms support automated and real-time collaboration. Integrating the insights and results from the various other digital technologies, into an accessible platform. For key actors to share and interact with. This could include software that provides NPP personnel with a centralized interface of the learning process, the results and insights gather, monitoring progress and coordinating roles, tasks and efforts. Furthermore, compliance reporting and governance tools assist in automated and systematic compliance monitoring. By automatically sharing data or resilience insights with regulators. Flagging inconsistency with safety protocols, enabling auditable trails, ensuring regulatory upkeeping. Further automating the information dissemination to the public and external stakeholders through online status boards or dashboards hosted on the websites of the plant and regulators. (Rad et al., 2021), (Ogie et al., 2018), (Shah et al., 2019).

Role within learning process: Governance & compliance platforms can support the actors with data accessibility and the collaboration under a shared knowledgebase. And help streamline learning processes. As well as automating and systematizing the current practices. Enabling the insights gained from digital technologies to become effectively distributed to the appropriate actor. Hosting online dashboards, to automatically inform external stakeholders on the metrics of develop resilience strategies. Streamlining the learning processes and supports the maturity of data-driven decision-making processes and supported resilience strategy development.

Digital Twins

A digital twin is a virtual model of a physical real-world system Brucherseifer et al. (2021). NPP systems and their operations can therefore be replicated by digital twins. These digital counterparts serve several purposes, such as simulation, testing, monitoring and integration. Past disaster can be simulated by digital twins, as well as testing of disaster responses and the effectiveness of newly integrated safety or resilience measures can be assessed. Digital twins serve as a controlled environment where various scenarios can be recreated or simulated, and the effects of these scenarios on the system can be explored as well as the systems response. For example, the effects and impact on both infrastructure and operations of a simulated earthquake hitting a nuclear plant, can be investigated, evaluating the systems emergency response and devise recovery plans. (Brucherseifer et al., 2021), (Geihs, 2023), (Braik & Koliou, 2023), (Lin et al., 2021), (Ford & Wolf, 2020), (Kropaczek et al., 2023)

Role within learning process: When integrated, NPP systems can simulate past disaster to retrace steps taken, mistakes made and gain a comprehensive and deeper understanding of escalating factors, indicators of disasters and root causes. Lessons learned from these simulations can help in improving response and recovery strategies, enhancing the systems overall resilience.

AR/VR

Augmented Reality and Virtual Reality technologies can be used for simulating natural disaster scenarios (Zhu & Li, 2020). Enabling immersive training programs for employees of a NPP system to become familiar with response and recovery strategies, within a realistic but safe environment. Creating improved preparedness to natural disasters and its' effects through training exercises. Understanding that in a high-stress situation, human error is more likely, training can mitigate this effect (Medema et al., 2018). Furthermore, evaluating staff performance in-case of an emergency. (El-Maissi et al., 2024), (Zhu & Li, 2020), (Medema et al., 2018), (Logeswaran et al., 2024)

Role within learning process: By setting up AR and VR training programs, NPP system staff can become better prepared for emergency situations, reinforcing lessons learned from the past. Ensuring adequate and efficient response during a natural disaster, mitigating human errors. The enhanced staff preparedness contributes to the NPP systems resilience by timely and effective actions and adequate decision-making.

Visualization Tools

These tools can support the actor interpretation of complex datasets and facilitate comprehensive understanding of insights and results. Providing intuitive graphical representation of data, allowing actors to quickly understand metrics within, drawing conclusion from insights. Coupled with the digital platforms mentioned above, can provide a comprehensive system for data sharing and interpretation. Which further support the knowledge transference within the learning processes. (Rad et al., 2021), (Shah et al., 2019). (El-Maissi et al., 2024), (Argyroudis et al. 2022),

Role within learning process: These tools support the learning process by translating raw data and insights into actionable, interpretable visuals. Makes complex information easier to understand for the actors, regardless of expertise. Making the data more accessible, and further supports the actors present in the learning process to work under a shared understanding.

Appendix B.3 Benefits of digital technology integration

Benefits of a digital technology integrated learning process guideline

A learning process guideline ensures systemic documentation of any incident or operational weakness within a system. This approach prevents the oversight or loss of valuable data resulting in insights that can inform future operations (IAEA, 2018), (Selting, 2018). Failures or incidents within NPP systems provide critical insights into weak spots and vulnerabilities, and potential improvements. A learning process guideline makes sure these valuable lessons from the past is captured, analyzed and learnt from. Preventing similar scenarios to unfold (Aitsi-Selma et al. 2016). Communication and collaboration are promoted by a learning process guideline. Ensuring that lessons learnt are shared within the entire organization and measures are implemented throughout the system. Stakeholder engagement and collaboration on an industry level, allows for critical insights to be shared with other organization and operational practices to be improved. This collective learning enhances the NPP systems resilience but also of the network of Critical Infrastructures, safeguarding society in the event of a natural disasters.

Learning from the past allows NPP systems to identify and alleviate potential risk factors. A learning process guideline supports the systemic comprehension of the root-causes of past disasters and the chain-reactions that followed. Ultimately leading to the development of enhanced safety and resilience practices (NEA, 2015). A well-implemented learning process guideline encourages a pro-active and continuous learning culture within the organization. Ensuring that learning from the past is not a one-time effort but becomes an ongoing process on an organizational level, taking an innovative stance on resilience engineering. Enhancing the awareness of the system and its' surrounding hazards. Due to the complex and dynamic nature of the landscape surrounding NPP systems, with ever-evolving natural environment, technologies and regulatory compliance. NPPs need to adapt constantly to emerging challenges, a learning process guideline enables the system to tackle these challenges in a more efficient manner. By continuously integrating new knowledge and lessons learnt resilience enhancement is achieved. Employing a learning process guideline creates a constant feedback loop, incoming lessons are turned into operational practices, continuously being reviewed and tested, from which new knowledge again emerges. NPP systems resilience engineering is kept effective and current by this continuous process.

Digital technologies, especially Digital Twins, allows for scenario simulation and training, based on past events and lessons learnt (Kropaczek et al, 2023). Preparing employees for potential disasters and improving their abilities to respond in an adequate manner

(Selting, 2018). Incorporating digital twins into the learning process guideline supports testing, evaluation and improvement of new disaster response practices. Creating more effective response planning in case of a disaster. Utilizing AI tools will enable data-driven decision-making (Kumar, 2021). By extracting and analyzing historical data, AI tools are able inform the NPP system with data-driven insights, enhancing the systems resilience. If trained properly, a sophisticated AI system is able to make informed decisions on its own, where human actors play a more supervisory role, enhancing the systems efficiency. Moreover, incorporating the predictive capabilities of AI tools, using statistical analysis to identify trends, patterns and forecast scenarios. Will aid the system to anticipate events. Integrated into the protocol will have a pro-active approach on resilience enhancement. Helping NPP systems to make decisions based on prevention rather than responding to a disaster. The analysis of data on a long-term basis, allows for the discovery and identification of long-term patterns that may not be directly evident when investigating a single incident. Which is crucial for strategical planning and resilience enhancement on the long-term.

The landscape of NPP systems operate under strict regulations and policies, maintaining safe operations, best practices and environmental sustainability. A learning process guideline incorporating governance & compliance platforms guarantees that the NPP system keeps meeting these standards and best practices (Manna et al, 2013). Learning from past inspections and new regulatory changes makes sure that standards are upheld. Documentation of lessons learnt and actions taken, through the use of digital platforms is at the basis of a learning process guideline, ensuring transparent operations and accountability. Integration of a learning process guideline shows commitment to safe operations and regulatory compliance, fostering trust within the nuclear energy community, and with governmental and regulatory bodies (NEA, 2015).

Appendix C Expert Consultation

Below is the transcript of the expert consultation conducted. As well as the preparatory document containing a summary of the research, explanation of the theoretical learning process inside the ELP-model, consolidation of the insights generated from the literature synthesis and the propositions. Together with preparatory questions and a copy of the ELP-model diagram. Was sent ahead to the expert before the meeting, via email.

Expert consultation session
Date: 16/01/2024
Duration: Approx. 1 hour
Student: Maarten Hoogstad, MOT, Delft university of technology, (MH)

Introduction

MH: To what extent does your work and experience cover regarding learning?

EXPERT: Yes, all facets. In the nuclear world, learning from incidents and accidents has been an established phenomenon for a very long time. It is also considered very important, and indeed, especially the three major worldwide accidents have greatly contributed to continuously refining what it should focus on. Before Three Mile Island, it was actually only technical. After Three Mile Island, it became largely technical and procedural. At Chernobyl, a very large part of safety culture and behaviour was added to that. And at Fukushima, it was again underlined that it is of great importance to include that in your learning capability. But also again, think further than what you think you will face. The scenarios that you are prepared for should go a step further than what you think is relevant. To challenge that resilience or robustness further.

MH: So, from your perspective, unexpected scenarios are actually the most dangerous?

EXPERT: Indeed. Especially the unknown unknowns. A license applicant in the nuclear world is already obliged to compile a list of design-basis accidents. And they must be fully resistant to those. So, those should actually never lead to consequences. To significant consequences. Those are the design-basis accidents. Then you have a second category beyond design-basis accidents. These are things that you can reasonably foresee may occur in the lifetime of your installation. Or not even necessarily will. But could occur. And what is reasonably foreseeable is always a point of discussion. And you cannot be fully resistant to that. But you must have a certain robustness. So that you minimize the consequences. And there are strict requirements for that as well. And that is also part of the licensing assessment. And since Fukushima, a third step has been added. You must also look at combinations. And you must analyse whether there is somewhere at the end of those beyond design-basis events a sort of cutting edge where, if it goes beyond that, it stops. Or whether you can still mitigate that effect.

MH: So are there also specific procedures in place for when you exceed the secured critical parameters? And there is also a certain form of preparation for that?

EXPERT: Yes, for example: Flooding at the nuclear power plant in Zeeland. Then you have the beyond design-basis accident value that has been taken into account in the context of internal crisis management and consequence mitigation, which is now set at 9.6 meters. So, that is quite substantial. Beyond design-basis is even higher, by the way. And then you still have: but what if an improbably large tsunami comes along? And yet, just like in Fukushima, our building with emergency material is washed away. What can we still do then?

MH: And what would, from your perspective, be an example of a digital technology that addresses this or is related to it? For instance, suppose such a tsunami of 20 meters occurs—how can we evaluate the consequences for the infrastructure, operations, etc.?

EXPERT: Well, I can imagine that if at least source information were more easily available for this type of [risk] model, where are we talking about? What is realistic, very unlikely, and virtually excluded, as it were? Of course, we ask this of every new license applicant as well. That comes from climate reports, etc. If that were available in a simple way with a kind of guideline already included on how to use it when designing design-basis, beyond design-basis accidents, and testing that extra robustness. All that guidance, if you have it structured in one place, it makes it easier to implement in license applications, but also to incorporate into continuous improvement for existing installations. And a lot of it is already taken into account, but as you also indicate [in the literature review], it does not always happen systematically in a supported system. So a lot of reinventing the wheel, searching independently, and also searching internationally. It would be great if you could incorporate international knowledge and experience into such a process. Or unlock it, so to speak.

Reflection of research findings with practice

MH: If I understand correctly, in practice, as you say, it is mostly a matter of figuring things out yourself. Instead of it being part of a systematic whole, or that there is a manual to systematically approach it?

EXPERT: Yes. And there are guidelines, for example, from the IAEA on how to do these things, which we [ANVS] also refer to. For a license application, that was the easiest to mention, but there is also much more. There is also a Dutch guide, called VOBK. The Safe Design and Operation of Nuclear Reactors, which is an implementation policy document from ANVS, essentially indicating, "Pay attention to this, this, this, and this, and you should at least do this and this." It also refers a lot to accident robustness. But suppose you could cleverly combine all of that and essentially make a link to each of those rules and recommendations and requirements stating, "You can do it this way," and then you have that source information available and extract it in a certain way. Not everything even has to be in the system—perhaps just a reference would be enough. That would, of course, make the learning process a lot easier. And that has value for both a party applying for a license, or a supervised entity [nuclear power plants], as well as for a supervisor or licensing authority [ANVS]. Then, at least, you have the same background information available.

MH: So, as you see it, if you establish a systematic learning process between different parties, they will speak the same language and be more aligned?

EXPERT: Certainly, yes. You may already know that there is a system of continuous improvement, which is also formally arranged. We have a system of ten-yearly safety evaluations, which are mandatory. That is a self-evaluation by the company, by the license holder. And that is assessed by us as the supervisory authority, by us as the regulator. And then you systematically go through all those requirements. And also the lessons learned from it. The whole idea is that every ten years, you take another look at the outside world. And ask yourself: What we considered acceptable ten years ago—do we still find that acceptable today? Or do we need to adjust things here and there?

MH: What you highlight is also something that emerged from my case-based evaluation of the model in relation to the Fukushima incident. It became clear that they were working with knowledge that was already outdated, making them vulnerable to natural hazards. That also underlined a gap. Where you can intervene or use, for example, a structured learning process with digital tools to identify vulnerabilities or patterns. Allowing the plant to constantly iterate and learn?

EXPERT: Yes, correct. Now, that is, of course, very difficult. Because, for instance, licensing regulations or legal requirements do not continuously change along with what happens in the outside world. But to ensure that they at least comply with the licensing regulations, these can also be adjusted after each ten-yearly safety evaluation. A formal agreement document then follows, determining which improvements are truly necessary and required based on that analysis. That is fixed. Additionally, there is the more general expectation, which is also fixed in regulations, that companies must continuously look around themselves. First, at their own incidents—usually small things. Small lessons from small incidents, big lessons from big accidents. And those big accidents usually do not happen at your own facility but elsewhere in the world. That is why we find it extremely important that all these facilities—stronger still, we require it—are themselves also connected to incident databases, engage in exchanges, conduct peer reviews, etc.

MH: To what extent do you recognize the challenges described in this research, such as the lack of a systematic learning mechanism and the limited use of digital technologies?

EXPERT: Yes, I recognize that. And that is also quite complicated. There are indeed databases where accidents are recorded, especially internationally. But not all of them are relevant to you as a company, for example. And filtering out what is relevant is now done entirely manually.

MH: So, in-house?

EXPERT: Yes, so you have, for example, IRS, which is an international database from the IAEA for reactor incidents and accidents. These are recorded there. There are fixed formats for that at the IAEA. From a certain level of severity, it is mandatory to share it there, but below that, it is voluntary. But it is done quite often. There is exchange, there are also symposia about it, and so there is knowledge exchange. But then the next step—how do you go from that database of large and small incidents worldwide, across all types of reactors, to what is actually relevant for your installation in the Netherlands? That is complicated. That involves an enormous amount of manual work and expert judgment. And well, whether it is possible or not is another matter. But it would be very helpful if digital systems could assist with that.

MH: So, for example, models that are aware of the environment, of the specific nuclear power plant where you are, and take other specific parameters into account?

EXPERT: Exactly, that recognize the parameters and match them to historical incidents, for example. So that you then get a kind of pre-selection. That does not mean you can automate everything, but at least you get a preliminary selection. Which provides insights like, "This could be relevant for your installation."

MH: So there is indeed a demand for assistance in recognizing patterns, insights, etc.?

EXPERT: Yes, I think that would be very welcome. But then you immediately run into one of the challenges you already mentioned in the literature review: data quality.

MH: I would like to come back to that in a moment when discussing the propositions. So, if I understand correctly, there are indeed mechanisms for exchanging incident knowledge. But in terms of communication between policy organizations and nuclear power plants themselves, there is still room for improvement?

EXPERT: Yes, a lot happens in parallel. So we have people who follow this, they have people who follow this, and they do have some mutual contact. But everyone does it in their own way, because there is no single centralized system. As you indicated in the model [Stage 1: Data Analysis], the interaction between actors.

MH: How systematic is that interaction?

EXPERT: Well, actually, not very systematic.

The ELP-Model

MH: Now looking at the ELP-model diagram. These are, according to the literature, the interpreted network of actors involved in the stages of the learning process. To check with your experience, is this a correct interpretation of the actors present in the learning process?

EXPERT: Exactly. There you have specialists at the plant itself and there is also a connection to the plant manager.

MH: In this case, it is interpreted that the plant manager ensures that the strategic objectives, etc., remain visible during the learning process. Can you tell me more about whether these governance platforms are already being used or not? Because this research was conducted from the perspective of how digital technologies could possibly be used. This is, of course, purely from a theoretical perspective, where governance platforms emerged. In which compliance parameters are incorporated, allowing for an automatic compliance check between regulators, inspectors, and the plant itself.

EXPERT: Between these parties, in terms of communication, which you just mentioned, for example, also with policy implementation and compliance, not really as a platform. There are many lines of communication. There is, of course, supervisory activity. There are many contacts. Each party has its own systems for this, and information is exchanged, but for the most part, documents are simply sent back and forth. To some extent, we at least have the ability with the Borssele nuclear power plant to look into their systems as well. To some extent. And that was deliberately done to get a better understanding of the hierarchy of documentation. Otherwise, you get individual, fragmented documents or pieces of information, which is not desirable. So, to some extent, a platform exists there. That is primarily on the compliance side. But collaboration? Less so. But you could say that if you do more in this area, especially in terms of digital tool integration, particularly in the learning process, there is progress to be made.

MH: So, for example, automation with the help of digital platforms?

EXPERT: Yes. Automating everything related to learning from incidents and accidents. That would be very useful because we often encounter issues where we do not clearly see what they are doing with it, and we have to extract everything through conversations. And we also do not always know whether they are aware of certain events, especially those that happened abroad, which could be relevant. A system for this could be quite beneficial.

MH: From your perspective, DT integration—what I mentioned before—platforms can certainly support and strengthen the dynamics within the learning process?

EXPERT: Yes, certainly.

MH: If we then look further at Stage 2, data analysis, then again using these platforms, particularly internally between actors, to make this process as efficient as possible. But also utilizing ML models to enhance the analysis of these datasets and directly link them to the capabilities and parameters of the specific plant.

EXPERT: Yes, and what you see there is that you actually want to link two things. You have an internal reporting system and a registration system for internal incidents, reports from employees, and how these are internally handled, including investigations and accident analysis methods like the Tripod method, which is commonly used. Every nuclear installation is required to have such a registration system. With categorization as well. And generally, attributes are included, such as: Does this concern cooling? Does it concern ventilation? Is it a procedural deviation? Or is it a technical deviation? So, in this way, each facility has its own system, which is searchable, filterable, and analyzable to varying degrees. The data quality of incoming material [incidents] is not always great because it depends on the reporter.

MH: By that, you mean reports?

EXPERT: Exactly. But with those attributes, provided a good administrator is in charge, it is quite usable and searchable.

MH: So, there is still a lot of human input/manual work?

EXPERT: Yes. And what we do as an authority, when we oversee their learning process, we also oversee that process in a systematic way. We conduct an annual inspection of how they do this. Then, we also go through that database in a somewhat risk-based manner. And we check whether there are any issues that should have been reported but were not. Or if we see a lot of similar incidents with the same cause. What are they doing with that? Are they analysing those incidents collectively? What you often see is that registration is done quite well, but analysing the registered data is not always done systematically.

MH: Because that, again, involves a lot of human labour?

EXPERT: Yes. That is a lot of manual work, and it is not always easily done. It depends on expert judgment and how proactive someone is. Or whether they recognize patterns themselves—like, "We have frequently had issues with a leaking pipe or a connection. Maybe there is a systemic issue here." They have to figure that out on their own. There is no system to assist them with that.

MH: So there is no integrated digital tool that can indicate, "This has already happened three times; there might be something more going on," or that can recognize a pattern in it?

EXPERT: No. And this is for small things. Another example—leaks happen, though not often. Contaminated clothing. Contaminated shoes—people walking out of a controlled area with contaminated shoes. That is usually a procedural issue. If it happens once, fine, mistakes happen. It is not a big deal. But if it happens twenty times in a short period, then there is a structural problem. Then you need to adjust training, procedures, or implement a better transition system, or an alarm, or whatever. There are many possible solutions. But currently, people have to identify this on their own. Occasionally, we notice these patterns while reviewing those records. And then we ask, "Have you taken any action based on this accumulated picture?" Sometimes, the answer is, "No." Then we initiate a discussion. So, something does happen with it, but a system could be very helpful here.

And internationally, you could actually mirror this with what comes from outside. And then there needs to be some kind of relevance filter because the severity might be different for reactor types that we do not have here.

MH: Looking at the Netherlands, the likelihood of certain natural hazards is lower than in other places.

EXPERT: Yes, although we still require robustness against earthquakes. But even here, while it is unlikely and the chances are small, and the magnitude of a significant earthquake is very low, it is not zero.

MH: So those kinds of scenarios are still taken into account?

EXPERT: Yes. And there is a certain robustness requirement for them, which is, of course, different from what would be needed in Japan, where you are practically sitting on a fault line, but it is still required. So, to some extent, you still need to weigh that relevance.

MH: Then we move onto stage 3, outcome evaluation. After those datasets of past incidents have been analysed and processed, as reflected in the ELP model, the insights gained from that analysis are then converted into lessons by testing disaster scenarios. These scenarios are modelled using DTs (Digital Twins) in Stage 2. The results are then tested against the plant's capacity and parameters, thereby measuring the performance of how the plant reacts to different disaster scenarios. For example, if certain areas are flooded due to an earthquake or other factors, what happens then?

With these simulated scenarios, using, for instance, Digital Twin technology, you can model what would happen in a controlled environment if a disaster scenario were to unfold at the plant. This allows you to directly test: What are, as you mentioned earlier, the cut-off parameters? So that you gain more insight not only into potential high-probability scenarios but also into extreme cases?

EXPERT: Yes, it's good to outline what is and what is not available. The Borssele nuclear power plant, and any new ones that might come in the future, as well as PALLAS, the isotope reactor under development in Petten, are required to have computational analysis simulators. These are probabilistic failure models per component, which are used for licensing applications, as well as in standard licensing revisions or updates, to demonstrate that they remain within the acceptable probability and consequence limits.

So, those computational simulators exist. There is also an independent regulatory simulator, developed and managed by an external technical agency, that allows us as regulators to verify plant analyses independently. This simulator can run major transient analyses, for example, what happens when the reactor cools down rapidly from a certain temperature—what breaks first?

MH: Where potential scenarios can be introduced, and then we analyze how the plant reacts to them?

EXPERT: Yes, correct. And they are highly accurate. They are also regularly validated against actual operational parameters. Then, there is a third type: a training simulator. This is an exact full-scale replica of the reactor control room, including all buttons and controls.

MH: A kind of physical Digital Twin?

EXPERT: Yes, it is physically identical, even down to the view from the control room, which is printed as a large image on the wall. This simulator was previously in Germany, as it is a German-designed reactor, but since Germany is shutting down its nuclear power plants, the simulator has been moved to the Netherlands. I'm not sure if it is fully operational yet, but it will be onsite soon. This simulator is particularly relevant for procedural training of operators. The operators are required to train on this simulator multiple times per year under accident scenario conditions. They must follow the correct procedures, press the correct buttons, and simulate real-world emergencies. The effectiveness of the emergency response measures taken is also assessed. Additionally, sub-scenarios can be programmed into it. For example, if an operator relies on a backup water tank, we can simulate that it is also leaking—what do they do then?

MH: So, you can identify domino effects and underlying failures?

EXPERT: Indeed. So those three types of simulators exist. They are available. Are they always fully connected, and can you directly input scenarios and extract lessons? Well, there might still be some room for improvement. But know that the foundation is there, and it is also mandatory. So, they do use them, and they also extract lessons from them. And what comes out of this, we also ask them to apply in the ten-yearly safety evaluation. And if events have occurred externally in the world, we also expect them to incorporate those as new design-based or beyond design-based cases, situations, and scenarios into their own safety analysis on the simulators. And they must then input them there, and they can also demonstrate this. This is often traced back to Postulated Initiating Events (PIE).

MH: If I understand correctly, this aligns closely with what I have researched. There is certainly value in using simulation tools—they allow you to train personnel, improving knowledge transfer and thereby reducing the chances of human error, as they are trained in these procedures?

EXPERT: Exactly. And these simulators utilize many Monte Carlo probabilistic simulation models. Both for actual particle transport, core-related issues, but also, for instance, for shielding, pressure incidents, and all sorts of other aspects.

MH: Can all the parameters of the plant be simulated in them?

EXPERT: Yes. All parameters can be simulated in them. And they all operate with realistic dimensions, working conditions, and everything else. What is often a challenge is: how do you simulate that initiating event? Because you simulate the reactor.

MH: Meaning, the reactor's response?

EXPERT: Yes. That is simulated very precisely, but how do you simulate the tsunami itself?

MH: So, meaning how the entire disaster scenario plays out in its entirety?

EXPERT: Yes, I personally have less insight into that, as I am not specifically involved in that whole scenario analysis—more so in the technical side, the modelling side. What I do know is that the current approach is: "If a tsunami occurs, then we assume this, that, and that will fail." That can all be simulated. But verifying whether those assumptions are correct—that is where the gap lies.

MH: That part is missing?

EXPERT: I believe that they cannot yet be simulated with the methods we currently have. And that is an interesting gap. That is precisely what I was getting at—what exists and what does not. The technical consequences of assumed failures or procedural errors—those can all be simulated. We have very good models for that. But the precondition—whether those failures and issues are actually in line with an external event—that is still a challenge.

MH: If I understand correctly, there is room for improvement in the front-end of scenario-based learning for these simulations—verifying whether the assumptions made about technical consequences or plant behaviour in response to an accident are accurate. And also at the back-end, in drawing lessons from the simulations—with support from digital tools—so that the simulation results can be evaluated or reviewed, and lessons learned from them?

EXPERT: Yes.

MH: Let's move on to Stage 4. Communicating strategies with the surroundings of the nuclear power plant. From your experience, is there already effective communication between the plant and policy organizations like ANVS regarding new developments related to resilience, risks, and learning?

EXPERT: Yes, and there is a lot of contact.

MH: Is that automated?

EXPERT: No, that is not automated. We do use, as I mentioned earlier, online databases, summaries, and reports, but there is no shared environment or, for example, a status board where we collectively track, "We have identified these issues—what is their status?" No, that still happens through supervisory activities or expert discussions. It does not always have to be strict supervision either. There are also expert discussions, where we actually talk about these findings and ask, "What are we going to do with this?" From those discussions, supervisory activities may follow. Then, our specialists talk to their specialists, our managers talk to their managers, and this happens at different levels. But no, the automation of this process does not exist.

MH: Understood. I actually have two follow-up questions. First of all, how effective are those discussions in your experience?

EXPERT: Quite effective. I think that a lot of human input is required here—by definition. And not everything is black and white. There are many parameters involved. Especially at strategy development [Stage 4], the management circle comes very strongly into play. Because yes, this involves serious money.

Particularly when it comes to modifications that need to be implemented. Then we encounter our regulatory principle of reasonableness. How do you deal with that? We can demand everything, but it must still be feasible. Our goal is not to shut down facilities, but to ensure that they operate as safely as possible. So, we enter into a discussion about this. And that is partially a negotiation, where we examine: What is feasible? What are the consequences? What costs are involved? Is this still reasonable? Etcetera, etcetera.
What could be helpful here is having a structured framework. Also what has been decided in similar situations in other countries? What considerations were made? What is a reasonable request? There are established values for how much money can be justified to save a certain number of lives. That is an extreme example, but such criteria could be incorporated into decision-making. So that we achieve a shared understanding of what is reasonable. That could be a valuable addition, but I believe that these conversations will always remain necessary.

Socio-Technical Balance in the Learning Process

MH: So, the goal is not to leave everything to DTs, but to use them in combination with human factors, where DTs function as supporting tools?

EXPERT: Yes. At least in the sense of shared information. That you talk to each other from the same context. Then, interpretations can differ, but you discuss those interpretations, while still operating from a common knowledge base.

MH: That gives me a clear picture of where there is still room for improvement regarding the learning process. Do you see clear gaps in the learning process, as outlined in the ELP model?

EXPERT: I think you have been very thorough in defining these steps and describing the relationships. I have mentioned “shared knowledge base” a few times. Where is that explicitly placed in your model?

MH: That is primarily addressed within various social elements, such as communication and transparency, where data accessibility and visibility of results play a role.

EXPERT: That is what I thought, yes.

MH: Where it is important that within communication, people find each other and align. And in doing so, work with a shared knowledge base, supported by, for example, digital platforms.

EXPERT: That is what it is about.

MH: So, that coordinated collaboration, and that the data and insights are accessible to everyone involved within that process, and that they work under a shared understanding, is in your view also crucial for this process?

MB That concerns, on the one hand, data about the installation and data about the incident scenarios. But it also concerns the knowledge base, background information, international knowledge, and indeed decision-making.

MH: Do you think that the systematic learning process as outlined in the model can bring realistic improvements, based on the theoretical knowledge obtained in this research, within the learning processes and resilience of the industry?

EXPERT: I think so. I do want to say that the nuclear industry and also the nuclear regulator, in this collaboration, in this interaction, are already quite advanced in learning from incidents and accidents. I cannot say that nothing ever happens, but in that regard, the nuclear industry, just like aviation, is quite a forerunner compared to many other sectors. But that it can indeed certainly be simplified and, I think, also strengthened. By indeed the proposals you make here, and by further developing this model, and particularly also by that technical support alongside it. To better structure the process. Because if it becomes easier, it will happen more often. And as a result, you will get more out of it. I think that is mainly it. It already happens, only it takes a lot of time and effort.

MH: So, as outlined in the model, the support that DTs can offer to support the learning process—will it also make it easier?

EXPERT: Yes. That support will help to gain even more insight. And the part about cumulative lessons learned will become much easier. So that you start looking at: Not just, "I have an event, is it relevant to me?" "And what can I take from it?" But also, over a certain period, maybe there have been ten somewhat similar events. Then we actually need to prioritize it higher. Because then it might be more interesting, more pressing, or there might be an underlying cause.

MH: So, again, with the help of digital tools, recognizing patterns and weaknesses?

EXPERT: Yes. And that you then take another look at those individual cases: "Did we identify them?" "Or is there maybe something underlying that we can only now see because we are combining these ten cases?"

MH: So that, with digital technology, one can better uncover an underlying weakness, by looking at aggregated data?

EXPERT: Yes. And I think that the learning process now relies very heavily on expert judgment and chance recognition. And if you are talking about actual safety improvements, not just efficiency improvements, then you could really gain something valuable from this.

Practical application of the ELP-model within the industry

MH: From your perspective, could such a theoretical learning process, as outlined in this research, serve as a basis for a formalized learning protocol? At an industrial or industry-wide level, and in what way?

EXPERT: Look, you are dealing here with many international frameworks. A lot is already established in terms of what a formalized learning process should look like. Interfering with that is not easy, I can tell you. But, actually, that is not even necessary. Because your process, as you have outlined it, actually fits quite well into what is already formalized and established for the sector. And it could be a further elaboration of that. So, whether you would want to formally or legally establish that it must be done this way, I do not think so. You would encounter resistance with that. But if you develop something like this or further develop it, and you want to offer it—so, certain systems related to it: databases, methods of working, information exchange. Then at some point, you could establish something like that in a—well, there are various formats for it, but in a manual, a guidance document, or an information document. At the international level, that could be done via the IAEA as a technical document.

MH: As a protocol or directive?

EXPERT: No, it is not a directive, that is too high-level, because those must be goal-setting. And this is really about a tool, where you say: "This could potentially be a good approach." And that layered structure is also present in national and international regulations. In general, most countries try to formulate goal-oriented requirements: They set requirements. They establish guidelines. These are the more rigid rules that ultimately land in regulations or licenses. And below that are the technical guides or technical documents. And those state: "This is how you could do it properly." "If you do it this way, we as regulators will approve it." "But you may also do it differently." And I think that such a system [ELP model], if it is well developed, would fit very well as a technical guide or technical document. Which would then ideally be placed at the international level. At an IAEA or OECD NEA level. That is another organization that also publishes these kinds of things. Because there are working groups of people who deal with this, and they could implement such a model further into daily practice.

MH: To further develop and refine the model into a practical application?

EXPERT: Yes. So that would be the path forward—towards further guidance on improving learning through data support, etc. Within the existing process, where the objectives are already established in requirements. And then providing further elaboration on that.

MH: So, as you say, it has value as an addition in the form of a technical guide to the existing learning process?

EXPERT: Yes, exactly. And because it is already more towards implementation than towards defining new goals. Because the goal of the model is clear. The goal is already present within the existing process. The goal is to learn as effectively as possible. And there are already requirements for that. And those requirements align with your model. So you do not need to change anything at that level. It is about the further elaboration. And that fits into the system as we operate it, at an operational level, closer to the practice.

Propositions

MH: To what extent do you think a structured learning process, in which DT integration is aligned with social factors from an STS perspective, contributes to a strengthened learning culture? And the learning process?

EXPERT: Yes, I agree with that. I can support that. In certain areas, it clearly brings a safety gain. And it certainly has an efficiency gain. So yes, across the entire spectrum of learning.

MH: To what extent do you recognize the influence of moderating factors, such as data quality and the complexity of technologies and learning culture, on the impact of DTs on the learning processes themselves?

EXPERT: Yes, that is quite significant, of course. So definitely. The quality of your data is something you do not always have full control over.

MH: That is also a limiting factor in practice?

EXPERT: Yes, exactly. But you can implement smart systems to improve it as quickly as possible when recording events. By starting at the front end, even from the moment incidents and accidents are registered, and ensuring clear attributes and language are assigned to them immediately. That is being worked on, but it can be done much better than it currently is.

MH: Do you believe digital technologies can play a reinforcing role?

EXPERT: Digital technologies can certainly play a role. They ultimately add great value to usability. And therefore, to the learning capacity.

MH: To what extent do my findings from the literature review and the theoretical framework, as mentioned in the preparatory document and discussed in this conversation, align with practice from your perspective?

EXPERT: From the perspective I have now, based on what you have told me and what I have read, you are quite close to reality and have a good understanding of it. There were a few aspects where you might have had less insight, such as the fact that those simulators are already quite advanced. You could adjust that slightly if needed because you do not always see that in the literature. That is in-house, and for understandable reasons, those simulators are quite well protected. If you can run realistic scenarios in full detail through such a simulator, you can also reverse engineer them to find weaknesses. So, those things are well protected. We do not like to make them too widely known, but they do exist.

MH: Understandable. So, what you are saying is that they are available in the Netherlands, but do you know if these simulators are also used at an international level?

EXPERT: Well, within Europe, that is certainly common practice. So, all Northwestern and Western world installations have such simulators. Some are more advanced, and others are less advanced. And there are different sources, but almost all reactors have such systems. Often based on similar principles. But there are differences in quality, depth, and accuracy, for sure. And there are also reactors where that is probably less developed, at least globally.

MH: Would there also be something to learn from that, that across the entire industry, a minimum requirement should be set regarding simulation capabilities?

EXPERT: That could indeed be a good idea, to establish some form of requirements or a global baseline level for that. And within Europe, we are much further ahead. That is also good to know because often, such models are required by the operator of a reactor to be developed. Because, after all, they have the best knowledge of their own installation. These operators are also united in a group, the WANO. And we also have our own, the Western European Nuclear Regulators Association, WENRA, which consists of the regulators from the Western world.

WANO represents the nuclear facilities themselves. They also have their own alliance. And within that, they also share knowledge, information, insights, and so on. Including these kinds of technical matters. But yes, they are also commercial companies, so they will have their own interests to a certain extent.

MH: What advice do you have to further refine and make the propositions from this research more practical?

EXPERT: A lot ultimately comes down to discussion. A lot of it involves talking with experts. Looking into things one by one. Also, make extensive use of existing systems. Designing something completely new and expecting everyone to use it remains very difficult. So, if you can connect to a number of widely accepted existing systems, databases, etc., and you could start, for example, with the IAEA and what they already have, I think that would be of great added value.

Firstly, because it saves part of the work. Because sometimes there is more available than you might think. And secondly, because it increases the likelihood of adoption, as people are already used to working in such formats. And not modifying too much, so to speak.

No, as long as you can align with those systems and show that by integrating such systems and models, you can make them even more accessible, better unlock them, and in fact, evolve them rather than creating a complete revolution. I think that would make it easier to gain support. And also make implementation more feasible. And I think that is certainly possible, although it may sometimes be a challenge with all the different aspects involved. I can certainly imagine that.

The expert input is given from their own perspective and does not reflect the official position of their affiliated organization.

Appendix D Discussion of topics synergy

By synergizing the concepts discussed in the preceding chapter, a clearer picture of the context surrounding this study is attempted within this chapter. Throughout this research of NPP system resilience enhancement, certain clusters of topics emerged. First of all, the interconnection between a learning process guideline, learning culture, absorptive capacity and stakeholder engagement, and how this adds to organizational learning resulting in systemic resilience is conceptualized in this discussion chapter. Secondly, a conceptualization of an integrated learning process guideline is endeavoured, drawing on topics discussed in Chapter 3, laying the foundation for a learning approach to be developed in the form of a learning process guideline for enhancing NPP system resilience. A top-down analysis will be constructed and visualized on how this proposed protocol may have influence on resilience within the various levels of a NPP system and its' surroundings. Lastly, the lessons learned from this study will be taken into consideration to propose an adjusted STS theory framework, striving to be a more customized framework for resilience enhancement, whilst holding onto the simplicity of STS theory, which makes it so accessible and frequently implemented.

Synergy between topics of organizational learning

This synergy of the topics surrounding organizational learning is aimed at showcasing how these topics interact and influence each other. Already touched upon in Chapter 3.4, there is certain virtuous cycle at play. Having a strong learning culture within an organization drives the implementation of a learning process guideline that encourages active stakeholder engagement, understanding that various actors all have worthwhile knowledge to bring to the discussion. Fostering organizational and sector wide support for the protocol. The learning process guideline in turn, creates a structured learning process design. Therefore, reinforcing the systems absorptive capacity, which makes certain that the system is able to effectively integrate new knowledge and lessons learnt from the past and turn them into actionable insights, leading to continuous improvement and therefore strong learning culture. Which ultimately results in a creates a strong organizational learning, from the past, system building systemic resilience.

By actively creating a learning culture that encourages stakeholder engagement with the learning process guideline. If well-designed will promoting continuous learning, facilitating the capture and analysis of new knowledge, turning these lessons into actionable insights. Thereby, strengthening the absorptive capacity. Thus, fully realizing the potential benefits of this interplay.

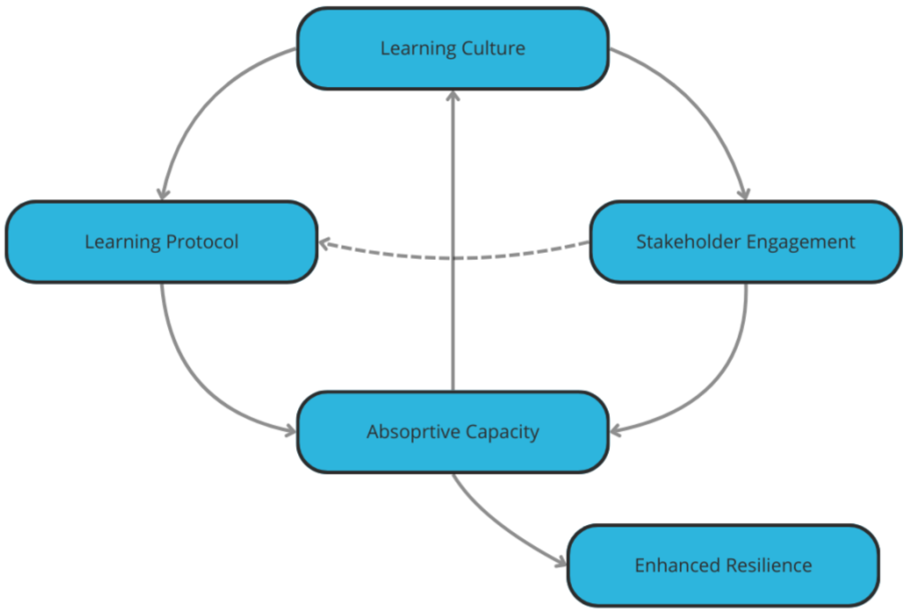

Figure 14: Positive reinforcement loop of organizational learning

A strong learning culture provides the system with the foundations for an effective learning process guideline, which in turn builds and reinforces the systems absorptive capacity. Active stakeholder engagement leads to an inclusive and well-rounded learning process. Creating a strong continuous learning structure, for resilience enhancement.

Synergy of an integrated learning process guideline

The proposed foundation of the learning process guideline leans on the synergy of a combined digital solution approach. Where both AI technologies and a Digital Twin of the NPP system work together with existing IoT devices, and digital platforms coupled with data visualization tools to enhance system resilience learning. Furthermore, STS theory serves as a basis onto which various key concepts outlined in this research are presented and highlighted. This includes resilience engineering, risk management, digital technology integration, stakeholder engagement. Resulting in a well-rounded structure for enhancing NPP resilience.

AI-capabilities can be integrated to enhance disaster data analysis and turn the extracted data into actionable insights. Utilizing the predictive analysis capabilities of ML models to offer enhanced anticipation of potential risks and weaknesses in the system. Working together with the digital twin, a virtual representation of the NPP system, to continuously monitor the system's parameters and surroundings (pro-active analysis). Furthermore, the Digital Twin will allow simulation of various disaster scenario's. By offering a digital environment to test and evaluate resilience strategies and iterate where necessary and train employees for preparedness (data-driven evaluation), ensuring adequate resilience practices against disruptive events. Overall leading to a data-driven decision-making process regarding NPP system resilience enhancement strategies and engineering (strategic decision-making).

STS theory integration ensures that the learning process guideline considers both technical and social factors, and does not overlook the importance of organizational aspects such as learning and culture. Employing STS theory, strengthens the systems ability to integrate technological advancements whilst considering and improving human capabilities. Allowing the system to become more prepared, adaptive and responsive. Actively engaging stakeholders in every stage of the protocol development, establishing that all needs, requirements and perspectives are taken into account therefore, the decisions made in the protocol design to be practical and effective to address the systems weaknesses regarding resilience.

Building a sophisticated learning process guideline as outlined in this study to have a multi-faceted approach to NPP system resilience enhancement. Revolving around AI and Digital Twin technology utilization and STS theory. Creating a balance between technical and social facets in the learning process guideline. Together, this approach forms the basis for the learning process guideline, making sure that NPP system are able to anticipate, react to, withstand and recover from disruptions in an efficient and timely matter, minimizing cascading effects of natural disasters.

Top-down analysis of the NPP system

This study has laid out the three stages which the learning process guideline addresses to enhance systemic resilience. In order to convert these stages towards an understanding of the influence that this study, ie. STS theory projected on the learning process guideline has on the NPP system and its' surroundings regarding resilience in case of a natural disaster, a top-down analysis is performed. The NPP system is divided into four separate levels; Policy, regulations and (inter)national government / Emergency services, local community / The nuclear plant / Technical systems. The levels are set up in such a way to provide an outside-in overview of the context of the NPP system and how the findings of the study affect the NPP system.

Level 1: Policy, Regulations, and (Inter)national Government

The highest level of the NPP system context includes regulatory bodies and governmental oversight of the NPP system. Setting policy and regulations within which the system operates.

Influence of STS theory

STS integration supports stakeholder engagement with these regulatory bodies and policy makes, creating a continuous feedback loop of new insights and regulatory adjustments. This interplay can become valuable for the entire nuclear sector, by promoting best practices and adequate resilience measures. Moreover, socio-technical integration makes sure that both technical compliance and implications of regulations on the organization are taken into account.

Influence of the learning process guideline

Resilience strategies will need to be aligned with national safety policies and international regulation standards. The learning process guideline also supports compliance with these standards, by continuously incorporating regulations and best practices. Simultaneously policy makers and regulatory bodies benefit from data-driven insights made from the historical disaster data analysis, by keeping these actors informed can help shape and improve future policies and regulations.

Level 2: Local Communities and Government, Emergency Services

This level encompasses the collaboration of the NPP system with their immediate surroundings. Such as the inhabitants of the immediate vicinity of the plant, as well as local government and the emergency services. This level is especially important in case of a natural disaster, since they may be the first affected by a disaster.

Influence of STS theory

Sophisticated learning from the past enhances the systems ability to create adequate disaster response strategies, together with stakeholder engagement via collaboration with emergency response services. Facilitates close-coordination with these services, the local communities and municipalities. Safeguarding the plant, its' infrastructure and the inhabitants around the plant.

Influence of the learning process guideline

AI technology and predictive models allows for the disruptions of a natural disaster to be forecast, supporting preparedness and mitigation of cascading effects of the impact of a natural disasters. Furthermore, collaboration with the community ensures their concerns and needs are integrated into the strategies.

Level 3: The Nuclear plant

Concerning the organization and operations of the plant. This includes management, staff, and decision-making processes.

Influence of STS theory

Organizational strategic decision-making is balanced by human factors (coordination, communication and training) and advanced technologies capabilities (Data analysis, predictory models, simulations and monitoring). STS emphasizes the importance of integrating social aspects (culture, behavior etc.) into the learning process guideline. In case of a natural disaster, clear communication and collaboration between departments and facilities within the plant is paramount, proper stakeholder engagement cultivates this.

Influence of the learning process guideline

A strong learning culture is facilitated by a well-designed learning process guideline. Continuous learning is driven by feedback loops between human actors and technological systems. A digital twin allows for new strategies to be evaluated by disaster simulation, assessing how the organization and its's personnel react to such a scenario and are better prepared in case of a natural disaster. Furthermore, the systems absorptive capacity is strengthened by enhanced disaster data analysis. From these lessons learnt and digital tool utilization, data-driven decision-making is fostered. Strengthening the resilience strategies. In the case of a natural disaster, these improved emergency protocols should be deployed in a timely manner, when staff is properly prepared and trained, this is ensured.

Level 4: Technical systems and infrastructure

The technical core of the NPP system, including the physical and digital infrastructure.

Influence of STS theory

STS theory appreciate that the design and operation of these technical systems is within the boundaries of human capabilities. Understanding that the interaction of human actors with the technical system has an impact on the overall resilience.

Influence of the learning process guideline

Integrated with digital twin technology, the systems performance is monitored continuously, offering real-time analysis of parameters. As well as assessing the systems performance during simulations under various conditions. This flow of data with the help of AI predictive models, supports pro-active maintenance and identify system weaknesses. Strengthening the systems resilience by mitigating risks before they happen and escalate into further disruptions.

Figure 16 below is a schematic visualization of this analysis on the influence of the proposed integrated learning process guideline, on the NPP system and its' context in the event of a natural disaster. The illustration has an inverted pyramid shape to underline the top-down approach of this analysis. Going through the levels provides an outside in view of the context of the NPP system and this study. With each descending level narrowing the scope of the analysis.

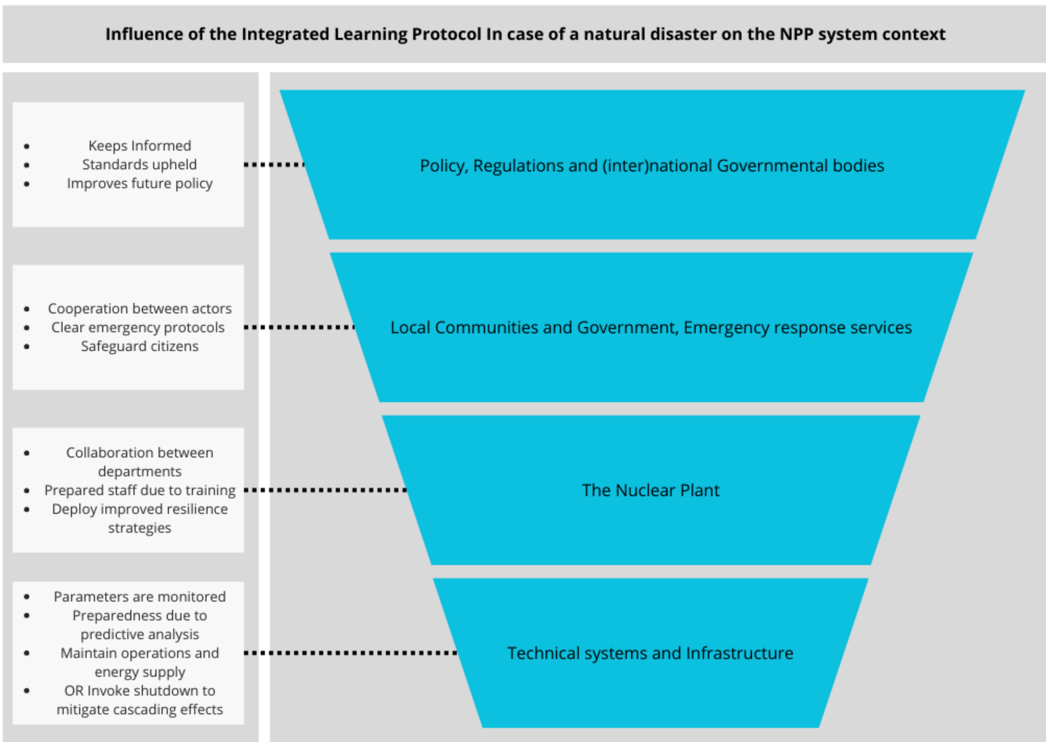

Figure 15: Top-down analysis of the NPP system

Composing an adjusted STS framework

The Social-Technical systems framework is a frequently employed framework within the literature of critical infrastructure management, as is evident from the preceding chapter. STS theory has been utilized and learnt from throughout this study, to create a comprehensive understanding of the varying facets surrounding NPP systems and resilience enhancement engineering. However broadly applicable, the STS theory has proven to be very useful in application to the NPP system and the aim of this study. To showcase the utilization, process the following schematic is made;

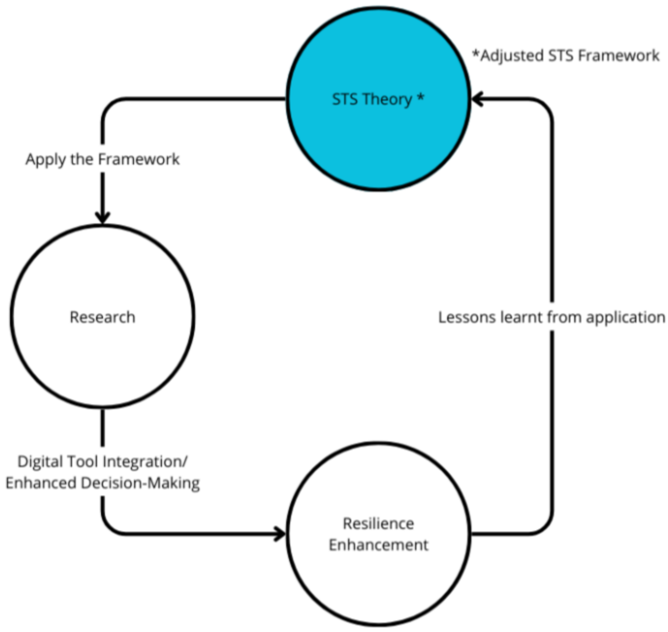

Figure 16: STS Theory feedback-loop

By applying the original Socio-Technical Systems theory, a greater understanding is adopted on the importance of the interconnected between human facets and technical aspects within a system. Considering these principles allowed this study to learn from the framework and therefore create a comprehensive structure for resilience enhancement. Once the theoretical resilience enhancement of the NPP system, through the implementation of an integrated learning process guideline is achieved. It is time to reflect and take away lessons learnt from the utilization of STS theory within this study. And with reflection, propose an adjusted STS theory framework, customized for resilience enhancement engineering of critical infrastructure.

Building upon the core principles of STS theory; the interaction between social systems (human facets) and technical systems (technology), within an organization. Emphasizing on the understanding that the better organizational performance is achieved through the harmonious interplay between these two types of systems. From this study, it became evident that not only the nuclear plant itself has a major role to play in striving to achieve systemic resilience enhancement. However, also the context and the actors surrounding the plant have key roles to play. This study highlighted how interconnectedness of the context of these systems is, and how different actors have various levels of influence/power and interest in the stakes of the system as well as resilience enhancement.

A framework, customized to address the challenges and create in-depth comprehension of what is required to achieve systemic resilience enhancement, to support adequate organizational management. Needs to be relatively simple and easy to implement on a wide range of applications, which the STS framework in part addresses. Therefore, the adjusted STS framework proposed, needs to be all-encompassing of the challenges of resilience management, but not too complex, allowing understanding of the theory throughout the system.

By adding another layer to the core Socio-Technical Systems principles, a contextual pillar, this proposed adjusted framework aims to deepen the reach of the framework, in regard to resilience engineering. Yet, keeping the simplicity of the original framework. By appreciating that apart from Social and Technical systems, the interplay between these two systems with the broader context must not be forgotten when aiming to enhance a systems resilience. Collaboration and communication with the broader context surrounding a system is of critical importance for the development of effective resilience strategies. These strategies need to be compliant with policy and regulations. At the same time, these innovative strategies should not be kept within the system itself, but shared throughout the systems community, therefore improving the overall resilience and best practices of the industry. Furthermore, collaboration with emergency response services is vital, in case of a disaster, all actors surrounding the system need to be aware of emergency strategies and protocols, for smooth and swift action, protecting the system and the inhabitants surrounding them. In the event of a natural disaster, better prepared and responsive NPP systems or other Critical Infrastructures are collectively more resilient than a single system. In addition, mitigating the cascading effects when one system fails, in case of a natural disaster. Thus, being able to safeguard broader society, maintaining the vital role these systems play in society. This enhanced framework; *Socio-Technical-Contextual Systems framework*, takes on a three-pillar approach to resilience enhancement engineering. Aiming to be applicable to Nuclear Power Plants systems as well as other Critical Infrastructure systems.