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Developing an Integrated Model of Resilience and System Dynamics for NPP Accident

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ABSTRACT

The Fukushima Daiichi nuclear power plant (FDNPP) accident highlights the role of resilience and system dynamics in maintaining the safety of nuclear power plants (NPP). A brief literature review is conducted regarding the FDNPP accident, and an integrated model of resilience and system dynamics (IMRSD) for an NPP accident is proposed. This IMRSD is developed based on four key elements of resilience: anticipating, monitoring, responding, and learning. These elements are influenced by thirteen factors. The identified factors in the proposed model are requisite imagination regarding expected initiating event, the organizational safety culture, the proper human resource with adequate training, the requisite interpretation regarding the progress of the event, the monitoring procedures during the accident, the proper support from the human resources, the proper system to notice the developments of the accident, the adequate resources, the responding procedures, the availability of flexibility of responses, the trained personnel for emergency responses, experiences from the past events and responses, proper modeling of accident and analyzing natural hazard. Responding is found as the most vital element for effective resilience in the event of an NPP accident. Decision-makers of operating management at an NPP can consider the identified factors and how they interact with various elements to ensure the safety of NPPs.

Keywords

FDNPP Accident, IMRSD, Resilience, Severe Accident, System Dynamics.

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1. Introduction

When a nuclear power plant (NPP) experiences a severe accident, radioactive material is released, causing significant core degradation (IAEA, 2008). The earthquake and the ensuing tsunami caused the catastrophic accident at the Fukushima Daiichi nuclear power plant (FDNPP). The FDNPP accident revealed multifaceted issues related to ensuring the safety of complex socio-technical systems (Yoshizawa et al., 2016). The research on the lessons of the FDNPP accident is still ongoing from different perspectives and views. To ensure safety during an NPP accident, the resilience and system dynamics (Williams, 2002; Hollnagel and Fujita, 2013) approaches can be used.

A computer simulation modelling technique called system dynamics is used to frame, comprehend, and discuss complex problems in a complex system (Radzicki and Taylor, 1997; Azar, 2012). A qualitative and quantitative tool for developing inter-relations, such as cause-effect relations, non-linear behaviour, and dynamic changes for a complex project, is system dynamics, which includes causal loop and feedback loop diagrams (Williams, 2002). While feedback loops are closed chains of cause-effect links that can generate additional actions, casual loops in a system dynamics model illustrate the relationships between various causes of a system (Wang et al., 2005; Hossen et al., 2016). The complexity of system dynamics must be handled properly to ensure the safety of an NPP during accident conditions (Kamanja and Jonghyun, 2014).

Resilience systems require four key elements: anticipating developments, threats, and opportunities; responding swiftly and efficiently to both expected and unexpected circumstances; monitoring system performance and critical developments; and learning from past experiences, both successful and unsuccessful (Hollnagel and Fujita, 2013; Hollnagel et al., 2010). These four elements interact with one another rather than existing independently of each other. Through study and practice, one can enhance the ability to anticipate and respond (Yoshizawa et al., 2016). Examining the interaction between these four elements and other factors that boost resilience in the event of an NPP operation and accident is helpful.

A brief literature review on the FDNPP accident from the perspectives of resilience and the system dynamics approach is appropriate. The development of an integrated model by applying the approach of resilience and system dynamics during NPP operation and accident conditions is useful to ensure the safety. The main objectives of this study are to analyse the FDNPP accident from the perspectives of resilience and system dynamics approaches, and to develop an integrated model using these approaches during an NPP accident qualitatively.

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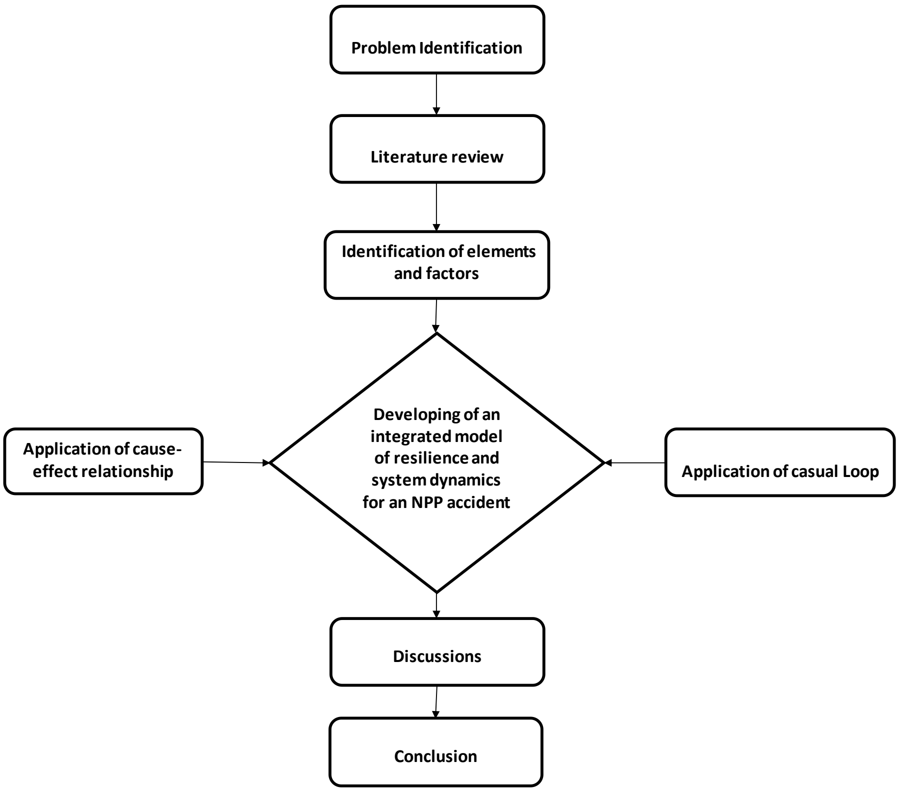

Figure 1. Research methodology

The research framework of this study is shown in Figure 1. As shown in Figure 1, the research problem is identified first, which is the investigation of the resilience and system dynamics during NPP operation and accident conditions. Secondly, a brief literature review of the FDNPP accident is provided from the perspective of resilience and system dynamics approaches. Thirdly, elements and factors affecting the resilience and system dynamics are identified. Fourthly, an integrated model by applying the approach of resilience and system dynamics during NPP operation and accident conditions is developed using cause-effect relationships and causal loop qualitatively. Finally, the study concluded by discussing the importance of the developed model to ensure the safety of NPP and signalling future research.

2. Literature review

The FDNPP site was designed based on the tsunami during Chile's earthquake in 1960, and the tsunami height was considered as 3.122 m above the Onahama Port (OP) level according to the 1966 approval for the establishment of FDNPP. Tsunami height for the FDNPP site was reviewed in 2002 and 2009 as 5.7 m and 6.1 m above the OP level, respectively, and measures were taken to raise the pump elevation and make buildings watertight (TEPCO, 2012; IAEA, 2015).

The FDNPP site had six boiling water reactors. The devastating earthquake occurred on March 11, 2011, at 14:46, with a magnitude of 9.0 (JMA, 2013). Units 1, 2, and 3 of the FDNPP were operational, while units 4, 5, and 6 were shut down. With a range of intense pulses and aftershocks, the earthquake lasted for over two minutes (IAEA, 2015). All operating reactors were automatically shut down, and the basic safety function to control the reactivity was sustained just after the earthquake. The earthquake caused the FDNPP to lose all of its off-site electric power supply, and emergency diesel generators were activated to provide power and ensure reactor safety (TEPCO, 2012; IAEA, 2015).

Subsequently, a massive tsunami wave arrived at the FDNPP site. The design-based tsunami height at the FDNPP site failed due to tsunami-induced flooding, which was nearly 11.5 to 15.5 meters above the OP level. In addition to damaging the emergency diesel generators, which resulted in the loss of on-site AC power, the tsunami-induced flooding damaged the cooling seawater pumps and motors, causing the ultimate heat sink to fail, and it flooded the on-site DC batteries and power panels, resulting in a loss of DC power in FDNPP (TEPCO, 2012). Operating EDGs were shut down, and numerous power panels were flooded. As a result, FDNPP units 1, 2, 3, 4, and 5 lost the AC power and these units experienced a station black out (SBO) scenario except unit 6, with its one remaining air cooled EDG supplied emergency AC power (IAEA, 2015). All AC-powered cooling functions were lost, and flooding of the cooling seawater pumps rendered the reactor unable to transfer decay heat to seawater. Core cooling functions, which were designed to operate without an AC power source, were sequentially shut down at FDNPP units 1, 2, and 3 due to the DC power outage (TEPCO, 2012).

In FDNPP, the extended SBO events lasted longer than nine days in units 1 and 2, and fourteen days in units 3 and 4. Reactors in units 1, 2, and 3 suffered damage as a result of the fuel overheating and melting because NPPs were unable to manage the extended power outages and plant heat removal. The radioactive material contained in the primary containment vessels was released into the environment after the reactor pressure vessels in those units were damaged, causing radioactive material to leak from the reactors. This resulted in radiological contamination of the surrounding environment and exposure to radiological hazards for on-site workers and local residents (IAEA, 2015).

The earthquake and the following tsunami caused the loss of AC and DC power, with multiple failures of safety systems, and a severe accident occurred in all three operating reactors in FDNPP (IAEA, 2015; Mizokami and Kumagai 2015; Kim et al., 2016). The cascade of engineering and regulatory failures can be considered as the reason of the FDNPP accident

(Synolakis and Kânoğlu, 2015). The Fukushima Daiichi accident was a result of a combination of earthquake, tsunami, and human factors, such as inadequate plant design, failure of backup systems, and insufficient safety measures.

The resilience engineering applications can be related to industrial systems, focusing on the effects of socio-technical factors, multi-disaster situations, design optimisation, and restoration strategies (Pawar et al., 2021). Resilience engineering involves multifactorial, multilevel and multidimensional aspects for successful outcomes for a complex system (Pillay, 2017). Critical infrastructure systems can be considered as resilient if it has the ability to imagine, protect and resist disruptions, absorb adverse effects, adapt to new conditions and changes and recover from disruptions (Mottahedi et al., 2021). The modelling of the effect of extreme events on multiple interdependent critical infrastructure systems is useful for improving their resilience (Wang et al., 2024). Resilience is a distinguishing aspect of a socio-technical system (Hollnagel and Fujita, 2013). A system's resilience is defined as its capacity to withstand a disruptive event, adjust to mitigate possible repercussions, and recover (Adjetey-Bahun et al., 2016). The ability of hardware, software, and organizational systems to adapt to changing circumstances, lessen the likelihood and severity of failures or losses, and react appropriately after the fact is known as system resilience (Jackson, 2007). Resilience is a characteristic that results from the interactions between the hardware, software, and people that comprise the system (Cilliers, 1998). The capacity of a system to bounce back from both anticipated and unforeseen disruptive events is known as resilience (Abimbola, Khan, 2019).

Resilience engineering is a relatively new approach to safety management in NPPs, which can deal with complexity under pressure or disturbance to succeed (Kim et al., 2018). A resilience engineering approach can be applied in design, operation, and maintenance in the response and recovery of accidents for high-impact low-probability events to ensure nuclear safety (Yan et al., 2023). As demonstrated by the nuclear accidents at Three Mile Island, Chernobyl, and Fukushima, NPP is a complex system where disaster risk is real and requires resilience to both internal and external challenges (Hollnagel, 2014). Thus, the resilience of NPPs can be referred to as their capacity to endure and bounce back from a variety of events, such as natural disasters, technological malfunctions, and human error, by maintaining safety and lowering risks to the environment or public health.

System dynamics is capable of capturing the reciprocal and temporal causal relationships in a complex system (Fang et al., 2018). A conceptual model of system dynamics is capable of managing nuclear safety in an operational organisation of an NPP on the basis of the human, technology, organisation, and environment framework (Acuña et al., 2023). A system of systems management framework can be applied for the emergency recovery of the Fukushima Daiichi nuclear disaster (Gunawan et al., 2017). The dynamic response to possible emergencies in a NPP was analysed on the basis of the evolutionary change of an emergency plan in light of the organisational learning, innovation and risk communication (Quadros et al., 2022). The application of a combined approach of resilience and system dynamics during NPP operation and accident conditions can be valuable for ensuring safety.

3. Model development using resilience and system dynamics approach for an NPP accident

Vensim computer software tool (Ventana Systems, 2007) was used to develop a qualitative integrated model using resilience and system dynamics approach for an NPP accident from the perspective of the FDNPP accident. In this study, the model was qualitatively formulated using key components of the resilience system, namely, anticipating, monitoring, responding, and learning, with other dominating factors.

Due to the occurrence of the earthquake and tsunami, the flooding led to the failure of the design basis for the Tsunami height at the FDNPP site. In addition to damaging the EDGs and cooling seawater pumps and motors, which resulted in the loss of the ultimate heat sink, the flooding also inundated the on-site DC batteries and power panels, causing a loss of DC power in the FDNPP (TEPCO, 2012). As a result, the plant lost its ability to cool. It implies that the failure of anticipating the required design basis Tsunami height, as well as the loss of all AC and DC power, caused the FDNPP accident.

Anticipating possible outcomes is essential for identifying and managing undesirable occurrences (Lundberg and Johansson, 2015). The ability to anticipate possible obstacles or systemic changes by identifying risks and opportunities early on enables better preparation and adaptation. In a resilient system, anticipating means being aware of what to expect or having the ability to foresee future opportunities, threats, and developments, such as possible disruptions or shifting operating conditions (Hollnagel and Fujita, 2013). The anticipation largely depends on requisite imagination, which is the ability to foresee future problems (Westrum, 2006). Prescription, human resource, human machine interface, training, safety culture, and previous experience can contribute to anticipating the resilient system (Kamanja and Jonghyun, 2014). Anticipating characterizes the measures that are in place before the occurrence of an initiating event in order to ensure that there is preparedness for it. The NPP operation procedures, operator training, organizational culture, human resources, and human–system interfaces are all part of anticipating (Kim, 2018). Thus, the requisite imagination regarding the expected initiating event, the organisational safety culture, and the proper human resources with adequate training can positively affect the anticipation. The proper anticipation can positively impact the prevention of the occurrence of an NPP accident.

Due to the prolonged power outage, the Fukushima Daiichi NPPs lost most of their safety systems, including instrumentation and control systems, which made it extremely difficult to respond to the accident (Yang, 2014). Operators were unable to monitor critical plant parameters, such as the reactor's water level, temperature, and pressure, because of the loss of on-site and off-site power during the FDNPP accident. The plant status of key systems and components used for core cooling could not also be confirmed due to the loss of displays of monitoring instruments and various inoperable lamps of the main control room during the FDNPP accident (IAEA, 2015). It indicates that the failure of the monitoring of the status of important thermal-hydraulics parameters and the status of the key systems and components in FDNPP was occurred.

The monitoring in a resilient system looks for or monitors what could seriously affect the performance of the system positively or negatively (Hollnagel, 2015). Appropriate anticipation serves as a guide for monitoring, which is the surveillance of important system parameters and events. Anticipating is a prerequisite for establishing modes of monitoring in advance of signs for the onset of events (Lundberg and Johansson, 2015). The requisite interpretation is the ability to see the facts of an accident and to accept that it happened and to coordinate a process of adaptation in response to the emerging events (Lundberg and Johansson, 2015; Lundberg and Johansson 2006). For emergency response organization of a nuclear power plant, monitoring procedures, information, and support are immediate contributing factors of monitoring capability (Lee et al., 2022). Monitoring must cover the changes in the system and environment (Hollnagel and Fujita, 2013). Thus, the requisite interpretation regarding the progress of the event, the monitoring procedures during the accident, the proper support from the human resource, and the proper system to notice the developments of the accident can positively affect the monitoring. Proper monitoring and respective actions can prevent the progression of an NPP accident.

In the case of the FDNPP accident, the failure to anticipate and monitor led to a failure to respond to the control of abnormal operation and a failure to detect using control, limiting, and protection systems, as well as other surveillance features.

Because of the prolonged station blackout, operators were unable to successfully operate the safety systems during the FDNPP accident (Yang, 2014). In the FDNPP accident, plant instrumentation was lost or severely reduced, and operating the safety systems for cooling the reactor cores became extremely challenging (Pellegrini et al., 2015). During the FDNPP accident, the failure to protect the critical safety equipment at the plant from flooding has occurred (National Research Council, 2014). In the case of the FDNPP accident, the failure to anticipate and monitor resulted in the failure to respond to the control of abnormal operation and the failure to detect using control, limiting, and protection systems as well as other surveillance features.

In a resilient system, responding means knowing what to do or being able to react to opportunities, disruptions, and regular and irregular variability by either activating pre-programmed responses or changing the way things are done (Hollnagel, 2015). In order to effectively respond to a problem, there must be adequate resources together with the capability to coordinate those resources in a meaningful way to deal with the progress of the problem (Lundberg and Johansson, 2015). Knowledge and competence are prerequisites for making decisions on how to respond, but to make such decisions, learning from successes is also important (Yoshizawa et al., 2016). Anticipating is a prerequisite for establishing modes of response in advance of events, and monitoring is necessary to detect problems and remain in control of a situation (Lundberg and Johansson, 2015). The availability of necessary resources is required to respond in a resilient system (Hollnagel, 2014). For emergency response organization of a nuclear power plant, responding procedures, performance, staffing, adaptability, and tools and equipment are immediate contributing factors of responding capability (Lee et al., 2022). Thus, adequate resources, the responding procedures, the availability of flexibility of responses, and trained personnel for emergency responses can positively affect the response during an NPP accident. The proper responding and responses can prevent the occurrence of any worst situation during an NPP accident.

Evidence of massive tsunamis flooding the area in the past had not received sufficient attention, and the tsunami hazard analysis appeared to contain methodological errors in determining the maximum likely tsunami height at Fukushima Daiichi (Synolakis and Kânoğlu, 2015). Steps that could have prevented the FDNPP accident, namely, protecting emergency power supplies, including diesel generators and batteries; establishing watertight connections between emergency power supplies and key safety systems; and enhancing the protection of seawater pumps (Acton and Hibbs, 2012).

Experience-based learning, specifically the ability to draw the appropriate lessons from both successes and failures for a resilient system (Hollnagel, 2015). An accident is an exceptional source of insight into future events (Lundberg and Johansson 2006). For emergency response organisation of a nuclear power plant, training and experience dissemination are immediate contributing factors of learning capability (Lee et al., 2022). Overconfidence in anticipating what might go wrong limited the ability to monitor and respond and to learn, hence impeding the development of resilience (Hollnagel and Fujita, 2013). Thus, the experiences from the past events and responses, proper modelling of accidents and analysing natural hazards, and organisational safety culture can positively impact the learning capability of an NPP accident. The proper learning can positively impacts the safe operation of the plant during an accident. The integrated model of resilience and system dynamics (IMRSD) during NPP accident conditions is shown in Figure 2. The positive '+' sign shown in Figure 2 represents a positive effect of one factor on the incidence of another factor, contributing to effective resilience.

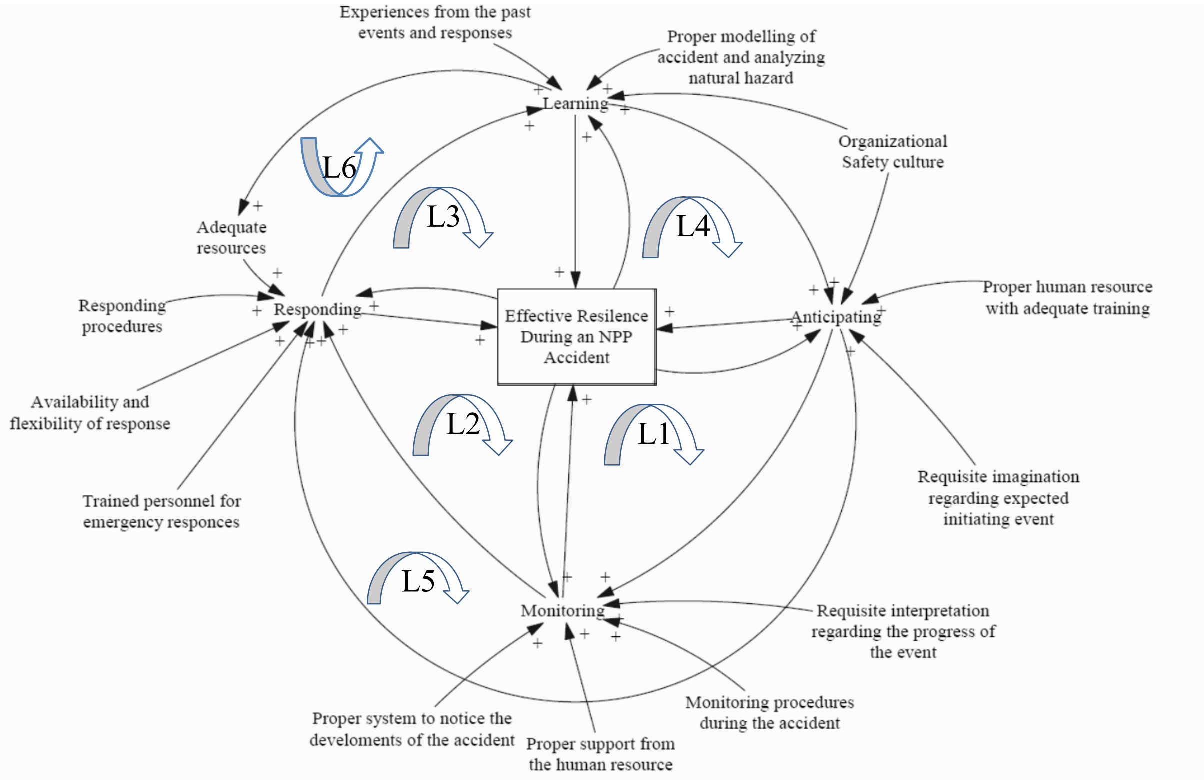

Figure 2. Integrated resilience and system dynamics model of an NPP accident

The proposed IMSRD is formulated of four elements, namely, anticipating, monitoring, responding and learning, which can positively impact the resilience during an NPP accident. The anticipation can be impacted by element learning and by three factors, namely, requisite imagination regarding the expected initiating event, the organisational safety culture, and the proper human resources with adequate training. The monitoring can be impacted by element anticipating and by four factors, namely, the requisite interpretation regarding the progress of the event, the monitoring procedures during the accident, the proper support from the human resource, and the proper system to notice the developments of the accident. The response can be impacted by two elements, learning and anticipating, and by four factors, namely, adequate resources, the responding procedures, the availability of flexibility of responses, and trained personnel for emergency responses. The learning can be impacted by the element responding and by three factors, namely, experiences from past events and responses, proper modelling of accidents and analysing natural hazards, and organisational safety culture.

From the proposed IMRSD, it can be observed that the response is a critical element for effective resilience. The response is directly affected by the anticipation, monitoring, and learning with other factors, namely, adequate resources, the response procedures, the availability of flexibility of responses, and trained personnel for emergency responses. The factor organisational safety culture can positively impact two elements of learning and anticipating in the proposed model. The factor of adequate resources is created through learning and affects the element responding. It can be considered that responding and monitoring are more influential elements than learning and anticipating during the accident of an NPP.

The effective resilience for NPP accident conditions is comprised of four elements and thirteen factors according to the developed IMRSD. If the effective resilience occurs during an NPP accident, it will positively impact four elements and six causal loops can be directly observed in Figure 2. Anticipating has a positive impact on monitoring, which ultimately enhances the effective resilience of the system, and this in turn positively impacts the anticipating process again. A positive causal loop L1 is generated by it. Monitoring positively impacts responding, which ultimately boosts effective resilience in the system, and this, in turn, positively impacts the monitoring again. It creates a positive causal loop L2. Responding has positive impacts on learning, which ultimately boosts effective resilience positively in the system, and it will positively impact the responding again by generating a causal loop L3. Learning has a positive impact on monitoring, which ultimately boosts effective resilience in the system. This, in turn, positively impacts the system, and the system's learning is further enhanced by generating a causal loop L4. Anticipating also impacts responding, which ultimately boosts the effective resilience positively in the system, and it impacts anticipating again by generating a causal loop L5. Learning positively impacts adequate resources, which ultimately boosts the response, and it will impact the learning again, generating a causal loop

L6. Besides, by the combination of two or more loops in the model, more new loops can also be formed in the developed model.

Figure 2 illustrates the positive relationship between the factor and the element of effective resilience. However, the elements may also be adversely affected by these factors, which will ultimately have a negative impact on the model's resilience. Consequently, ineffective resilience for an NPP accident condition can occur due to the negative relationship between the factor and the element of the developed model.

4. Discussions

The developed IMRSD is a generalised qualitative model for NPP operation management and accident conditions to enhance the safety of NPP. The proposed model can increase the understanding of the dynamics of the operational safety management of an NPP. It may be possible to decrease risk during the normal operation of NPP and during the accident condition by implementing the elements and factors of the developed model.

The safety philosophy of an operating nuclear power plant (NPP) is grounded in principles of diversity, redundancy, and defence in depth (Clayton, Poore, 2015). It is recommended to consider the system resilience during the design of NPP to ensure the safety. Besides, operators and technical personnel must be trained and aware of the four elements of resilience, namely, anticipating, monitoring, responding and learning. Improving the resilience of NPPs requires a multi-faceted approach, encompassing physical, operational, digital, environmental, and human factors. Maintaining and improving resilience for NPP requires ongoing investment, technological innovation, and a robust regulatory framework. The resilience of an NPP depends on the robustness of its design, the effectiveness of its safety systems, and the response of its operators under accident conditions. System dynamics during an NPP accident are interconnected procedures that occur within the NPP and its various safety systems in response to an event.

Nuclear safety encompasses more than just preventing accidents; it involves the development of systems that can adapt and improve over time. By integrating the four elements of resilience, anticipating, monitoring, responding, and learning, into nuclear operations according to the suggested model, the nuclear industry can move towards ensuring the safe and sustainable operation of NPP in the future. The operating management of an NPP can visualise the identified factors and their interaction with elements according to the suggested model for safe operation and accident management. It is expected that the suggested model can enable managers to enhance operational safety and to ensure more resilient and efficient plant performance.

Although the model can identify causal relationships and feedback loops within a system, it cannot provide numerical predictions of failures of factors and elements during an NPP accident. Thus, the proposed qualitative model does not provide specific numerical output and the exact required time between elements and factors during an NPP accident, which is a limitation of the developed model. Besides, the model considers only thirteen factors, but external factors beyond the control of the NPP operating organisation are not considered in the suggested model, which is another limitation.

The proposed model has not been implemented yet in any specific NPP accident. In further studies, the implementation of the suggested model to a specific NPP accident can be performed. Furthermore, the developed model can be further enriched by incorporating additional factors and adopting a quantitative approach to ensure the safe operation of NPP.

5. Conclusion

In this study, an integrated model of resilience and system dynamics during an NPP accident is proposed from the perspective of the FDNPP accident. The proposed IMRSD is formulated based on four elements and thirteen key factors to ensure the safety of NPPs. The conceptual model is developed qualitatively.

The traditional four elements — anticipating, monitoring, responding, and learning —are positively impacted by the thirteen factors according to the model. The identified factors in the proposed model are namely, requisite imagination regarding expected initiating event, the organizational safety culture, the proper human resource with adequate training, the requisite interpretation regarding the progress of the event, the monitoring procedures during the accident, the proper support from the human resource, the proper system to notice the developments of the accident, the adequate resources, the responding procedures, the availability of flexibility of responses, the trained personnel for emergency responses, experiences from the past events and responses, proper modelling of accident and analysing natural hazard. The response can be considered as the critical element for effective resilience during an NPP accident.

Combining resilience and system dynamics for an NPP accident is an innovative approach to enhancing the safety and long-term sustainability of NPPs. Decision-makers of the operating management of an NPP can consider the identified factors and their interaction with elements in the suggested model to ensure the safety during an NPP accident.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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