National University of Science and Technology POLITEHNICA Bucharest

Doctoral School of Entrepreneurship, Engineering Business and Management

The summary of the doctoral thesis

Research on nuclear accident risk management on the population adjacent to Cernavoda Nuclear Power Plant

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Fundamental Field: Engineering Sciences

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ABBREVIATIONS

A.I.E.A. - International Atomic Energy Agency

A.R.L. - Air Resources Laboratory, USA

C.N.C.A.N - Nuclear Commission for the Control of Nuclear Activities - The national authority competent in the nuclear field that exercises regulatory, authorization and control attributions according to Law 111/1996 on the safe conduct of nuclear activities, as amended and subsequent additions.

JAM. - General Euclidian Model (General Euclidian Model)

G.U.I.- Graphical user interface (graphical user interface)

H.Y.S.P.L.I.T. – "Hybrid Single Particle Lagrangian Integrated Trajectory", is a model of langrangian integrated hybrid particle hybrid trajectory is a software model that is used to calculate the trajectories of air parcels and the deposition or dispersion of pollutants atmospheric. It was developed by N.O.A.A. and the Australian Bureau of Meteorology.

ICE - European critical infrastructure

ICN- National critical infrastructure

M.A.I.: - Ministry of Internal Affairs

M.P.I.- Message Passing Interface, the interface that connects several processors

N.O.A.A. - National Oceanic and Atmospheric Administration, USA, National Administration Oceanic and Atmospheric, developer of the HYSPLIT program

O.M.M. - World Meteorological Organization

O.R.N.I.S.S. -The Office of the National Register of State Secret Information

P.I.C. - Protection of critical infrastructures

PSO - Operator's Security Plan

R.S.M.C. - Specialized Regional Meteorological Centers

INTRODUCTION

In the context of contemporary societal development, nuclear technology is becoming increasingly accessible on a global scale, both in terms of energy production and its use in research and weaponry. Considering emerging threats with significant socio-economic and geopolitical impacts—such as the Covid-19 pandemic, the lack of global consensus on nuclear policy, and nuclear threats in the context of the conflict in Ukraine—the risk of potential radioactive contamination is growing, regardless of its origin. The withdrawal of the United States from the Intermediate-Range Nuclear Forces (INF) Treaty, the possible resumption of nuclear testing by the United States and other countries, as well as the increasing number of nuclear reactors worldwide, necessitate a reevaluation of protection means and regulations in the nuclear domain.

This doctoral thesis proposes a dual approach, focusing on the legislative framework and risk analysis for critical infrastructures, including nuclear ones, and on scientific aspects aimed at improving emergency response using higher-fidelity predictive tools. The first part of the thesis examines the criticality of processes in a nuclear power plant through the development of a criticality matrix based on the ACIS methodology (Analysis of Critical Infrastructural Sectors). The second part is dedicated to simulations of nuclear incidents using the HYSPLIT and Rhodos programs. These simulations predict the behavior of radioactive particles and clouds based on complex meteorological forecasts. The results of these simulations, conducted in the context of extreme weather phenomena in Romania and the increasing nuclear threat, highlight the pressing need to modernize security protocols.

Simulations were carried out using these programs, replicating past events, such as the Fukushima accident, and modeling new scenarios, such as a hypothetical explosion at the Cernavodă nuclear power plant. Various meteorological maps were utilized, and simulations were run for different timeframes, accounting for recent extreme weather events in Romania. The calculation of transport and dispersion from the source was performed using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (Draxler, Hess, 1998).

In HYSPLIT simulations, results comprised four components: particle transport at average wind speed, turbulent transport, removal and radioactive decay, and, finally, the calculation of radioactive particle concentration in the air. Alongside dispersion, velocity, and trajectory calculations, HYSPLIT enabled a comparative analysis between simulators used in Romania, such as FLEXPART and Rhodos.

Using Rhodos and HYSPLIT, each simulation determined the affected population and localities for every incident scenario. New security measures and emergency response strategies were proposed through the Operator Security Plan. The technical capabilities of these programs meet EU requirements, enabling Romania to develop dispersion analysis models for radioactive deposition and decay at distances exceeding 300 km from the pollutant source.

With the extension of predictive radiological behavior models to greater ranges, including radioactive clouds and precipitation, the main application is to propose adjustments and enhancements to the “emergency zones” surrounding nuclear power plants. This would align Romania with European Union and IAEA Vienna standards. Such optimization could lead to the approval of new preventive measures in newly defined high-risk areas, improve emergency response speed in nuclear incidents, and prevent potential environmental contamination and loss of life. The emergence of new emergency planning zones has significant social (for the affected populations) and economic (both micro and macro) implications.

To achieve the general objective of this doctoral thesis, several research activities were undertaken:

- **Bibliographic research**: Topics included “Concepts and Types of Critical Infrastructures,” “Threat, Vulnerability, and Risk Assessment and Integration,” and “Nuclear Security, Radiation Protection, Environmental Protection, and the Operator Security Plan.”
- **Qualitative research**: This encompassed “Simulations of Major Risks in a CANDU Nuclear Power Plant and the Associated Criticality Matrix,” “The HYSPLIT Tool: Its Importance in Protecting and Optimizing Critical Infrastructures in the Nuclear Energy Sector,” “Simulation of a Nuclear Accident at the Cernavodă Nuclear Power Plant Using HYSPLIT and Rhodos,” and “Risk Assessment Based on Threat Scenarios.”

The research resulted in several key findings. Notably, the thesis introduced a detailed analysis of the current context of a nuclear power plant, focusing on the Cernavodă facility, using the ACIS criticality matrix and the most advanced atmospheric dispersion programs (HYSPLIT and Rhodos). It provided a robust risk assessment of the nuclear plant, identified current vulnerabilities, proposed the expansion of emergency response zones, and recommended measures to protect the nuclear facility and its adjacent population under present-day conditions.

Simulations of nuclear accidents at the Cernavodă nuclear power plant revealed the extent of radioactive particle transport and deposition. On days with high wind speeds (associated with orange and red meteorological alerts), the dispersion of the radioactive cloud exceeded the boundaries of the current emergency response zones. Additionally, during local wind-related meteorological alerts, the radioactive cloud exhibited accelerated movement. This research underscores the need to expand emergency response zones for nuclear accidents and proposes modifications to better protect the population near the Cernavodă nuclear plant.

In the current social and geopolitical context, accurate risk assessment and prevention are crucial for ensuring the resilience of the Cernavodă nuclear power plant and the optimal protection of the surrounding population. By developing general threat scenarios and correctly categorizing the impact and likelihood of events using the most effective programs and methods, this doctoral thesis highlights the primary risks and proposes measures to address them.

In conclusion, the thesis makes significant contributions both theoretically and practically. Its findings represent a modern approach to risk in the current context, offering proposals for revising emergency response zones and concrete measures to safeguard the population adjacent to the Cernavodă nuclear power plant.

CHAPTER 1 THE CONTEXT AND GENERAL STRUCTURE OF THE DOCTORAL THESIS

This chapter aims to provide an overview of the doctoral thesis. It addresses the current context, as well as the special importance and relevance of the chosen research topic. At the same time, the main topics of current interest addressed throughout the paper are highlighted.

The concept of risk is based on the potential of a future danger—either near or far—and is the field where philosophy and statistics intersect. Risk represents the future, unlike a real existing problem, which represents the present time. Risks are events that have not yet occurred, they can have a large or small impact, and they can be negative or positive. They can be more or less probable. It is already known that almost every activity involves risks. Nuclear, aerospace, petroleum, railway, and military industries have a long history of dealing with risk assessment. Risk assessment methods may differ between industries, depending on whether they relate to general financial decisions or environmental, ecological, or public health risk assessments. The goal is to eliminate risk, but it would be naive to believe that this can be fully achieved, which is why we will always face the notion of acceptable risk.

In recent decades, there has been a strong focus on establishing concepts in the field of critical infrastructure, both at the European and global levels. The European Union constantly updates the criteria and security measures proposed for the protection of European Critical Infrastructures. Member states have the responsibility to process European norms and apply them to National Critical Infrastructures. Moreover, the field of nuclear energy is very sensitive, and the updating of protection systems against human error or terrorist attacks is mandatory.

Main Objective of the Research

The primary objective of the research conducted by the author is to reduce the economic and social impact of a nuclear accident on the population adjacent to the Cernavodă Nuclear Power Plant (CNE Cernavodă) and to redefine the radii of emergency response zones. From this main objective, several specific objectives are derived, as outlined below.

Specific Objectives

O1: Modeling and simulating risk management processes specific to critical infrastructures in the nuclear energy sector using atmospheric prediction tools such as HYSPLIT and Rhodos. **Specific activities for achieving this objective include**:

A1.1: Presenting the main atmospheric prediction tools and their impact on preventing critical events.

A1.2: Identifying key changes and differences observed during nuclear accident simulations conducted with HYSPLIT and Rhodos atmospheric prediction programs.

A1.3: Identifying the key performance factors used by these forecasting programs to enhance the prevention process of a social and economic disaster following a nuclear accident.

O2: Risk analysis of the primary critical elements of a nuclear power plant using the ACIS criticality matrix.

Specific activities for achieving this objective include:

A2.1: Identifying the framework for using the ACIS matrix.

A2.2: Identifying the main critical elements of a CANDU-type nuclear reactor.

A2.3: Highlighting the most significant risks identified through the ACIS matrix analysis.

O3: Developing a new approach that includes adapting the current Emergency Zoning (EZ) by interpreting the results of numerical simulations using forecasting programs.

Specific activities for achieving this objective include:

A3.1: Identifying current national and international standards for emergency response zones.

A3.2: Updating the primary zones potentially affected by a nuclear accident at the Cernavodă NPP.

A3.3: Identifying the optimal emergency response zones for the Cernavodă NPP.

O4: Developing intervention measures and optimizations to reduce the impact of risks specific to critical infrastructures in the nuclear energy sector, as well as addressing the social and economic response to these risks.

Specific activities for achieving this objective include:

A4.1: Assessing the risks at the Cernavodă NPP based on threat scenarios.

A4.2: Proposing solutions to mitigate risks and protect the adjacent population.

A4.3: Highlighting the current geopolitical context and the relevance of optimizing preventive measures in the event of a nuclear accident.

Key Results (R(i))

R1: There remains the possibility of contributing to risk management processes for critical infrastructures in the nuclear energy sector using other atmospheric prediction tools. This is because no single prediction tool can fully meet all requirements for mitigating risks specific to critical infrastructures in this field. This objective was partially achieved using combined simulations with Rhodos and HYSPLIT.

R2: By conducting simulations with identical input data across multiple atmospheric simulation programs, differences in accuracy and detail of final results were observed. These findings can improve preventive processes, ensuring better protection for a larger number of citizens in the event of a nuclear accident.

R3: Using updated data such as average wind speeds and directional patterns, along with advanced forecasting systems like HYSPLIT and Rhodos, simulations identified affected zones, populations, and vulnerable infrastructures in case of a nuclear accident.

R4: To obtain a comprehensive perspective on criticality in the nuclear energy sector, particularly regarding the CANDU reactor type used in Romania, the ACIS criticality matrix was employed.

R5: With the ACIS criticality matrix and expert input, criticalities in each reactor sector were ranked. Connections between primary risks and sectors, as well as their impact on the plant's functionality and the risk of a nuclear accident, were identified.

R6: By ranking the main vulnerabilities that could lead to a nuclear accident within their respective sectors, the ACIS matrix introduced an innovative approach. It interconnected reactor sectors and ranked vulnerabilities across the entire reactor, highlighting the most hazardous vulnerabilities in all reactor sectors.

R7: National and international standards were presented to better understand emergency response zones in nuclear accident scenarios and the coverage area they provide.

R8: Simulations conducted with HYSPLIT and Rhodos under varying meteorological conditions revealed the affected area of the radioactive cloud, its radiation levels, and particle deposition on the ground. In cases of orange or red meteorological alerts, average wind speeds have increased in recent years, resulting in a broader affected area in a shorter time frame.

R9: Precise results from numerous simulations using advanced atmospheric forecasting programs and recent meteorological changes led to the proposal of expanded emergency response zones exceeding current standards.

R10: To efficiently protect the population near the Cernavodă NPP, the primary risks and vulnerabilities of the plant must be identified based on their probability and impact. This can be achieved through threat scenarios analyzed in the current social and geopolitical context, using the ACIS criticality matrix and atmospheric prediction programs.

R11: Effective solutions were proposed to mitigate and address risks, ensuring the protection of the nuclear plant, its personnel, and the adjacent population. The most significant proposal is to expand emergency response zones to include more citizens and infrastructures under the state authorities' protection.

R12: The primary risks posed by the current geopolitical situation, particularly nuclear accidents outside Romania's sovereign territory, were analyzed. The importance of using the latest atmospheric dispersion programs to prevent incidents and accidents and protect the population was demonstrated.

CHAPTER 2: CURRENT RESEARCH STATUS ON CRITICAL INFRASTRUCTURES

The unprecedented increase in recent decades of dangers and threats to the vital objectives of states and international organizations, along with the growing number and vulnerability of these targets, has led to the emergence and solidification of a new concept, generically termed "critical infrastructure." The "critical infrastructure" paradigm was officially used in July 1996 when the U.S. President issued the "Executive Order on Critical Infrastructure Protection." Thus, the concept of critical infrastructure was defined as that "part of the national infrastructure that is so vital that its destruction or incapacitation could severely weaken the defense or economy of the U.S." At that time, it was acknowledged that this included telecommunications, electricity and water supply systems, gas and oil storage facilities, finance and banking, emergency services (medical, police, and fire), and the continuity of governance.

The initiative to define and protect critical centers was adopted by international organizations. For instance, within the North Atlantic Alliance, critical infrastructure is understood by member states as: "facilities, services, and IT systems that are so vital to nations that their incapacitation or destruction could destabilize national security, the national economy, public health, and the efficient functioning of the government." National and international security are interconnected and dependent on the critical structures of states. Over time, these vulnerabilities have increased, along with the growth and refinement of means of attack. In specialized literature, there is an abundance of materials analyzing and describing potential ways to protect critical infrastructures. Two constants are generally accepted regarding the protection of critical structures:

- It is practically impossible to provide 100% protection for critical infrastructure.
- There is no single, universal solution to solving this problem.

The set of critical infrastructures is always open and variable. There are as many critical infrastructures as there are systems and processes, but to better illustrate this reality, we will divide them into three major categories, based on where they are located, in society or outer space. These are:

- Infrastructures in the physical space;
- Infrastructures in outer space;
- Infrastructures in the virtual space.

CHAPTER 3: MAIN VULNERABILITIES, THREATS, AND RISKS SPECIFIC TO CRITICAL INFRASTRUCTURES IN THE NUCLEAR ENERGY SECTOR

The term "risk" can have many definitions and classifications, thus risk is defined as "a probable event that generates losses; a possible danger." Risks can be classified based on various criteria. To analyze an organization’s exposure to risk, these can be classified into:

- Long-term risks
- Medium-term risks
- Short-term risks

This classification is closely related to the strategy, tactics, and policies of the respective organization. In this context, they can be considered interconnected and interdependent with the events, decisions, actions, and circumstances the organization faces. For example:

Long-term risks are those that may have a potential impact over a few years, closely tied to major decisions taken by the organization, such as launching a new product.

Medium-term risks are those that could have an impact after a decision has been made or a risk-inducing event has occurred. These are closely linked to newly implemented projects or programs within the organization, such as risks associated with changing the organization's IT system.

Short-term risks are those that could have an immediate impact following a risk event or decision, such as the risk of accidents or theft. These are usually insurable risks because they are easily identifiable, controllable, and mitigable.

Emergencies that may occur at facilities in Emergency Preparedness Categories (EPC) I and II, as well as in EPC V territories, are classified as follows:

a) alert;

b) facility/unit emergency;

c) on-site emergency;

d) general emergency.

An on-site emergency at EPC I and II facilities involves a significant reduction in protection levels for on-site personnel and nearby populations due to the failure of two or more layers of defense in depth. A general emergency at EPC I and II facilities represents a substantial risk of radioactive material release into the atmosphere or exposure to radiation, caused by the failure of three or more layers of defense in depth, necessitating the implementation of preventive and/or emergency measures outside the site as a final level of protection. Activities or practices within EPC IV can generate unexpected emergencies that may have severe effects on public health.

Emergencies resulting from activities or practices in EPC IV and EPC VI can be declared radiological emergencies. An emergency at EPC V facilities represents a significant potential risk of radioactive material release into the atmosphere or radiation exposure, caused by the failure of protective barriers, warranting the implementation of urgent protection measures across Romania. CNCAN (Romanian National Commission for Nuclear Activities Control) is responsible for declaring and classifying an emergency in EPC V, based on information received from the state where the accident occurred and/or via the IAEA (International Atomic Energy Agency). CNCAN will take immediate action to assess and verify the incident, notify stakeholders, and activate the national response.

The nuclear industry carries a specific risk—ionizing radiation—which is encountered throughout the activities of exploration, extraction, processing and transportation of nuclear fuel, the actual operation of the nuclear reactor, management of radioactive waste, and decommissioning of nuclear installations (power plants). To evaluate the significance of nuclear and radiological events and to properly inform the public about their effects, the International Nuclear and Radiological Event Scale (INES) was created. INES was developed by a group of specialists in nuclear energy between 1989 and 1990, at the request and under the guidance of the IAEA, with the aim of classifying and assessing the severity level of events (incidents and accidents) in nuclear power plants. The INES scale, used for understanding nuclear events and their severity, is just as important and useful as those used for understanding other physical phenomena.

CHAPTER 4: CERNAVODĂ NUCLEAR POWER PLANT AND THE IMPACT OF A POTENTIAL NUCLEAR ACCIDENT ON THE ADJACENT POPULATION

This chapter presents the main characteristics and systems of the Cernavodă Nuclear Power Plant (Cernavodă NPP), as well as the primary points of interest in the emergency zones surrounding the plant. Additionally, it identifies businesses, villages, and towns that may be affected in the event of a nuclear accident.

Cernavodă Nuclear Power Plant is located in Constanța county, approximately 2 km southeast of the town of Cernavodă and about 1.5 km northeast of the first lock of the Danube–Black Sea navigable canal. The plant is bordered to the north by the Cişmelei valley and to the southwest by county road 223 and the secondary railway line that provides access to the industrial and port areas of the town. The Cernavodă NPP platform was created through the excavation of the former Ilie Barză limestone quarry and is situated at an altitude of +16.00 mdMB above the level of the Baltic Sea. The land on which the plant is located was designated by State Council Decree no. 15 on 10.01.1979 and is owned by S.N.N. SA, according to the Certificate of Land Ownership Rights Series M03 no. 5415/25.04.2000, issued by the Ministry of Industry and Trade. The Cernavodă NPP site contains the following nuclear installations:

- Unit 1, operational since December 2, 1996;
- Unit 2, operational since November 1, 2007;
- The structures and installations for Units 3 and 4, which are preserved;
- Unit 5, repurposed from a nuclear power plant into a support facility for Units 1 and 2, as well as for future Units 3 and 4, as part of the emergency facilities building project;
- The Intermediate Spent Fuel Storage Facility (DICA), used for the dry storage of spent CANDU-6 (Natural Uranium) fuel bundles from Units 1 and 2.

For C.N.E. Cernavodă, threat category I is relevant: it applies to installations such as nuclear power plants (NPPs), where on-site events, including very low-probability events, could generate severe deterministic effects or where such events have occurred at similar facilities. On-site events involve an atmospheric or liquid release of radioactive material or external exposure originating from a location. The IAEA document sets out numerous requirements related to generic zones: on-site and off-site. Additionally, the document establishes requirements for two off-site emergency zones: the Preventive Action Zone (PAZ) and the Urgent Protective Action Planning Zone (UPZ) for facilities in threat categories I and II (for example, some types of research reactors). These require extensive off-site emergency arrangements. According to the authorities

(SN Nuclearelectrica - SA and ISU Dobrogea, 2018), the following EPZ or emergency planning zones are determined for C.N.E. Cernavodă, used as a case study in this report:

- **PAZ Zone** - *Preventive Action Zone* - **3 km**

A zone where urgent protective actions are implemented immediately upon the declaration of a general emergency. Established to implement emergency protective actions and other response measures before significant releases of radioactive material based on the facility conditions that trigger a general emergency, to prevent severe deterministic effects.

- **UPZ Zone** - *Urgent Protective Action Planning Zone* – **5-25 km**

A zone around C.N.E. Cernavodă where local emergency plans call for the prompt implementation of pre-determined urgent protective actions, prepared in advance. For CPU I and II, it is the zone extending beyond PAZ, where preparations are made for the initiation of urgent preventive protection actions and other emergency response measures, if possible, before the release of a significant amount of radioactive material, based on the facility conditions (those that trigger the general emergency), as well as for monitoring and evaluating the off-site radiological situation to reduce the risk of stochastic effects.

- **EPD Zone** - *Extended Planning Distance* - **25-100 km***

A zone extending beyond the UPZ, established for monitoring and assessing the off-site radiological situation to identify areas over time where effective risk reduction of stochastic effects can be achieved by implementing:

a*) Urgent protective actions and other response measures, such as evacuation or preventing accidental ingestion, one day after significant emissions.*

b) Early protective actions and other response measures, such as relocation for a week or a month after significant radioactive emissions.

The ICPD Zone - *Distance for Planning the Restriction of Food and Non-Food Products* - **100-300 km** from the facility in CPU I or CPU II installations is the zone extending beyond the EPD, established for carrying out response actions:

a) To protect the food supply chain and water systems, as well as non-food products, against contamination following a significant radioactive release.

b) To protect the population by restricting the consumption of contaminated food, milk, and drinking water, as well as non-food items that may be contaminated due to significant radioactive emissions.

Protective actions for emergency situations are essentially protective options against radiological exposure, forming the mitigation aspect of the consequences. Emergency planning

(EP) actions for preventing and limiting exposures are generally known: evacuation, sheltering, respiratory protection, relocation, prophylaxis through potassium iodide (KI) administration, decontamination of individuals, decontamination of land and buildings, protection of the food chain, and medical treatment. As of February 2005, urgent protection actions and countermeasures have been more precisely specified and should include the following: isolating a contaminated area or radioactive source and preventing inadvertent ingestion, evacuation, sheltering, respiratory and skin protection, individual decontamination, stable iodine prophylaxis, protection of food supplies, and prevention of the consumption of significantly contaminated food and water, medical response management, and protection of international trade.

CHAPTER 5: DEVELOPMENT OF A RISK MATRIX FOR A CANDU NUCLEAR POWER PLANT

Chapter 5 discusses the complex dynamics and safety challenges associated with operating a CANDU-type nuclear reactor. Through detailed simulations, it provides deep insights into the reactor's reactivity and control, highlighting the importance of prompt and correct responses to various risk scenarios. The fine control of reactivity was emphasized as an essential component for maintaining reactor safety and stability. Experiments demonstrated that errors in handling control rods or automated response systems could lead to dangerous fluctuations in reactor power, illustrating the importance of thorough training and strict protocols for operators.

The main objectives of the focus-group in this chapter were the detection of potential malfunctions and the quantification of associated risks, ranking the main errors in terms of probability across critical sectors of nuclear energy infrastructure, determining the consequences of a terrorist attack or sabotage, clarifying economic aspects related to the maintenance of Cernavodă NPP, and interconnecting key risks of terrorist attacks, sabotage, earthquakes, and fires with identified errors.

Table 5.1 Main errors identified and probability of system failure

Event probability	Errors Sector 1 (Reactor)	Errors Sector 2 (Heat transport)	Errors Sector 3 (Steam, turbine and feed water)	Errors Sector 4 (Control Room)
Almost sure			Steam flow sensor error	Power failure
Probable	Reactor lock		Blocking of all supply valves	Human error
			Turbine "rollback" error	
Potential	Reactor setback routine fails	Main circuit safety valve opening error	Turbine blocking	Error panel
		Error when opening the pressurizer relief valve	Failure to close all valves	Cyber attack
		Error closing pressurizer isolation valve	of isolation for steam level control	
		Error when opening the supply valve		
		Error when opening the purge valve		
Low probability	Stepback routine for reactor fails			Unauthorized access
	Physical damage to the reactor			
	A bank of absorbent bars falls into the reactor			
Improbable				

Source: Own contribution with the help of Focus-group research

Following the analysis of questions addressed to experts in the nuclear energy field, individual rankings of the chosen sectors were extracted, along with the values for probability and impact indices. Next, using the CANDU-9 simulator, the true value of the impact will be determined based on the interconnection of errors and the results obtained.

The area to emphasize is the one related to probabilities because, in the real world, there have not been enough accidents to establish a history of errors that led to a nuclear accident and how they generated or interacted with other errors within the same sector or across different sectors at the Cernavodă Nuclear Power Plant (NPP). Moreover, it is crucial to consider the correlation made by experts during the focus group, linking the number of errors caused in each sector by each of the four significant risks analyzed: sabotage, terrorist attack, earthquake, and fire. The impact will be calculated using the CANDU-9 simulator for each identified error, after which the ACIS risk matrix for the entire nuclear power plant will be created, divided by sector. The responses collected provide an overview of the plant's protection level, current measures for population protection, and potential consequences in the case of sabotage, terrorist attacks, etc. Additionally, this focus group highlighted the need to update the values considered as input data for nuclear accident scenarios, specifically the potential wind speeds, to create more accurate threat scenarios. Meteorological predictions can only be accurate for a period of 7–14 days, depending on weather conditions. Thus, for nuclear accident simulations, the wind speeds input may need to be increased to give a more accurate representation of the potentially affected areas.

The ACIS (Analysis of Critical Infrastructural Sectors) methodology, developed in Germany, proposes a different approach to protecting critical infrastructure, based on the relationship between risk analysis and criticality assessment. In the case of critical infrastructures, a typical risk analysis based on cataloging objects, threats, vulnerabilities, and probabilities is difficult to apply due to insufficient statistical data. However, a positive aspect is the presumption that there will not be enough disasters or terrorist attacks to generate sufficient statistical data. Therefore, in practice, expert opinions are primarily used. In the case of critical infrastructures, a typical risk analysis based on the classification of objects, threats, vulnerabilities, and probabilities is difficult to implement due to a lack of sufficient statistical data. However, a positive aspect is the assumption that there will not be enough catastrophes or terrorist attacks to generate adequate statistical data. Therefore, in practice, expert opinions are primarily utilized.

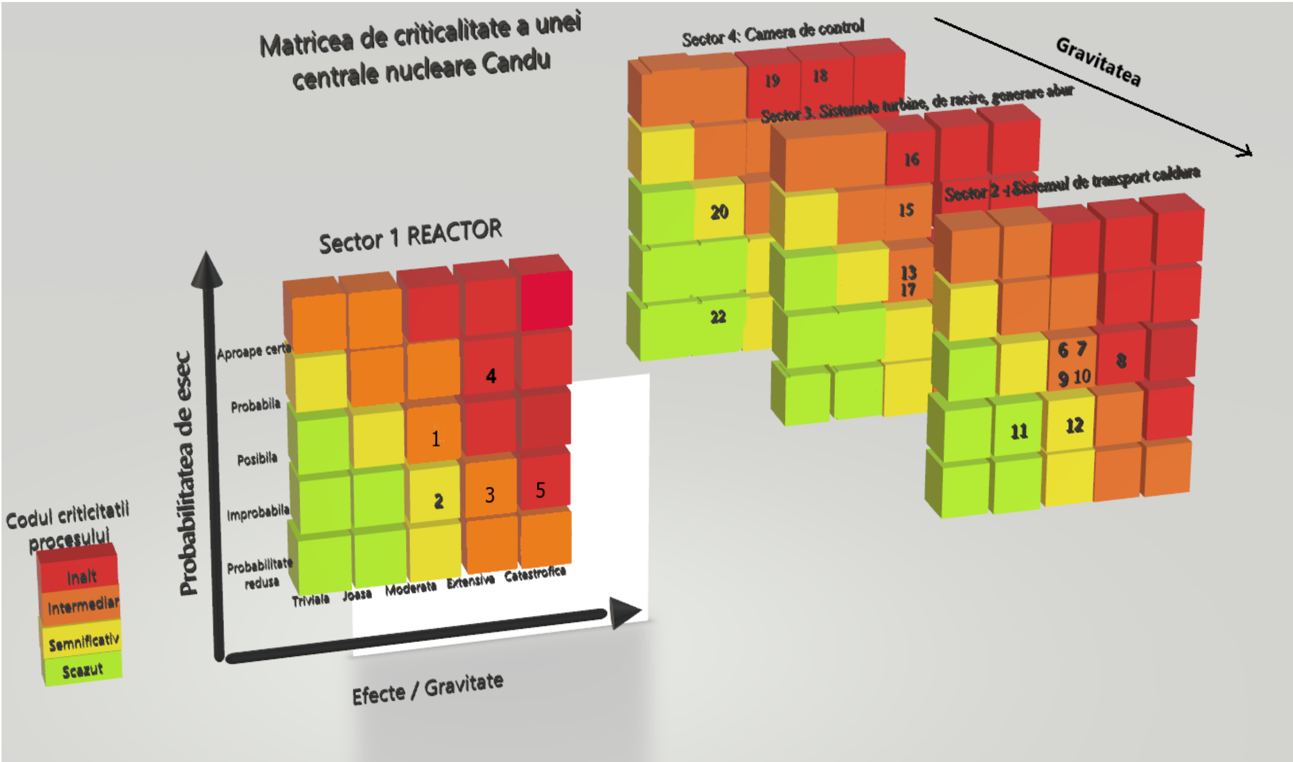

Figure 5.1 Analysis of Critical Infrastructural Sectors (ACIS) criticality matrix

Source: Own contribution

Figure 5.1 illustrates the ACIS criticality matrix based on the identified sectors and errors, considering the probability of failure and the effects on the nuclear power plant. The smart development objective must be achieved through the efforts of specialists in the field and should aim to enhance the protection of the energy sector, seen as critical infrastructure. The criticality matrix helps improve the protection of critical infrastructures in the nuclear energy sector by:

- Highlighting all existing and anticipated risks while identifying critical elements and processes within a nuclear facility.
- Determining the criticality of subsectors, sectors, and processes into which we can decompose the functionality of the chosen critical infrastructure (CI).
- Developing a criticality matrix for the selected infrastructure model (nuclear power plant).
- Reducing dysfunctions that could affect the stability and optimal functioning of critical processes and services within the CI by implementing proactive measures within an effective risk management system.
- Increasing the level of expertise in the field through the constant updating of risk analyses, including comparative evaluations with specific situations manifested in other countries, and incorporating these results into national standards.

- Adhering to confidentiality rules regarding data and information, the unauthorized dissemination of which could affect the protection of IT systems within a nuclear facility. Knowing the criticality matrix for a given CI makes the computer-based management of the plant and its physical protection management a more manageable task.

With the help of the "Compact CANDU 9 Simulator" and based on the simulations performed earlier in this chapter, we created a model of the critical sectors and processes that comprise the criticality matrix for a CANDU-type nuclear power plant. The components of a nuclear power plant were divided into sectors based on functionality:

Table 5.2 Critical sectors for the CANDU Nuclear-Power Plant 9

Sector 1	**Sector 2**	**Sector 3**	**Sector 4**
Reactor	Heat transport	Steam, turbine and feedwater	Control Room
The "setback" routine for the reactor fails	Error opening the main circuit safety valve	Error closing all isolation valves for steam level control	Human error
The "stepback" routine for the reactor fails	Error when opening the pressurizer limiting valve	Blocking all supply valves	Panel with errors
A bank of absorbent bars fall into the reactor	Error when closing the pressurizer isolation valve	Error in the steam flow sensor	Power outage
Reactor lock	Error opening the supply valve	Turbine lock	Cyber attack
Physical damage to the reactor	Error opening the purge valve	Turbine "roll back" error	Unauthorized access

Source : Own contribution

CHAPTER 6: DETERMINING RISK REDUCTION MEASURES FOR NUCLEAR ACCIDENTS IMPACTING POPULATION ADJACENT TO A NUCLEAR POWER PLANT USING HYSPLIT AND RHODOS SIMULATORS

This chapter highlights modern prevention and forecasting tools used by major nuclear power plants, as well as national and international authorities. Utilizing these tools, which have been identified as among the most advanced in the field, along with the atmospheric prediction program "RHODOS," numerous simulations have been conducted. These simulations, carried out under all meteorological conditions and for all hazardous substances that could be released in the event of a nuclear accident at the Cernavodă Nuclear Power Plant, have accurately determined the affected population and the dispersion of pollutant clouds across the country.

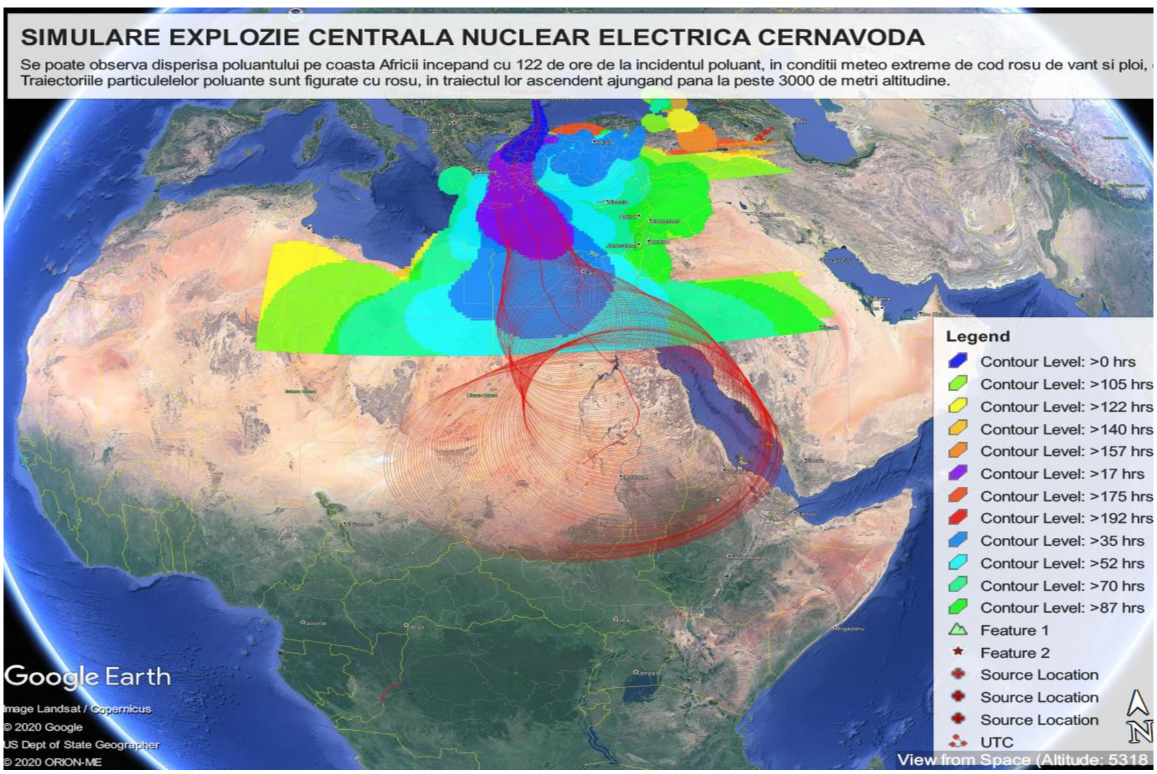

Figure 6.1 Particle dispersion following the simulation of an explosion at the Cernavoda Nuclear Power Plant

Source: Own contribution using the HYSPLIT simulator

In Figure 6.1, the dispersion of the radioactive cloud from Simulation 3 (Cernavodă NPP, 44.322405 long.: 28.056464) under strong wind conditions (Beaufort scale 10, 88–100 km/h), conducted on 07.07.2020, using the GFS meteorological model, is illustrated. The total duration of the simulation was 196 hours, using hypothetical particles of Cs-137, starting the simulation with a hypothetical unit of mass. The atmospheric release duration was brief, lasting 10 minutes from a height of 50 m, with radionuclide deposition occurring at a rate of 0.1 cm/s. Radioactive decay due to precipitation was not calculated in this simulation. In the particle section, the model particles of Cs-137 and their convective transport function, as well as the particle trajectories, represented in red, are depicted. These particles rose from the ground, reaching heights between 0 and 12,000 m. The total simulation lasted 196 hours, and the pictogram illustrates, with color, the time at which radionuclides reach a specific geographic area. The map style was set to "satellite," and the resolution was adjusted to a global scale. Figure 6.1 is one of the pictograms generated by the HYSPLIT simulator, chosen to exemplify this function. HYSPLIT integrates the simulation results into complex applications such as "leaflet map" or "GoogleEarth," which are easy to follow in an interactive format for dynamic observation.

Simulation conducted on 24.05.2021

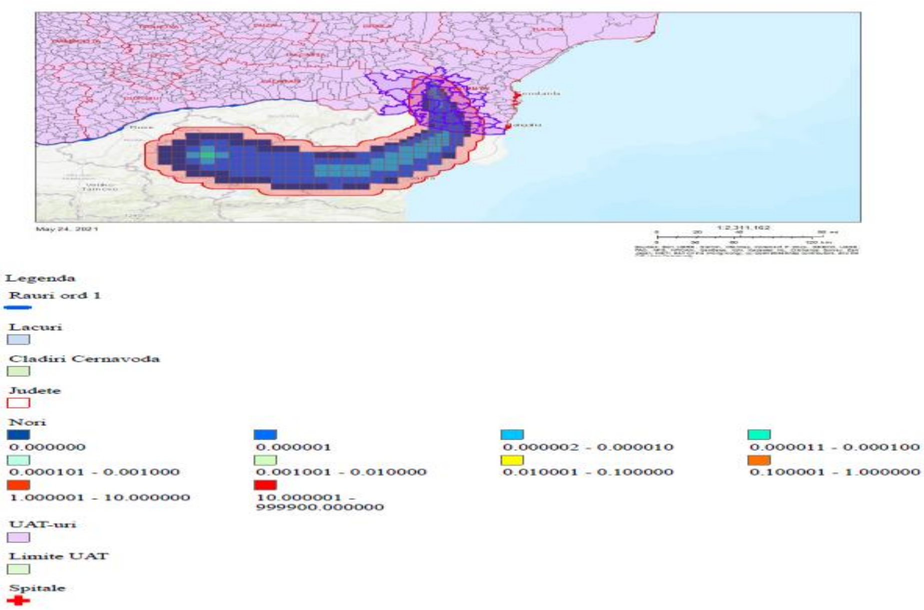

Figura 6.2 Raport nor Cs-137 la o oră/ zone afectate 24.05.2021

Sursa: Contribuție proprie cu ajutorul simulatorului Rhodo

Figure 6.2 shows the movement of the radioactive cloud over a one-hour period and the areas it affects following the simulation from 24.05.2021.

Affected population information

The total population affected within the radioactive zone (plus a 10 km buffer) is 168,659 people. The simulation also provides key data for understanding the situation and needs of the population adjacent to Cernavodă NPP, such as the affected population in emergency areas (144,331 people), the population in the PAZ and UPZ zones affected in the first 30 minutes after the radioactive substance release: 412 and 19,945 people, respectively, and the total population affected in the first 30 minutes: 38,565 people. The majority of protective measures that can save the affected population are implemented within the first 30 minutes after the nuclear accident begins. The simulation was conducted under a meteorological orange alert issued by the Romanian National Meteorological Agency.

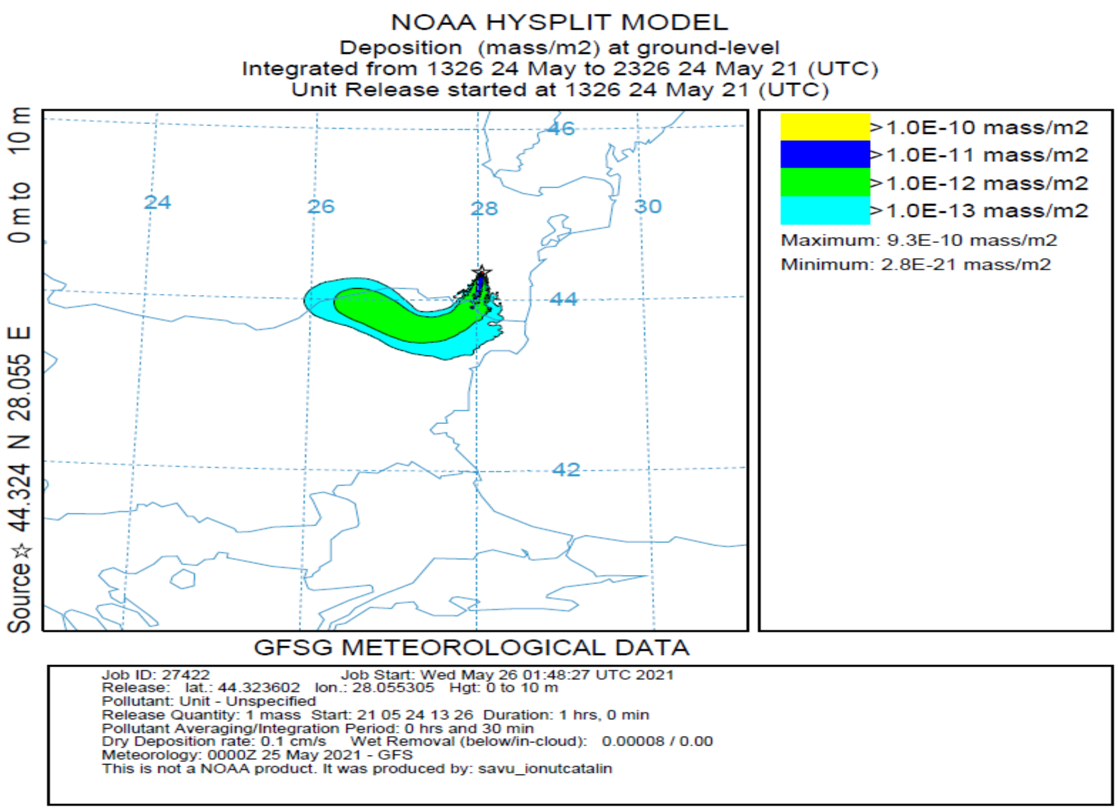

Figure 6.3 Storage of radioactive particles on the ground mg/m2 24.05.2021

Source: Own contribution with the help of the Hysplit simulator

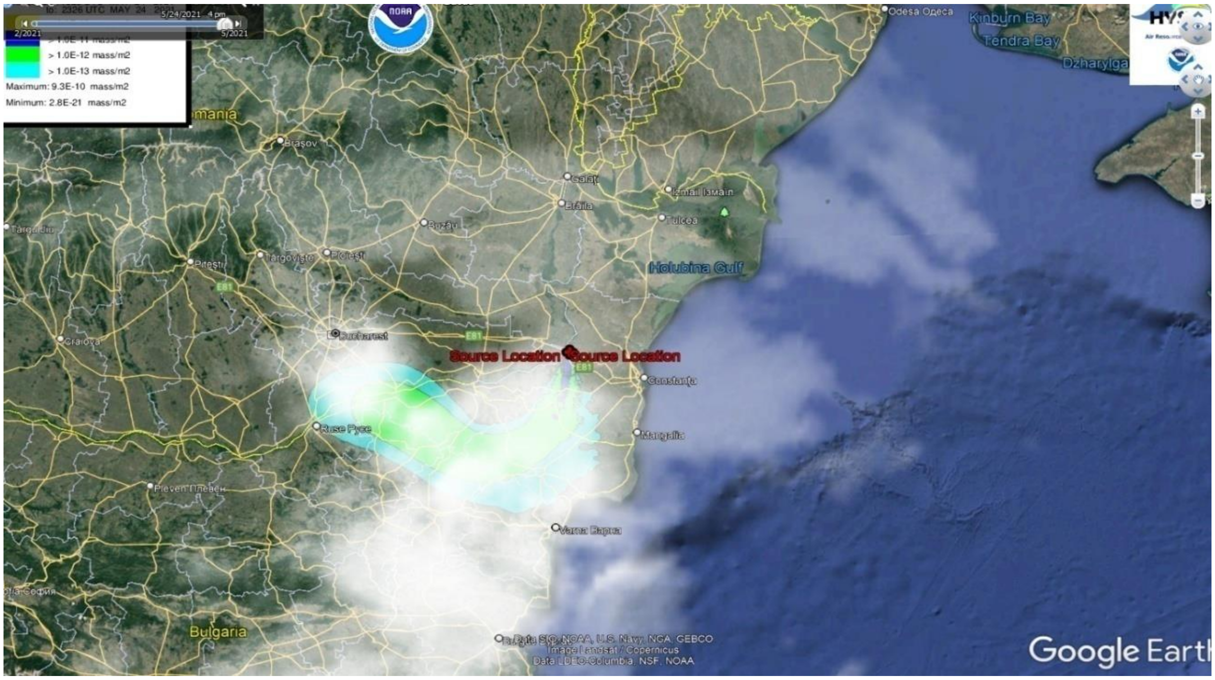

Figure 6.4 Google Earth particle storage 25.05.2021

Source: Own contribution with the help of the Hysplit simulator

Figures 6.3 and 6.4 present the deposition of radioactive particles on the ground using the HYSPLIT simulator or Google Earth. In all simulations, it can be observed that the radioactive clouds extend beyond the country's terrestrial borders. In all periods where simulations were conducted, the deposition of particles from the radioactive cloud exceeded an area of 400 km, reaching distances of 500–600 km within 24 hours. The maximum extended planning distance, according to CNCAN 2018, is 100 km. The distance at which particles are deposited in a given direction, over 24 hours, is 400–500 km greater than the maximum extended planning distance. Previous simulations have shown that in the event of nuclear accidents combined with extreme weather events, the severity of the nuclear incident increases.

According to ISU Dobrogea, in the Dobrogea region, where Cernavodă NPP is located, natural phenomena are represented by extreme winds with speeds between 88 and 117 km/h and above, as well as extremely rare phenomena such as tornadoes and earthquakes (Cernavodă city is located on the Vrancea micro-fault). Whether it's a nuclear incident precipitated by an earthquake (e.g., the Fukushima earthquake) or a phenomenon that spreads radioactive pollutants faster, as seen in simulations conducted under "red wind code" conditions, modifications to the measures and the adoption of new ones are necessary to ensure more efficient protection against radioactive pollution.

Considering the following factors:

- Precision in radiation measurements has improved even over long distances.
- Global cooperation has improved, and a limit of 350 km or more is no longer exaggerated for international cooperation concerning pollutants crossing borders.
- Cooperation in the exchange of measurements and population alerts between countries is essential for conducting more complex environmental and urban studies regarding the placement of a new nuclear power plant, thereby minimizing risks.
- The incidence of cancers more than 300 km away, with Chernobyl etiology, has significantly increased as diagnostic tools have evolved.
- In the case of extreme weather phenomena, radioactive pollution reaches considerable distances faster than estimated under normal meteorological and pressure conditions.

Simulation for the Chernobyl nuclear power plant /21.03.2022

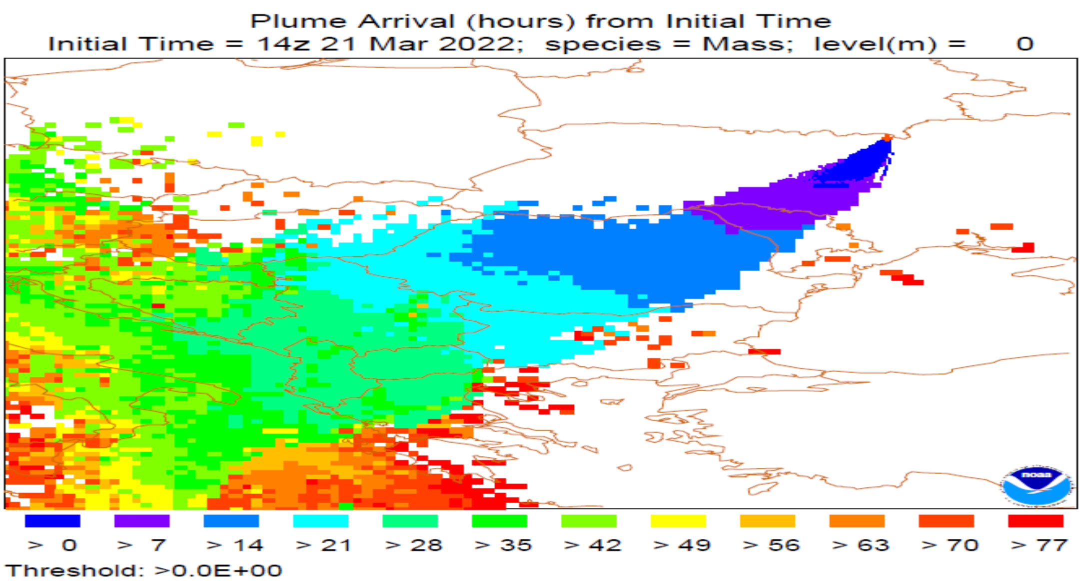

Figure 6.5 Time of arrival of the Chernobyl cloud 21.03.2021

Source: Own contribution with the help of the Hysplit simulator

Simulation for the Zaporizhzhia nuclear power plant/ 21.03.2022

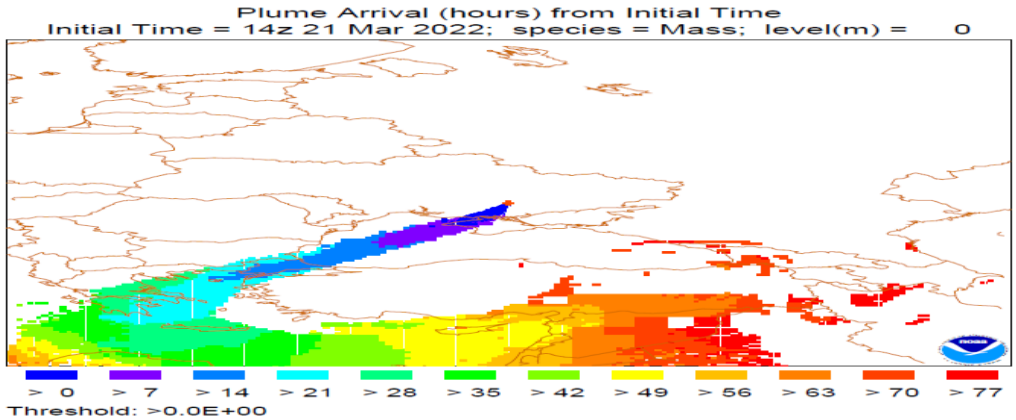

Figure 6.6 Time of arrival of the Zaporizhzhia cloud 21.03.2021

Source: Own contribution with the help of the Hysplit simulator

According to meteorological conditions from 19-21.03.2022, if the wind direction favors the radioactive cloud crossing Romania, it would reach the country's borders approximately 4-5 hours after the nuclear accident, with a strong impact on the soil and population. Thus, a nuclear accident on Ukrainian territory could have catastrophic effects on Romania's population, considering that the Zaporizhzhia Nuclear Power Plant operates six reactors, making it about three times more powerful than Cernavodă NPP. In the current context, it is crucial to continuously use meteorological forecasting and atmospheric dispersion simulators, as well as those testing the resilience of critical infrastructures in the nuclear energy sector. Additionally, extending the response areas in the event of a nuclear accident is more necessary than ever to efficiently protect populations adjacent to nuclear power plants and the environment. The international community, together with the IAEA, in light of major geopolitical changes and the emergence of conflict near NATO borders, proposes nuclear-level cooperation, whereby each country monitors the areas surrounding its nuclear plants, as well as plants on Ukrainian territory. This distance becomes crucial for implementing the main protective and preventive measures for populations adjacent to nuclear power plants.

Following all simulations conducted with the RHODOS/HYSPLIT simulators, particularly those on 17, 18, 19, and 24.05.2021, under red and orange wind warnings, it was shown that Cs-137 clouds and particles traveled over 400 km from the emission site. In some scenarios, over 400,000 residents were exposed to high gamma radiation doses, and the radioactive cloud affected the majority of Romania's counties, as well as areas in Moldova and Bulgaria.

Proposed changes for Cernavodă NPP:

1) ***Increase the PAZ limit from 3 km to 10 km.***
2) ***Increase the UPZ limit from 25 km to 50 km.***
3) ***Increase the maximum EPD limit from 100 km to 150 km.***

Risk mitigation after applying threat scenario reduction measures

To reduce the risks analyzed, measures must be taken to address the following vulnerabilities and/or improve the following capabilities:

Table 6.1 Risk mittigation

Vulnerability	The associated risk factor	Treatment measures
Inadequate intervention plans	Fire, earthquake, terrorist attack	Updating specific intervention plans and procedures Updating protocols by the structures with responsibilities in the objective.
Inadequate evacuation plans		Updating specific evacuation plans and procedures Updating protocols by the structures with responsibilities in the objective.
The socio-economic situation	Terrorist attack, sabotage	Improving the ways of communicating the event Ensuring a rapid response
Functionality of secondary control systems	Fires, earthquakes	Acquisition of modern population prevention systems Quality maintenance
Improper management of the event	terrorist attack, sabotage	Intensification of training and further training courses Collaboration with several institutions in order to immediately apply the measures to protect the population.
Ensuring protection measures in case of non-functioning of the CANDU rector's control panel	Fires	Modernization of a detection and signaling system
Staff training	Fires, earthquake, sabotage	Intensification of training and further training courses
Degree of wear of auxiliary systems	Fires	Ensuring maintenance at least 2 weeks
Geo-political situation	Terrorist attack, sabotage	Increasing the level of security of the population by strengthening internal physical and cyber security Increasing the level of security of the population by collaborating with the competent authorities

Source: Own contribution based on the PSO implementation guide

Table 6.2 The level of risk after implementing reduction measures

PROBABILITY						
	Very high 5					
	High 4		**TERRORIST ATTACK**			Terrorist attack
	Medium 3		**FIRE, SABOTAGE (following the application of the measures)**		Fire, Sabotage	
	Low 2			**EARTHQUAKE (following the application of measures)**		Earthquake
	Very low 1					
	0	Very low 1	Low 2	Medium 3	High 4	Very high 5

Calculated risk level	Level	Score	**SEVERITY CONSEQUENCES**
	Very low	1-3	
	Low	4-6	
	Medium	7-12	
	High	13-16	
	Very high	17-25	

Source: Own contribution based on the PSO implementation guide

The criticality matrix in Table 6.2 clearly shows how the values of the main identified risks have decreased and now fall within the accepted limit for the critical infrastructure analyzed, in this case, Cernavodă NPP. Thus, the concrete application of prevention and risk management measures has been effective, and the main identified risks can be considered under control. The population adjacent to the plant benefits from preventive and protective measures, as well as those implemented at the critical infrastructure level. Additionally, over 100,000 people are included in emergency zones, and specific measures can be applied to them. In any of the main risk cases identified—sabotage, terrorist attack, earthquake, fire—while one component of the risk (probability) may remain unchanged, the impact can be reduced through the application of preventive and protective measures.

CHAPTER 7: SOCIO-ECONOMIC IMPACT OF THE PROPOSED MEASURES ON THE POPULATION ADJACENT TO THE CERNAVODĂ NUCLEAR POWER PLANT

This chapter highlights the most important prevention and protection measures for the population adjacent to the Cernavodă NPP and the economic and social impact caused by expanding the emergency response zones, as well as the total damages resulting from a potential nuclear accident, simulated using the Rhodos and Hysplit programs, under weather conditions classified as yellow, orange, or red alert, issued by the National Meteorological Agency for the Dobrogea region.

The affected localities are as follows:

Table 7.1 Affected localities simulation 24.05.2021

Nr.crt.	Affected locality	Number of inhabitants
1	ADAMCLISI	2419
2	ALBESTI	3751
3	ALIMAN	2923
4	AMZACEA	2863
5	BARAGANU	2146
6	BORCEA	8360
7	CERCHEZU	1454
8	CERNAVODĂ	19577
9	CHIRNOGENI	3421
10	CIOCÂRLIA	3142
11	COBADIN	9447
12	COMANA	2026
13	DELENI	2502
14	DOBROMIR	3417
15	DUMBRAVENI	579
16	INDEPENDENTA	3092
17	LIMANU	6510
18	MEDGIDIA	46636
19	MERENI	2464
20	MIRCEA VODĂ	5325
21	MURFATLAR	11662

Nr.crt.	Affected locality	Number of inhabitants
22	NEGRU VODĂ	5804
23	PECINEAGA	3423
24	PEŞTERA	3534
25	RASOVA	3892
26	SALIGNY	2249
27	SEIMENI	2230
28	STELNICA	1890
29	TORTOMAN	1921

Source: Own contribution with the help of the Rhodes simulator

Table 7.1 presents the localities, population numbers, and the total number of objectives affected by the radioactive cloud as a result of the simulation on May 24, 2021.

In Chapter 6, multiple simulations were carried out using the Rhodos and Hysplit simulators. These simulations also provide key data for understanding the situation and needs of the population adjacent to the Cernavodă NPP, such as the affected population within the emergency zones, the population in the PAZ and UPZ zones impacted within the first 30 minutes from the onset of radioactive substance release, as well as the total affected population during the first 30 minutes. The vast majority of protection measures that can save the affected population must be implemented within the first 30 minutes from the initial moment of the nuclear accident. The simulations were conducted under meteorological conditions categorized as yellow, orange, and red alerts, issued by the National Meteorological Administration of Romania.

Table 7.2 Affected population and inclusion in emergency areas

The date of the simulation	24.02.2021	21.04.2021	17.05.2021	18.05.2021	19.05.2021	24.05.2021	14.07.2021
Affected population	98723	71231	415055	238829	252232	168659	82431
Mortality about 1/40 of the affected population	2468	1780	10376	5971	6306	4216	2061
Affected population in emergency areas	79447	52368	331740	183333	194002	144331	55921
The population in the PAZ area (3 km) affected within 30 minutes	321	304	671	420	503	412	293
The population in the UPZ area (25 km) affected within 30 minutes	17035	14209	31877	20654	21456	19945	14137
Total population affected within 30 minutes	30034	28455	78966	42611	44529	38565	29459
Affected population not included in emergency areas	19276	18863	83315	55496	58230	24328	26510

Source: Own contribution

According to the data presented in Table 7.2, simulations performed on the dates of February 24, 2021, April 21, 2021, May 17, 2021, May 18, 2021, May 19, 2021, May 24, 2021, and July 14, 2021, indicate that the population affected by the radioactive cloud and ground particle deposition exceeds the number of residents near the Cernavodă NPP, included in the emergency zones according to current regulations. Thus, significant discrepancies are highlighted between the number of people exposed to the radioactive cloud and those protected according to current norms for each emergency zone. The simulations were conducted under weather conditions characterized by yellow, orange, and red alerts issued by the National Meteorological Administration for the Dobrogea region. On the specified dates, the following numbers of individuals were affected: February 24, 2021 – 19,276 people, April 21, 2021 – 18,863 people, May 17, 2021 – 83,315 people, May 18, 2021 – 55,496 people, May 19, 2021 – 58,230 people, May 24, 2021 – 24,328 people, July 14, 2021 – 26,510 people, all of whom were potentially included in emergency zones and could benefit from adequate protection in the event of a nuclear accident.

The extension of the UPZ, PAZ, and EPD limits proposed in Chapter 7 of this thesis would fully encompass the affected population, even in the case of a severe red weather alert, as occurred on May 17, 2021, when a total of 415,055 people were severely affected by the radioactive cloud, and 83,315 individuals would not have benefited from prevention and protection measures in the event of a nuclear accident. In the simulated scenario, the mortality rate could have exceeded normal values for the population located in the emergency zones adjacent to the Cernavodă NPP by two or three times.

An essential factor in the prevention and protection of the population is response time. The most important measures must be implemented within the first 30 minutes of the initial moment of the nuclear accident. The simulations performed with HYSPLIT and Rodos emphasize the urgent need to modify the PAZ zone limit from 25 km to 50 km. All simulations demonstrated an overreach of the affected population in the PAZ zone by between 70% and 100%. Thus, within just 30 minutes, the radioactive cloud extends beyond the PAZ zone by up to 20–25 km, and the protection measures applicable in this zone should be extended to a distance of 50 km, as proposed by the author. Furthermore, the main points of interest in the area adjacent to the Cernavodă NPP, the number of residents/employees, and the registered business turnover were identified. Within a 3 km radius, small businesses were considered, and beyond this distance, only villages, communes, towns, and major points of interest were included to determine one of the three components of the financial damages caused by a potential nuclear accident due to the risks analyzed in this paper.

Table 7.3 Financial damage caused by a possible nuclear accident

	Date	Possible damage to CNE Cernavodă	ossible damage on the trajecto	Loss of electricity	Total damage
Fire	24.02.2021	300-500 mil $	1 mld $	107 mil$	1.6 mld $
	21.04.2021	300-500 mil $	800 mil $	107 mil$	1.4 mld $
	17.05.2021	300-500 mil $	5 mld $	107 mil$	2.1 mld $
	18.05.2021	300-500 mil $	2.2 mld $	107 mil$	2.8 mld $
	19.05.2021	300-500 mil $	2.5 mld $	107 mil$	3.1 mld $
	24.05.2021	300-500 mil $	1.8 mld $	107 mil$	2.4 mld $
	14.07.2021	300-500 mil $	900 mil $	107 mil$	1.5 mld $
Earthquake	24.02.2021	500mil - 1mld $	1.1 mld $	214 mil $	2.3 mld $
	21.04.2021	500mil - 1mld $	1 mld $	214 mil $	2.2 mld $
	17.05.2021	500mil - 1mld $	6 mld $	214 mil $	7.2 mld $
	18.05.2021	500mil - 1mld $	2.5 mld $	214 mil $	3.7 mld $
	19.05.2021	500mil - 1mld $	2.8 mld $	214 mil $	4 mld $
	24.05.2021	500mil - 1mld $	2 mld $	214 mil $	3.2 mld $
	14.07.2021	500mil - 1mld $	1 mld $	214 mil $	2.2 mld $
Terrorist attack	24.02.2021	1mld-1.5mld $	1.3 mld $	321 mil $	2.1 mld $
	21.04.2021	1mld-1.5mld $	1.1 mld $	321 mil $	2.9 mld $
	17.05.2021	1mld-1.5mld $	7 mld $	321 mil $	8.8 mld $
	18.05.2021	1mld-1.5mld $	2.7 mld $	321 mil $	4.5 mld $
	19.05.2021	1mld-1.5mld $	2.8 mld $	321 mil $	4.6 mld $
	24.05.2021	1mld-1.5mld $	2.1 mld $	321 mil $	3.9 mld $
	14.07.2021	1mld-1.5mld $	1.1 mld $	321 mil $	2.9 mld $
Sabotage	24.02.2021	400-500 mil $	`1 mld $	86 mil $	1.6 mld $
	21.04.2021	400-500 mil $	800 mil $	86 mil $	1.4 mld $
	17.05.2021	400-500 mil $	5 mld $	86 mil $	5.6 mld $
	18.05.2021	400-500 mil $	2.2 mld $	86 mil $	2.8 mld $
	19.05.2021	400-500 mil $	2.5 mld $	86 mil $	3.1 mld $
	24.05.2021	400-500 mil $	1.8 mld $	86 mil $	2.4 mld $
	14.07.2021	400-500 mil $	900 mil $	86 mil $	1.5 mld $

Source: Own contribution

Table 7.3 details estimates of the potential damages that could result from a nuclear accident caused by one of the four major risks highlighted in this work, for each of the simulations performed. The total damage is calculated by aggregating the losses incurred by the Cernavodă NPP, repair costs, the total value of businesses partially or fully affected, damages to food, agricultural land, and the population, as well as losses related to electricity production. The average price per MWh is 549.52 lei. Units 1 and 2 of the Cernavodă NPP together produced 11,377,435 MW in one year, and the estimated duration for which at least one unit would be unable to produce electricity is 50 days in the case of fire risk, 100 days in the event of an earthquake, 150 days in the case of a potential terrorist attack, and 40 days in the case of sabotage at the Cernavodă NPP.

Thus, the calculations indicate significant differences in terms of economic losses, which can range from \$1.4 billion to \$8.8 billion, depending on the analyzed risk, extreme weather conditions, and wind direction and speed. The potential financial losses that would directly affect the Cernavodă NPP were discussed during in-depth interviews and numerous debates held within the G.L.E.N.U.R. working group, with the participation of specialists from C.N.C.A.N.

Personal contributions

Within this doctoral thesis, significant contributions have been made in the following areas and aspects, essential for the protection and optimization of critical nuclear infrastructures and the safety of the population adjacent to them:

1. **Adaptation of the ACIS Methodology for Critical Nuclear Infrastructures**

The ACIS (Analysis of Critical Infrastructural Sectors) matrix was developed for the Cernavodă Nuclear Power Plant. This matrix facilitated a detailed analysis of critical sectors and processes within the plant, including identifying major potential errors and ranking them based on their relevance and impact on the operational sectors of the Cernavodă NPP. This analytical tool provides a solid foundation for prioritizing safety measures and optimizing risk management within the plant's critical infrastructure.

2. **Development of Risk Scenarios and Identification of Protective Measures for the Population Adjacent to the Cernavodă NPP**

The doctoral thesis included a detailed investigation of potential risk scenarios associated with the Cernavodă NPP to better understand the risks of possible accidental or intentional emissions. The study identified optimal protective measures for the local population and proposed strategies for effective emergency intervention, contributing to the strengthening of public safety plans in the region.

3. **Research on Comparative Atmospheric Simulations with HYSPLIT and RHODOS**

A comparative study between the HYSPLIT and RHODOS simulators was conducted to highlight the advantages and limitations of each in forecasting radioactive dispersion. The analysis included a detailed evaluation of precision and predictive capabilities over short, medium, and long-term periods, providing a rigorous basis for selecting the most suitable tools in nuclear emergency management.

4. **Assessment of the Impact of a Nuclear Accident on the Population Adjacent to the Cernavodă NPP and the Environment**

The potential impact of a nuclear accident on the population and the environment was evaluated using precise data and models. This assessment quantified potential losses of life, injuries, material damages, and economic impact, offering a comprehensive picture of the consequences of such an event.

5. **Proposals for Expanding Emergency Zones and Optimizing Protective Measures for the Population Adjacent to the Cernavodă NPP**

Proposals were made to extend the PAZ (Precautionary Action Zone) and UPZ (Urgent Protective Action Zone) around the Cernavodă NPP based on research on the impact on the adjacent population, derived from simulations, analyses of economic and social effects, and evaluations of dynamic meteorological conditions. These proposals include expanding protection perimeters, implementing additional preventive measures, and optimizing the response capacity in nuclear emergencies, thereby enhancing the safety of the local population.

6. **Research Based on In-Depth Interviews**

In-depth interviews with experts in the field were conducted, providing essential information for correlating and adapting input data for simulations, as well as determining the probability of errors occurring within the plant. These interviews contributed to the accuracy and relevance of the results obtained, allowing for a more rigorous interpretation of the analyzed risk scenarios.

7. **Development of Protection and Prevention Measures for the Population Adjacent to the Cernavodă NPP**

Based on the prioritization of identified risks, concrete protection and prevention measures were proposed for the Cernavodă NPP. These include developing emergency action plans, detailed procedures for evacuation and sheltering, and specific decontamination measures. These measures are essential for reducing identified risks and bringing them below the acceptable thresholds established for the Cernavodă NPP, in compliance with the standards for critical infrastructure.

List of published works

The list of scientific works published during national and international scientific events represents the results of scientific research during this period and the dissemination of the findings obtained during this time. To date, the following types of works have been published:

- 4 scientific articles published in volumes from national and international scientific events indexed in ISI.
- Scientific articles indexed and published in volumes from national and international scientific events indexed in BDI.

List of published or pending works

Scientific articles published in volumes from national and international scientific events indexed in ISI.

[1] **Savu, IC** and Militaru, G, Critical infrastructures development aligned with European union procedures. Evidence from Romania,15th International Conference on Business Excellence (ICBE) - Digital Economy and New Value Creation, Dec 1 2021 | Proceedings of the International Conference on Business Excellence 15 (1) , pp.468-479, WOS:000747987000017

[2] Barbu, A., Militaru G., **Savu I C.,** 2019, Investigating the Factors that Influence the Adoption of Smartwatch Technologies Evidence from Romania, 34th International Business Information Management Association Conference (IBIMA) 13-14 November, Madrid, Spain, Vision 2025; Education Excellence and Management of Inovations through Sustainable Economic Competitive Advantage, pp. 5765-5776, ISBN: 978-0-9998551-3-3, WOS: 000556337407053

[3] Barbu, A., Militaru G., **Savu I C.,** 2019, Determining the acceptance level of smartwatches using the TAM model. Evidence from Romania. The 9th International Conference of Management and Industrial Engineering ICMIE 2019, November 14-16th, 2019, Management Perspectives in the Digital Transformation, Bucharest, Romania, Editura NICULESCU, 2019, pp. 191-201, WOS:000519338200018

[4] Georgescu, RM; **Savu, IC** and Militaru, G. How can social networks improve the recruitment process case study – linkedin, 12th International Management Conference on Management Perspectives in the Digital Era (IMC), 2018 | Proceedings of the 12th International Management Conference: management perspectives in the digital era (IMC 2018) , pp.644-652, WOS:000473413800071

Scientific articles published in the volumes of national and international scientific events indexed BDI

[1] Savu I. , Militaru G. (2021) Critical infrastructures development aligned with European union procedures. Evidence from Romania. Proceedings of the International Conference on Business Excellence, Vol.15 (Issue 1), pp. 468-479. https://doi.org/10.2478/picbe-2021-0043

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