Review of Artificial Intelligence applications in nuclear or radiological Emergency Preparedness and Response

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Overall context of the study and presentation

- A literature review regarding the use of Artificial Intelligence (AI) in several sectors of Radiation Protection is ongoing under PIANOFORTE project
- The results will be included in a PIANOFORTE Deliverable Report
- Here, we will present the results obtained so far in the sector of nuclear or radiological Emergency Preparedness and Response (EPR)
- The literature review is carried out in Scopus and has revealed an increasing number of AI use cases

AI use in emergency planning / decision support off site

- 5 publications from 2020 - 2025
- Applications / methodologies
  - Incorporation of Large Language Models (LLMs) in decision support frameworks (LLMs' contextual awareness, natural language interaction and capacity to comprehend queries in a radiation emergency response setting - interactions with ChatGPT)
  - Agent Based Model (ABM) for decision support on the most suitable protection strategies in different nuclear accident phases
  - Estimation of causal effects, using a VR system for collecting human behavioural data in response to causal factors and an ML-based model to estimate causal effects
  - Use of AI to safeguard frontline personnel in CBRN incidents, focusing on cognitive support, behavioural monitoring, psychosocial well-being, and training

AI use for NPP accidents

- AI applications for NPP accidents: assessment of nuclear plant accidents conditions, forecast of accident progression, decision support to operators or NPP staff, classification of NPP accidents based on off-site radiation measurements
- 36 publications from 2014 to 2026
- Examples of methodologies:
  - Deep learning techniques trained by data generated from dynamic probabilistic safety/risk assessment (DPSA/DPRA) to predict possible outcomes (off-site consequences) of the initiating event
  - Multilevel Flow Modelling for the accident management and Go-Flow for reliability analysis and quantitative risk assessment / generation of response plans, assessment of their effectiveness, and identification of safety-critical equipment
  - Combination of a probabilistic safety assessment tool - event tree analysis - with large language model (LLM)-driven agents to address unforeseen emergencies

AI applications for NPP accidents (2)

- Examples of methodologies for NPP accidents classification:
  - Classification and regression tree model trained with data generated by the Radiological Assessment System for Consequence Analysis (RASCAL)
  - Interpretable machine learning: K-Nearest Neighbors KNN, Randon Forest RF, and XGBoost optimized with the Harris Hawks Optimization HHO / trained with off-site gamma-dose rate data generated by RADC system for 9 PWR accident scenarios
  - backpropagation neural network (BPNN) classifier, combined with genetic algorithm (GA) and simulated annealing (SA) algorithm / simulated training data by the International Radiological Assessment System (InterRAS) / 9 PWR accident scenarios

AI use in radionuclides atmospheric dispersion modelling (ADM)

- 7 publications from 2016 to 2025
- Applications / methodologies
  - Dose spatial distribution maps around a NPP / mobile phone application / multilayer perceptron (MLP) or a general regression neural network (GRNN) trained by a simple ADM system
  - ML-based method for quick emulation of spatial deposition patterns from a multi-physics ensemble of dispersion simulations / uncertainty assessment / WRF-FLEXPART for meteorology and dispersion
  - Surrogate data-driven model to represent the 2D population doses over complex terrain / regression tree ensemble models
  - Prediction of the coordinates of the maximum radiation dose rate in the plume / Recurrent Neural Network (RNN) – Long short-term memory model (LSTM)

AI use in inverse source term estimation for radionuclides

- Source term estimation using environmental radioactivity monitoring data simulated by atmospheric dispersion model
- 9 publications from 2020 to 2026
- Examples of applications / methodologies
  - Deep feedforward neural network (DFNN) / Bayesian neural network / Back propagation neural network / trained by air concentration data of I-131 generated by a Gaussian dispersion model with a continuous point source
  - Temporal Convolutional Network (TCN), Long Short-Term Memory (LSTM), Gate Recurrent Unit (GRU) models / multiple nuclides, complex release scenarios Kr-88, Sr-91, Te-132, I-131, etc. / gamma dose rate data for training generated by the International Radiological Assessment System (InterRAS)
  - Decision tree-based ensemble learning / Random Forests (RF), Light Gradient Boosting Machine (LightGBM), Categorical Boosting (CatBoost), Extreme Gradient Boosting (XGBoost) / Gaussian plume model with I-131 generating radioactive air concentration data for training

AI use in visualisation / mapping / optimising monitoring of ambient dose rate following nuclear accidents

- 6 publications from 2017 to 2025
- Applications / methodologies
  - Using airborne (from UAV) radiation monitoring results / conversion of count rates and pulse height distribution to dose rates from deposited radionuclides using an ANN / training data set: radiation measurements around the Fukushima DNPP
  - Multi-scale, -type, -resolution, -accuracy data integration (ground-based and airborne surveys) using Bayesian hierarchical models and geostatistics / application at the FDNPP
  - Optimisation of long-term radiation dose rate monitoring locations / Gaussian process model and Bayesian geostatistical model / application at the FDNPP

AI use in visualisation / mapping / optimising monitoring of ambient dose rate following nuclear accidents (2)

- Applications / methodologies
  - Dynamical adaptation of a mobile monitors set (e.g., monitoring drones swarm) to follow the radioactive plume / using active machine learning (AML) approach, based on Gaussian process regression (GRP) and swarm intelligence / training data set generated by simple ADM
  - Use of autonomous intelligent robots to reconstruct dose rate maps in static radioactive environments / use Gaussian process regression (GPR) to model the radiation dose rate distribution and active learning (AML) to dynamically improve estimation of GP parameters

Miscellaneous cases of AI use in nuclear or radiological EPR

- Optimisation of radiation monitoring networks for improved emergency response in NPP accidents / use of GPCAM (Gaussian Process for Continuous-time Acquisition of Measurements) / use of meteorological fields and radionuclides dispersions ensembles
- Identification of radioactive sources
  - Localisation of radioactive hot-spots and identification of radionuclides / importance for the security sector and for naturally occurring radioactive materials / use of deep neural networks
- Detection of (location of) missing radioactive material
  - important capability for safeguards measurements
  - k-nearest neighbour (KNN), random forest (RF), support vector machine (SVM) classifiers

Miscellaneous cases of AI use in nuclear or radiological EPR

- Nuclides identification / 6 publications from 2016 to 2023
  - Automatic and real-time identification of radionuclides based on gamma-ray spectra / convolutional neural networks / fully-connected neural networks
- Robotics for disaster response
  - Artificial intelligence and internet of things (AIoT) / swarm intelligence for the collaborative operation of heterogeneous robots for search and rescue operations

Miscellaneous cases of AI use in nuclear or radiological EPR

- Radiation monitoring / classification / warning system
  - IoT-enabled intelligent system based on machine learning for personal radiation monitoring and warning by classifying radiations and their corresponding effects on infants
- Characterisation of radionuclides in the soil
  - rapid and repeated estimation of exchangeable potassium content in the soil for optimizing remediation of radio-caesium contamination in agriculture / using a Convolutional Neural Network (CNN) model trained on a large Mid-Infrared (MIR) soil spectral library

AI use in radiation protection from naturally occurring radionuclides

- Radon air concentrations indoors and outdoors
  - ANN-based model for prediction of radon concentration indoors based on meteorological and geological data
  - ANN-based model for fast prediction of radon dispersion from a uranium mine / input: uranium activity concentration in soil, gamma dose rate measurements, output: radon air concentrations

AI use in topics with potential application to nuclear or radiological EPR

- Radionuclides or other hazardous substances atmospheric dispersion modelling – forward in time, known source
  - Surrogate of Computational Fluid Dynamics models simulating dispersion of hazardous substances within complex urban areas to overcome the problem of long computational times; artificial neural networks (recurrent, deep, feed-forward)
  - Estimation of uncertainty in forecasted plume direction, using Bayesian machine learning based on the accumulated uncertainty estimation result in past cases

AI use in topics with potential application to nuclear or radiological EPR

- Estimation of an unknown emitting in the atmosphere radionuclides source and related uncertainties
  - ANNs trained through data generated by simple (Gaussian) models for cases of radionuclides atmospheric dispersion over flat terrain
  - Methods based on weather type / atmospheric circulation classification and corresponding dispersions
  - Applications concern mostly estimation of the emission rate of a source at a known location, with fewer applications estimating also the source location – one estimating uncertainties in location
  - No applications of AI were found for localization or characterization of an unknown source inside a complex urban environment

AI use in topics with potential application to nuclear or radiological EPR

- Prediction of (ambient / urban) air pollution
  - Air pollution forecasting using ANNs / long-term forecasting of outdoor PM10, PM2.5, nitrogen oxides and ozone ⇒ need for developing systematic protocols for developing powerful ANN models
  - Spatial downscaling to higher resolutions of larger scale air pollution models in urban environments (random forest model using as input population, land-use, surface greenness and vehicular traffic)
- Hazardous chemical substances detection and identification
  - Development of a system for chemical hazards detection, identification and monitoring based on machine learning, modelling algorithms and contaminant dispersion model to combine signals from different sensors and reduce false alarm rates

Preliminary conclusions

- ≈ 80 publications of AI–based applications in the area of nuclear emergency response
- Most publications are related to NPP accidents management and classification, followed by atmospheric dispersion modelling (forward and inverse) and then by mapping and optimizing dose rate monitoring
- Most frequent methods used: machine learning with various types of Neural Networks, followed by decision trees; limited use of LLM's
- Most applications use artificially-generated training data sets – fortunately, but posing questions for validity in real emergency cases
- Very few applications in off-site decision support
- No applications related to citizen measurements
- In radionuclides ADM applications almost entirely simple models are used; very few applications address uncertainties in model results
- Potential ethical issues ?

Thank you for your attention!