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THE ROLE OF INTEGRATED DATA SOURCES FOR ADVANCED MODELLING OF THE SPREAD OF HAZARDOUS SUBSTANCES

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ABSTRACT: *The number of industrial accidents in the developed world has been on a downward trend in recent decades, but the risk must still be considered. Therefore, modelling the atmospheric transport of hazardous substances is crucial to protect public health and the environment. Furthermore, it allows rapid and effective intervention in the event of an emergency, reducing the risk of negative health effects on the intervening personnel. In the 21st century, the availability of up-to-date information has become more valuable, and the development of information technology has created new opportunities for automated data collection and forecasting. This research aims to integrate a system providing real-time and predictive meteorological data with software for modelling the atmospheric dispersion of hazardous substances, which would increase the accuracy of modelling, reduce response times, and support decision-making processes around the incident.*

KEYWORDS: *disaster management, ALOHA, ESP32, meteorology, CBRN defence*

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INTRODUCTION

As the use and application of chemicals continue to grow, industrial accidents are likely to persist and their number may even increase due to key risk factors such as climate change, urban sprawl, and ageing industrial infrastructure. In parallel, maintaining current living standards and promoting sustainable development require the continued presence and advancement of the chemical industry, which forms the backbone of modern society. In the 21st century's information-driven world, the timely availability of reliable data is more crucial than ever, as information itself has become a key economic and social driver.

Industrial incidents involving hazardous substances not only pose direct health and environmental risks but can also lead to long-term socio-economic consequences. For this reason, the ability to accurately model the atmospheric dispersion of dangerous chemicals is of critical importance. Such models support rapid and informed decision-making during emergencies, allowing authorities to determine the most appropriate protective actions, such as evacuation or shelter-in-place measures, based on real-time risk assessments and the results of dispersion modelling. The integration of up-to-date meteorological data, including both real-time and forecasted conditions, significantly enhances the accuracy and usability of dispersion models, making them a vital component of effective disaster response and prevention strategies.

METHOD

The methodology of the research follows an applied, development-oriented approach based on four main pillars: document analysis, comparison of international practices, system development, and case study-based empirical validation. The author conducted a qualitative content analysis based on available documentation and information on US and European industrial security and propagation modelling tool systems. The study includes a comparative analysis of the principles of operation of a freely available US hazardous material spread modelling software and a comparative analysis of publicly available technical and policy documents of systems under the European Union's PESCO programme. This document analysis aimed to explore the potential for interoperability and the feasibility of decentralised, cost-effective solutions.

During the development phase, the author constructed a portable meteorological station based on an ESP32 microcontroller, capable of displaying real-time and predictive meteorological parameters and transmitting them in a format that free hazardous material atmospheric modelling software can process.

Following development, the author conducted a case study-based validation to test the system under different municipal scenarios and meteorological situations. The empirical testing aimed to demonstrate the applicability of the system to educational, decision support, and industrial safety practices. As part of the research, the author conducted a comparative literature analysis of artificial intelligence-based decision support systems, with a particular focus on the applicability of regression and deep learning models to population protection.

INTERNATIONAL PRACTICE IN THE INDUSTRIAL SAFETY REGULATORY ENVIRONMENT

This section examines industrial safety regulations in developed countries, with a focus on the United States of America and the member states of the European Union. In these regions, the prevention and management of industrial accidents is a high priority, yet despite a strict regulatory environment, hundreds of incidents occur each year, many of which have negative consequences, both environmentally and socially.

The European Union, as well as the United States, is paying particular attention to the safety of industrial facilities and their processes. In EU member states, hazardous substance plants are currently regulated by the SEVESO III Directive, which has been transposed into each member state's national legislation. Thanks to the Seveso Directives, the number of major industrial accidents has fallen significantly over the last two decades. According to statistics from the eMARS (electric Major Accident Reporting System), there are fewer than 30 major accidents per year in the EU. eMARS is a database operated by the European Commission that has been collecting data on major industrial accidents and near misses from EU member states and other participating countries since 1982.

In the EU, facilities dealing with dangerous substances are categorised into lower and upper tier establishments, depending on the quantity and type of dangerous substances they handle, store, or produce.

The United States has a safety framework like the Seveso Directive, called the Risk Management Program (RMP). The RMP is designed to reduce the number of major chemical accidents and to ensure that companies have adequate risk assessment, preventive measures, and emergency plans in place. More than 12,000 high-risk establishments are covered by the RMP, similarly to the approximately 12,000 establishments covered by the EU Seveso Directive.

Every five years, regulated establishments are required to identify and report accidents with reportable impacts that have occurred in the previous five years. Reportable impacts include on-site deaths, injuries, and property damage, as well as off-site deaths, hospitalisations, persons requiring medical treatment, the number of evacuees, the number of persons sheltered-in-place, and finally, off-site property and environmental damage.

In the U.S., the U.S. Environmental Protection Agency (EPA) is responsible for supervising the establishments. According to a 2023 study by the National Center for Environmental Economics, an average of 202 accidents per year occurred between 2004 and 2019, with 66.8% of these accidents (i.e., about 135 per year) involving hazardous gases. Over the 15 years covered by the study, nearly a quarter of the accidents had a negative off-site impact.[1]

Hungary has set stricter requirements than the Seveso Directive. The Hungarian legislation requires not only lower and upper-tier hazardous establishments to prepare safety documentation, reports, and prevention measures, but also establishments below the lower tier, which are often exempted from safety requirements in other member states. The criterion for this category is that these establishments must have at least a quarter of the quantity of dangerous substances found in lower-tier establishments. This stricter approach will contribute to a more transparent and comprehensive management of risks in this area, as well as to a higher level of protection for the population and the environment.

Operators must ensure that they have an internal emergency plan and a major hazard emergency response plan (called SKET) for facilities under the lower tier. The Hungarian Government Decree 219/2011 (X.20.) on the internal protection plan for the protection against major accidental effects of dangerous substances defines the tasks related to the protection against major accidental effects of dangerous substances, which include detection and chemical detection planning.

According to the guidance issued by the Hungarian National Directorate General for Disaster Management,[2] the detection and calculation of the spread of chemicals are necessary primarily in the event of a major accident or malfunction involving hazardous substances, especially if toxic or flammable substances, like ammonia, are released into the environment. In such cases, on-site responders, such as designated organisational workers, plant or professional firefighters, carry out a reconnaissance to identify the location, intensity, and equipment involved. Where there is a risk that the chemical release could reach an inhabited area outside the plant, atmospheric dispersion modelling, taking into account the current meteorological conditions, becomes essential. Based on the model's results, informed decisions can be made to protect civilians.

TOOLS FOR THE DETECTION OF INDUSTRIAL ACCIDENTS

It should be noted that CBRN risks can occur not only as a consequence of industrial accidents but also through intentional human actions. This includes, for example, acts of terrorism and sabotage, which can deliberately create CBRN hazards.[3] In the event of a release of

[1] Guignet et al. 2023, 5–8.
[2] Mesics et al. 2018.
[3] Dobor et al. 2024.

hazardous substances into the atmosphere, first responders in the United States and European Union member states use a variety of tools and techniques for detection and risk assessment. Responders and authorities in this region combine these tools and techniques to quickly and efficiently detect atmospheric releases of hazardous substances and take appropriate protective measures, while protecting the health and lives of first responders.

The U.S. EPA and other federal agencies use a variety of tools and technologies to detect and model atmospheric releases of hazardous substances, including:

ASPECT (Airborne Spectral Photometric Environmental Collection Technology) is EPA's unique aircraft-mounted system that can detect hazardous chemicals and radiological agents in real time, as well as function as an infrared and aerial imaging platform. It consists of sensors and software, mounted in a single-engine turboprop aircraft. It can provide scientifically-evaluated data in up to five minutes, including in a map format. It can start collecting data anywhere in the US within nine hours, making it a key tool for rapid detection of industrial accidents and emergencies.

The National Atmospheric Release Advisory Center (NARAC) is an advanced modelling centre that develops and operates a system for running atmospheric dispersion models at different scales (from local to global) to predict the effects of chemical, biological, and radiological releases. NARAC Modelling System is a closed, government-wide system developed and operated by the U.S. Lawrence Livermore National Laboratory (LLNL) for government and emergency response organisations. The system integrates real-time meteorological data, geographic and population databases, and health risk values (e.g., dose conversion factors, protection levels). Key features include weather forecasting, flexible spatial resolution, deposition and precipitation modelling, and even specific algorithms to simulate, for example, explosions or nuclear detonations.[4]

The European Union does not currently have a centralised system such as NARAC, but there are several regionally based systems to manage CBRN risks and support emergency response. In order to bridge these gaps, a comprehensive development has been launched within the European Union's Framework for Defence Cooperation (Permanent Structured Cooperation, PESCO) to create a single, modular, scalable, and flexible CBRN detection system. This system, known as CBRN SaaS (Surveillance as a Service), will provide CBRN surveillance and data collection capabilities as a service for operations, inside and outside the EU. The project is led by Austria, and Hungary is actively involved in its development. The primary objective of the system is to provide real-time situational awareness in a CBRN incident, including detection, sampling, and analytical processing. The resulting data will support common situation assessment and decision-making at the European level.[5]

In parallel, the EUROSIM project, which focuses specifically on training and simulation capacity building, aims to establish a common European simulation centre in Hungary, where the military, law enforcement, health, and cybersecurity organisations, and NGOs can jointly exercise crisis management. EUROSIM's IT system is based on a cloud-based infrastructure, complemented by edge computing, which distributes computing tasks between local computers (edge nodes) and the central cloud. This provides faster response times and lower latency, which is key for simulations.[6]

[4] Lawrence Livermore National Laboratory, [no year].
[5] European Defence Agency [no year].
[6] Ibid.

The EuroSIM system is based on the MSaaS (Modelling and Simulation as a Service) principle. The modelling and simulation capabilities are available to users as a service. The system operates with "mesh" functionality, i.e., national centres can communicate directly with each other, independent of a central server, thus providing high fault tolerance and reliability. The EuroSIM CBRN system is able to automatically collect, process, and interpret meteorological data, sensor data, space-based observation data, and GIS layers, such as population density. A key component of the EUROSIM system is the UrbanAware module, which specifically models and simulates CBRN hazards in urban environments.[7] The module can predict the spread of hazardous materials, designate protection zones, and provide real-time decision support to both responders through their mobile applications and command points at workstations. The system can be deployed globally as a cloud-based service or installed on-site.[8]

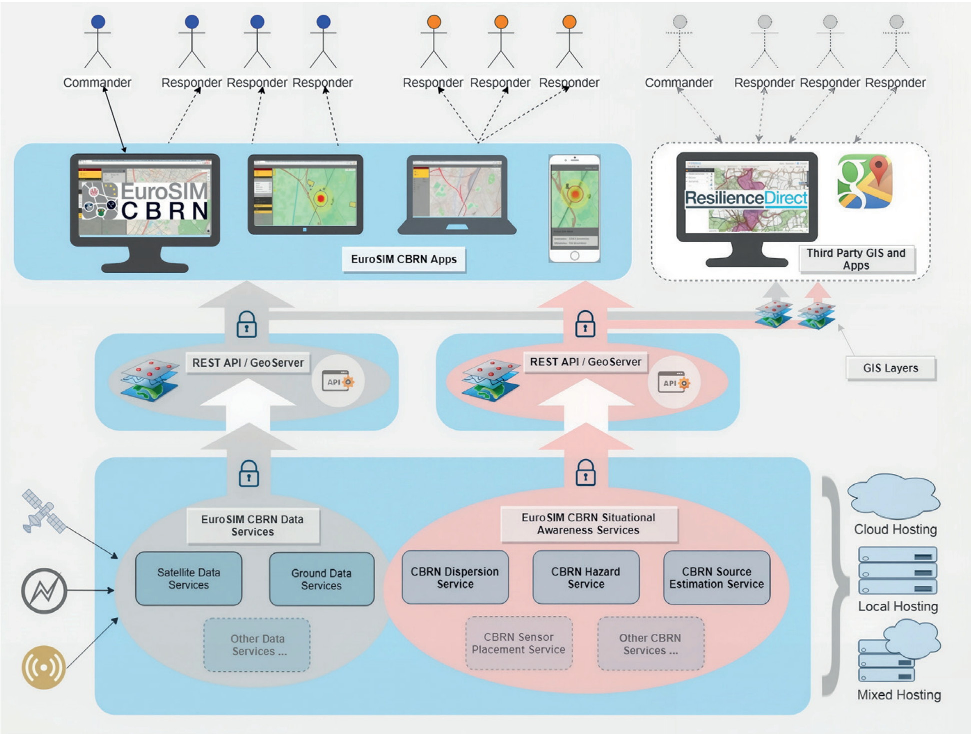

Figure 1 *High-level architecture of the system*

Source: *https://business.esa.int/projects/european-space-based-information-management-system-for-cbrn-eurosim-cbrn*

7 ESA [no year].

8 Riskaware [no year].

DEVELOPMENT OF OPEN-SOURCE MODELLING SOFTWARE

In selecting a modelling tool for the present research, a key consideration was the accessibility of the software to a broad professional and educational audience. While the Hungarian Defence Forces and the National Directorate General for Disaster Management employ advanced, validated, and multi-parameter consequence analysis systems, these are classified and not available for public or research use. Therefore, a direct comparison could not be undertaken, nor would it be permissible to disclose technical details in a scientific publication. For this reason, the ALOHA® (Areal Locations of Hazardous Atmospheres) software, developed by the United States EPA and the National Oceanic and Atmospheric Administration (NOAA), was chosen as the subject of this study. Although ALOHA is not the most advanced dispersion modelling tool available, it is free, internationally recognised, and characterised by low computational requirements, so it is deployable on a wide range of devices. The scientific novelty of the present work lies in demonstrating that established, decades-old software can be "modernised" through integration with contemporary microcontroller-based hardware, in this case, an ESP32-based portable meteorological station, thereby extending its functionality and improving its usability in a cost-effective and portable form. The software also has some limitations.[9] It basically uses two mathematical models to calculate the propagation: the Gaussian pulse model and the heavy gas model (Dense Gas Dispersion, DEGADIS).

The Gaussian pulse model is great for fast calculations and gives a good approximation for stable atmospheric motions. However, it is only good for stationary, homogeneous wind conditions on flat terrain, so the changing topography of urban environments is not taken into account. The model does not apply to explosive, pulse-like leaks. The DEGADIS model accounts for the propagation of heavy gases, the ALOHA software switches automatically if a heavier-than-air material is selected, but it takes a one-dimensional approach and does not account for time-dependent meteorological variations. The accuracy of DEGADIS is significantly reduced if the terrain is not smooth. An important limitation of both models is that ALOHA calculates up to a maximum of 10 km, which is not sufficient for large emissions. In addition, neither the Gaussian nor the DEGADIS model takes into account chemical reactions, temperature effects, soil moisture, radiative forcing, or explosive releases, which may cause discrepancies.[10]

A portable weather station (Station for Atmospheric Measurements, SAM) can be connected to the software to avoid manual data entry and to load the most accurate and up-to-date weather parameters. The primary objective of the author's research was to improve the preventive-detective capability of the ALOHA software by creating a digital SAM station that can provide forecast meteorological data in addition to current data, thus allowing a longer security incident to be better tracked and to produce propagation models of several future times at a single point in time. Finally, the software will have enhanced functionality.

The author used an ESP32 energy-efficient microcontroller as a "digital SAM station". The external portable physical device needs to be platform-independent. Another advantage of the ESP32 is that it is a very cost-effective solution, with Wi-Fi and Bluetooth capabilities. The device is programmed using the Arduino integrated development environment

[9] Office of Response and Restoration, NOAA [no year].

[10] U.S Environmental Protection Agency – National Oceanic and Atmospheric Administration 2007.

(IDE), which provides a programming environment optimised for microcontrollers based on the C++ language syntax.

In programming the ESP32, the author has taken into account a document published by the NOAA Emergency Response Division Office of Response and Restoration on portable weather station designing.[11] The purpose of the document is to define design guidelines for portable weather stations that can provide structured meteorological data for propagation modelling. Recommendations in the document include details on the required weather parameters, the format of data recording, and the characteristics of serial communication protocols. Based on this document, the author specified the baud rate, the data structure, and the minimum meteorological variables that the ESP32 had to provide to the ALOHA software.

In terms of the basic functionality of the tool, ESP32 runs an embedded web server, which allows the user to select a location and whether to retrieve current or forecast meteorological data by accessing a predefined local IP address via a web browser and using a graphical

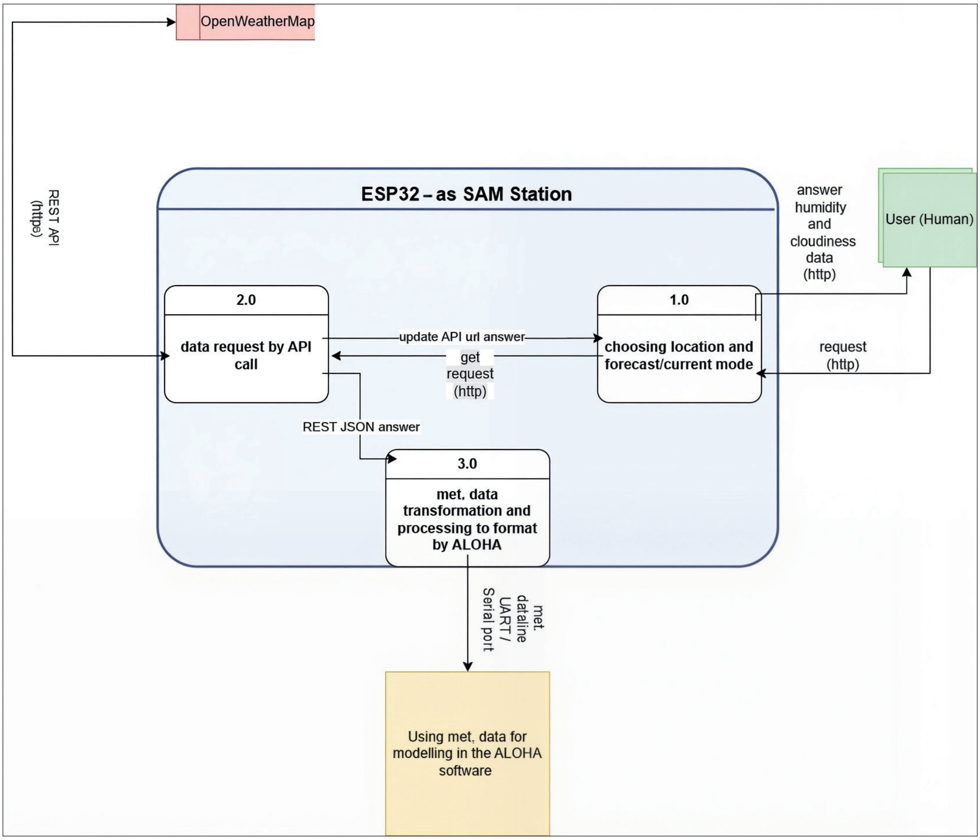

Figure 2 *"Digital SAM Station" operational processes*

Source: *author*

[11] Emergency Response Division, Office of Response and Restoration, National Oceanic and Atmospheric Administration 2011.

interface. ESP32 makes an API call to the meteorological data provider based on the selected parameters, using the APIs of openweathermap.org, which are received in JavaScript Object Notation (JSON) format. Finally, this data is transmitted to the software in a format that can be processed by ALOHA, which perceives it as if it were receiving data from a physical portable weather station via a serial port.

For successful operation, the author had to specify certain constants in the data set to be sent to the software, such as the device's battery voltage level and device ID, which are created data. Care had to be taken to ensure that the serial data rate was set correctly, which, for ALOHA, had to be set to 1200, and the number of bits was 8.

Furthermore, the tool also calculates the wind direction scatter; the wind direction is cyclic, so instead of using traditional scattering formulas, a method like Yamartino's was incorporated into the code line. This formula yields a deviation of +/– 2% in the worst case, which is very good accuracy for a simple and fast-to-calculate approximation.

Yamartino's method is as follows: $S = \frac{1}{N}\sum_{i=1}^{N} sin\theta i$; $C = \frac{1}{N}\sum_{i=1}^{N} cos\theta i$

$$\sigma_\theta = arcsin\left(\varepsilon\right)\left[1 + \left(\frac{2}{\sqrt{3}} - 1\right)\varepsilon^3\right] \text{ where } \varepsilon = \sqrt{1 - (S^2 + C^2)}$$

$\frac{2}{\sqrt{3}} - 1 = 0.1547$[12]

USAGE OF THE SYSTEM

The following section presents a fictional demonstration scenario to illustrate the operational workflow of the developed ESP32-based meteorological data acquisition system, integrated with the ALOHA® dispersion modelling software. The scenario is purely illustrative and does not represent an actual incident.

The scenario

A fictional chemical plant located along Soroksári Road in Budapest utilises liquefied sulfur dioxide (SO_2) as a feedstock in sulfuric acid production. The plant stores SO_2 in horizontal cylindrical steel pressure vessels positioned outdoors.

One such tank, with a capacity of 25 m^3 (approximately 50 tonnes of liquefied SO_2), operating at around 3 bars under ambient temperature, suffers a gasket failure at a flange connection. This defect results in a continuous vapour release, lasting approximately 60 minutes. Part of the liquefied SO_2 escapes onto the concrete-based ground, forming a shallow pool (approx. 200 m^2 surface area, 0.02 m depth) that continues to evaporate after the primary release ends.

To demonstrate the added value of predictive meteorological data integration, two dispersion modelling runs are performed:

– Run 1: Current meteorological data at 22:35 (local time), with the primary source modelled as a vertical cylindrical tank leak.
– Run 2: +3-hour forecast meteorology, with the primary source modelled as an evaporating puddle, representing the secondary phase of the incident.

[12] Yamartino 1984.

Finally, a comparison will be presented illustrating how evolving wind direction and stability conditions can significantly alter the predicted hazard zones during an extended incident, and how forecast-enabled modelling supports proactive evacuation planning, responder positioning, and public protection measures.

Given that sulfur dioxide has a molecular weight approximately twice that of air, the ALOHA software automatically applies the DEGADIS dense gas dispersion model for this scenario, which more accurately represents the ground-hugging behaviour of heavier-than-air gas clouds.

System connection and data retrieval

When initiating the operation of the integrated system, the user first connects the ESP32-based meteorological station to a laptop's or desktop computer's USB port. The operating system automatically recognises the device and establishes a serial communication link via the assigned COM port. This allows users to run the ALOHA software in parallel.

The next step is to access the device's configuration interface by opening a standard web browser and entering the local IP address of the ESP32 into the browser's address bar. This launches the embedded web interface hosted by the microcontroller, allowing the operator to select the desired target location and the preferred meteorological data mode (Current or Forecast).

The user interface has been designed with simplicity and transparency in mind, so as not to disproportionately overload the ESP32's computing power.

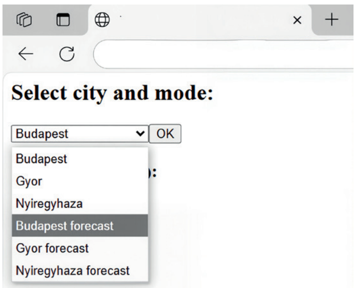

Figure 3 *User web interface drop-down list*
Source: *author*

Clear feedback is displayed in the user interface as soon as the user selects the desired settlement and the type of data request (current or forecast mode) from the drop-down menu. As the ALOHA software requires manual input of relative humidity and cloudiness values when using SAM Station, the frontend, powered by ESP32, automatically displays these values to the user, extracted directly from the API call response. This feature significantly speeds up the data entry process and reduces the possibility of errors.

In this research, the Forecast mode used is 3-hourly meteorological predictions for demonstration purposes, but the API also allows flexible adjustment of the forecast interval, enabling retrieval of shorter or longer time horizons, as needed. Multiple prediction modes can be set up in parallel for different scenarios. The ESP32 firmware also calculates a 5-minute moving average of the current meteorological parameters and updates its average data array with each new API query to provide stable, representative input values for ALOHA.

Results and visualisation in Google Earth Pro

Google Earth Pro was used to visualise the AEGL-based hazard zones generated by ALOHA as KML files. This platform enables georeferenced, high-resolution mapping of threat zones over real-world terrain and infrastructure, improving situational awareness for decision-makers. It also allows overlaying multiple scenarios (e.g., current vs. forecast meteorology) to directly compare plume behaviour under different conditions, which is valuable for both operational planning and training. In the ALOHA threat zone outputs, the wind direction confidence lines represent the directional uncertainty of the plume axis based on the variability in measured wind direction during the modelling period. In the present scenario, these lines are shown only for the longest threat zone, corresponding to the AEGL-1 (0.2 ppm) level, and indicate the possible lateral deviation of the hazard footprint. While they are not an additional threat zone, such indicators can be valuable in public protection planning.

Run 1: AEGL-based threat zones for SO_2 release from a fictional Soroksári Road industrial facility, modelled with current meteorological data (22:35). The plume extends west-northwest, with AEGL-1 reaching the sideline of Budaörs. The simulated release originated from a 2 cm diameter hole located at 55% of the tank height, resulting in a continuous vapour discharge for approximately 60 minutes.

Figure 4 *SO_2 tank release, which was modelled with current meteorological data*
Source: *author*

Run 2: The next figure is about the SO_2 puddle evaporation release from the same fictional facility, modelled with forecast meteorological data. The hazard footprint is broader due to different wind directions, temperature, and stability conditions. In the puddle evaporation scenario, the hazard footprint shifted northward compared to the initial tank release. This displacement reflects the influence of the forecasted change in wind direction.

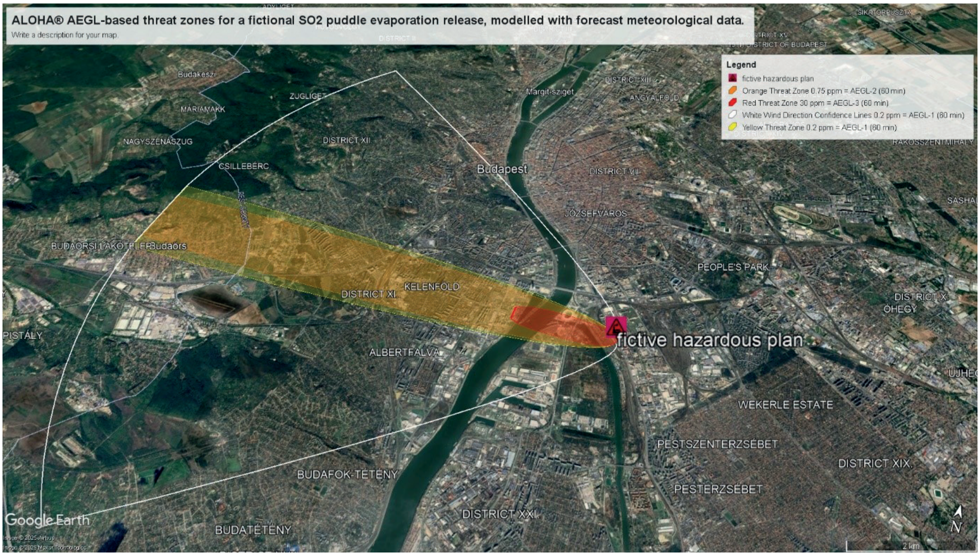

Figure 5 *Puddle evaporation with forecast meteorological data*
Source: *author*

How does the dispersion change if the same event occurs three hours later?
Compare AEGL-based threat zones for SO_2 release from a fictional Soroksári Road industrial facility, showing the effect of incident timing. The lower plume represents the dispersion modelled with current meteorological data (22:35), while the upper plume shows the same release parameters applied to an incident occurring three hours later, using forecast meteorology. The forecast scenario results in a northward-shifted hazard footprint, altering the potentially affected population and infrastructure. Notably, the AEGL-3 (red) threat zone in the forecast-based run extends by approximately 100 metres beyond the length calculated for the current meteorology scenario, and both the AEGL-2 (orange) and AEGL-1 (yellow) zones fully reach the built-up areas of Budaörs.

These visualisations demonstrate that forecast-enabled modelling can anticipate hazard shifts during prolonged or delayed incidents, enabling proactive evacuation planning, responder positioning, and public protection measures. Furthermore, integrating predictive meteorological data into dispersion modelling allows decision-makers to assess multiple potential incident timelines, compare their respective impacts, and optimise resource allocation. Even the use of a freely available, less complex modelling tool, such as ALOHA, is supported by the developed ESP32-based meteorological data integration system.

APPLICATION POSSIBILITIES

The development will primarily support educational applications, such as firefighting training, disaster management, or chemical workplace training, to demonstrate the potential for real-time or future applications of meteorological data. The system provides participants with the opportunity to experience how the dispersion characteristics of hazardous substances change under different weather conditions, using real-time and forecast meteorological data.

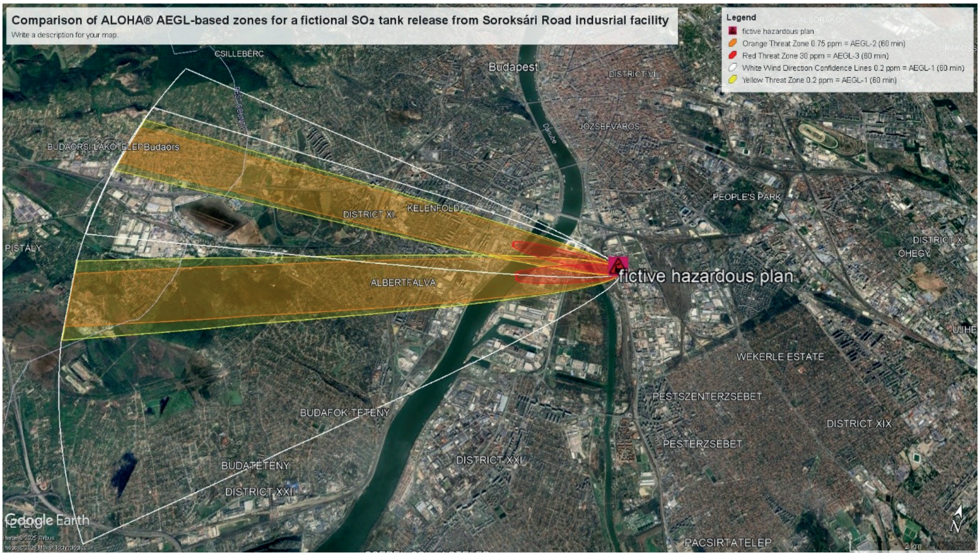

Figure 6 *Comparison of the same event, but with a different type of meteorological data*
Source: *author*

This aligns with recent disaster management research, emphasising the importance of integrating international and national best practices, technical innovations, and applied research findings into industrial safety education and capability development, in order to effectively reduce the risks associated with hazardous activities.[13]

A further use could be as a secondary, back-up system in addition to the primary system for professional intervention staff if, for some reason, the main system is not operational. It can even be used in smaller industrial organisations to simulate rescue exercises or to support the management of industrial accidents. Alternatively, it can provide a low-cost and easy-to-use solution for the operation of industrial facilities in third countries, as well as for disaster management, industrial safety authorities, and CBRN defence training or joint civil–military exercises. It should be emphasised that the ALOHA software, even with the proposed hardware integration, does not replace the high-precision, multi-variable hazardous substance dispersion modelling and analysis systems currently in operational use by the Hungarian Defence Forces and professional disaster management organisations.

In summary, this development adds additional functionality to the existing software, allowing the modelling of virtually any municipality with real meteorological or forecast data in the most cost-effective way possible. This can greatly assist decision-making, especially in the case of a prolonged release of a hazardous substance. The value of this research lies in its demonstration of a practical, low-cost enhancement to a legacy modelling tool, showing that real-time and forecast meteorological data integration can be achieved with readily available technology, thereby broadening the range of contexts in which such modelling can be applied.

[13] Vass et al. 2024.

FURTHER DEVELOPMENT OPPORTUNITIES

With the rise of advanced technologies, the use of artificial intelligence (AI) in environmental safety and emergency management is becoming increasingly important. The author of this paper, therefore, proposes the introduction of AI-based approaches that can facilitate predictive modelling of the spread of hazardous substances. Due to the working conditions of the disaster management response team, the author proposes a portable yet affordable device with higher computational power, such as the Raspberry Pi 5. This hardware family is also capable of running simpler supervised learning algorithms, such as regression models. The training process should preferably be performed on a system with higher computing power or in a cloud environment. In contrast, inference, i.e., model application, can be performed on the Raspberry Pi platform. The machine learning frameworks supported by Raspberry Pi, such as TensorFlow Lite, ONNX Runtime, or PyTorch Mobile, allow running optimised models in resource-constrained environments.[14]

The aim of the further development is to create a predictive system that is capable of interpreting the .kml-format propagation maps or .jpg dispersion images and meteorological inputs generated by ALOHA to formulate recommendations for protection zones and population protection measures. The concept of such systems is in line with state-of-the-art air pollution prediction models used in industrial and urban environments, where prediction is based on sensor data and meteorological information. CNN-LSTM architectures combining convolutional and recurrent neural networks are particularly promising for the joint treatment of spatial and temporal patterns, as they are able to handle both the complexity of spatial features (e.g., propagation maps) and the temporal dynamics of meteorological variables. Several studies confirm that such hybrid solutions provide explicitly high forecast accuracy for environmental systems, such as air quality prediction.[15] However, simpler regression models, such as Random Forest, can also be used to make estimations from actual meteorological data. These algorithms can be particularly advantageous on low-resource devices due to their faster learnability and lower computational requirements. Some studies have pointed out that in estimating certain environmental parameters, the random forest machine learning technique gives surprisingly accurate results, outperforming linear regression or SVM (Support Vector Machine) models.[16] However, the prediction accuracy of these machine learning techniques, especially when predicting temporal changes, is generally lower than the deep-mesh approach due to their inability to model temporal or spatio-temporal patterns efficiently. Therefore, CNN-LSTM models provide higher predictive performance for long-term forecasting tasks, while conventional models may be more suitable for rapid decision support and scenario-based analysis.

The further development of the system should also take into account population density-based estimation possibilities, as population protection measures must consider the number of affected people. The .kml files generated by ALOHA allow the geographical extent of the hazard zones to be determined at the coordinate level, and the system may be able to associate population density data with them. Population estimation can be based on a single, representative coordinate, such as the centroid of the zone, or on several randomly

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14 Tigadi – Rodrigues 2023.

15 Bekkar et al. 2021.

16 Meenal et al. 2021.

selected points, which can be structured using geohash-based spatial gridding. The aggregation (averaging or maximising) of the population density values that can be retrieved for the points thus defined can provide an estimate of the number of inhabitants in the danger zone.[17]

Population density data are available through various open-source Web APIs. These data sources are mostly based on official census data, disaggregated by satellite, land use, and light intensity data, and are available at a resolution of up to 30×30 m. The interpretation and use of population density based on AI to estimate the affected population of a given zone (polygon), for example, a hazard zone, is also not a new research direction. Previous studies have successfully used Random Forest[18] and deep learning models[19] to estimate the spatial distribution of permanent resident populations, typically from satellite imagery or remote sensing data. These approaches can also be adapted to decision-support systems where population density data provide an estimate of the population size that may be affected by a given hazard zone.

It is important to underline that such systems can only serve a decision-support function and that the final decision must always be taken by a human expert. Human validation ensures that the machine forecasts and recommendations are interpreted in the light of local specificities, operational options, and social context. This is particularly important in cases where the proposed measures have a direct impact on the safety and living conditions of the population.

CONCLUSION

Although the incidence of industrial accidents is decreasing in developed countries, they still pose a serious risk to the population, the health of first responders, and the environment. Appropriate protection measures are essential, supported by accurate modelling of the atmospheric dispersion of hazardous substances. The principal scientific contribution of this work is the functional enhancement of an established, widely used, but technically limited dispersion modelling software tool through the integration of a portable ESP32-based meteorological station capable of supplying both real-time and forecast data. This development demonstrates that even legacy software, originally designed in the 1980s, can be effectively adapted to meet modern information technology trends and operational needs. By enabling direct input of predictive meteorological parameters, the system can provide decision support not only under current conditions but also for anticipated changes in atmospheric variables during an incident.

While the system cannot match the accuracy and complexity of classified national consequence modelling and analysis tools, its portability, low cost, and open accessibility make it a valuable supplementary secondary asset for professional responders, a practical tool for operators of hazardous plants, and an effective platform for training purposes, such as simulation exercises. In addition, the architecture is adaptable for further development, so the research also suggests future directions for improvement, including the integration of machine learning models that could further increase the accuracy of predictions and the decision-support potential of the system.

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[17] Troy 2008.
[18] Stevens et al. 2015.
[19] Doupe et al. 2016.

Overall, the presented development offers an easily adaptable, practice-oriented approach for modern, real-time, and forecast data modelling of hazardous substance dispersion, illustrating how accessible technologies can extend the usability of legacy modelling tools in contemporary operational contexts.

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