



PandemIQ system in Poland: The hybrid approach to early detection of pandemic waves using interpretable AI models and GIS-based operational dashboards (ArcGIS)

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Summary

Humans live surrounded by a variety of threats. These threats can be diverse: natural, chemical, technological, psychological, social, ecological, global, biological, and health-related. The latter, namely biological and health threats, are the most pressing and dangerous from a human perspective as they affect living organisms' health. Examples include infectious diseases caused by viruses, bacteria, or parasites (e.g., influenza, COVID-19, Lyme disease). In Poland, epidemic cases of the acute infectious respiratory disease COVID-19, caused by the SARS-CoV-2 virus, were first reported on March 4, 2020. The pandemic lasted three years. This scientific article attempts to present the architecture and functionality of the PandemIQ system. The system was designed for the early detection and forecasting of the regional risk of pandemic waves. The system is based on a hybrid artificial intelligence model that combines predictions based on epidemiological, mobility, and transportation data with interpretability (attention) mechanisms enabling visualization and decision justification. This paper provides a detailed discussion of the structure of decision reports for authorities, GIS-based operational dashboards (ArcGIS), and alternative solutions using the Apache ECharts library. It also presents validation procedures, data security aspects, and compliance with legal regulations (GDPR, AI Act). Simulation results using historical data on the spread of the SARS-CoV-2 virus indicate that the system can detect waves on average 7–14 days earlier than traditional epidemiological methods can, while maintaining a low false alarm rate.

Keywords

pandemic early warning • interpretable AI • GIS dashboard • ArcGIS • regional risk analysis • crisis management • decision-making systems • human threats • Poland

1. Introduction

Humans live surrounded by a variety of threats. These threats could be diverse: natural, chemical, technological, psychological, social, ecological, global, biological, and health-related. The latter, namely biological and health threats, are the most pressing and dangerous from a human perspective as they affect living organisms' health. These include:

- infectious diseases caused by viruses, bacteria, or parasites (e.g., influenza, COVID-19, Lyme disease),
- hospital-acquired infections and bacterial resistance to antibiotics,
- infections through contact with toxic organisms or allergens.

Many researchers conduct scientific research and forecast human threats using GIS (Geographic Information System) tools. Natural threats are studied, by assessing and mapping flood-prone areas [Mohammed Ben Halima et al. 2025, Negese et al. 2022]. Another field of research covers chemical and technological threats [Arroyo-Ortega et al. 2024]. Psychological and social threats are also another scientific topic analyzed by many researchers, albeit rarely using GIS tools [Hadgu et al. 2025, Shin and Kim 2026, Jarkowska et al. 2026]. Similarly, although many studies have been conducted on biological and health threats to humans [Ezgin 2026], but scientific research has been conducted using GIS tools. From 2020 to 2023, infectious diseases, such as COVID-19, posed the greatest threat to human health. In Poland, epidemic cases of COVID-19 (an acute infectious respiratory disease caused by the SARS-CoV-2 virus) were first detected on 4 March 2020, in a hospital in Zielona Góra, Poland. From 14 to 20 March 2020, a state of epidemic threat was in force in Poland [Act 2008], and from 15 March 2020, a sanitary cordon was introduced at the Polish border, significantly restricting cross-border traffic. From 20 March 2020, to 15 May 2022, a state of epidemic was in force in Poland in accordance with the regulation of the Minister of Health [Regulation 2020]. On 16 May 2022, the state of epidemic was changed to a state of epidemic threat. On 1 July 2023, the state of epidemic threat was lifted. As of 30 June 2023, 6,517,852 cases of infection and 119,626 deaths had been recorded. The scale of the threat and the number of recorded deaths demonstrate the seriousness of this threat to human life. A scientific team conducted research on the COVID-19 pandemic [Luna-Ramírez et al. 2025]. However, these studies were not conducted with GIS tools. GIS tools are used in various spatial analyses, for example: the land consolidation [Basista et al. 2023, Janus and Ertunç 2023, Balawejder et al. 2023, Basista and Balawejder 2020], the noise impact analyses [Szopińska et al. 2022], the land and building register [Busko et al. 2023, Ogryzek et al. 2022], the solar energy [Coruhlu et al. 2022], the emission and air quality [Szopińska et al. 2025] and the landscape belt [Bieda et al. 2024].

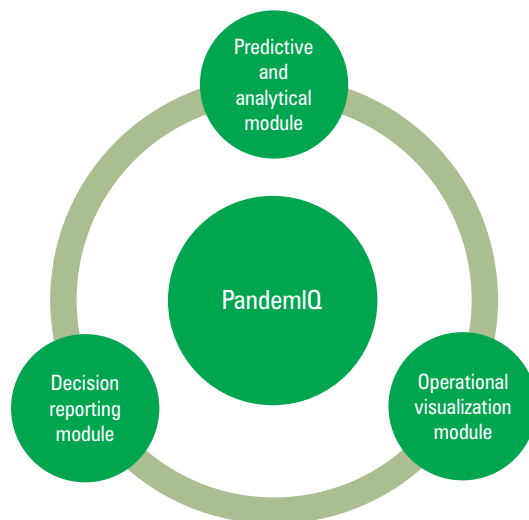
No publications of scientific studies using GIS analyses with ArcGIS were found in the available national and international literature on biological and health threats related to the COVID-19 pandemic. Therefore, in the face of rapidly evolving epidemic threats, not only accurate forecasting as well as the interpretability and reliability of decision support systems, including graphical GIS tools, are crucial. Traditional methods based

on reproduction rates (R) or disease trends often signal threats with a delay, limiting the time available for a response. This article presents the PandemIQ system project, which combines advanced predictive models (LSTM, attention mechanisms) with interactive visualization tools (ArcGIS graphics software), focused on the needs of decision-makers at the national and regional levels. The PandemIQ system was developed from a project aimed at creating an interactive operational dashboard that presents the pandemic threat status based on continuously collected data from various sources.

The project was carried out under the grant programme for R&D works by scientific entities, Call IV, Competition No. 1/2024. Project title: Interactive pandemic early warning system supported by machine learning (AI). Grant agreement number N4_076-co-financed under the project 'Podkarpackie Center for Innovation 2029' implemented under the regional programme 'European Funds for Podkarpackie 2021-2027'; priority: FEPK.01, competitive and digital economy; measure: FEPK.01.01, research and development; type of project: building the potential of innovation centres: Podkarpackie Center for Innovation.

2. PandemIQ system architecture

The system consists of three main modules: predictive analytics, decision reporting, and operational visualization, as graphically presented in Figure 1.



Source: Authors' own study

Fig 1. PandemIQ system architecture

Figure 1 illustrates the components of the PandemIQ system:

1. Predictive and analytical module (data collection) – processes input data (illness, mobility, air connections, global data) and generates risk forecasts using a hybrid model.

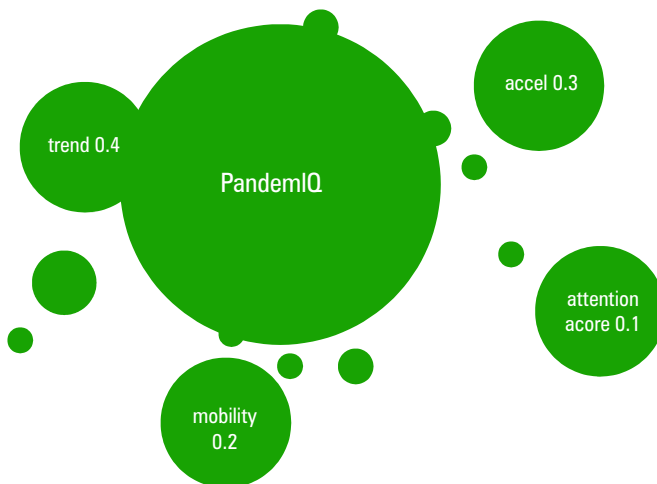
2. Decision reporting module – creates reports for authorities, including attention heatmaps, risk source identification, and operational recommendations.
3. Operational visualization module – a GIS dashboard (ArcGIS) or, alternatively, a solution based on Apache ECharts, enabling real-time risk monitoring.

2.1. Regional risk model and algorithm

The regional risk is calculated as a weighted average of four components, which allows for balancing trend predictions with sudden changes in dynamics. The system uses the following weights for individual variables:

- Trend (weight 0.4) – derived from the LSTM model forecast.
- Accel (weight 0.3) – acceleration of disease growth in the 7–14-day window.
- Mobility (weight 0.2) – indicators of local mobility and transport connections.
- Attention score (weight 0.1) – the result of the attention mechanism, assessing the similarity of the current situation in the region to historical pandemic epicentres.

The PandemIQ system variables are presented in Figure 2.



Source: Authors' own study

Fig 2. Variables in system PandemIQ

The implementation of the risk calculation algorithm (pseudocode) is as follows:

```
def regional_risk (trend, accel, mobility, attn_score):
```

```
    score = (
        0.4 * trend +
        0.3 * accel +
        0.2 * mobility +
```

```

    0.1 * attn_score
)
# # Normalize the result to the range 0.0 - 1.0
return min (score, 1.0)

```

2.2. Decision Reporting Module – structure and interpretation

Instead of pointing to a threat, the key objective of the PandemIQ system is to explain why the model is generating a warning. The Executive Summary is 1–2 pages long and answers three questions: Is a new wave coming? When will it occur ($\pm$ days)? What is the risk?

The report structure includes:

1. Executive Summary: for example, ‘The model indicates a high probability of a new wave within 10–14 days. Main factors: increased mobility (+18%) and analogy to the fall 2020 wave.’
2. Risk Source Table: presenting specific signals (e.g., urban mobility: +22%, high importance; international flights: +15%, medium importance).
3. Attention Visualization (heatmap):
 - Bright areas indicate key days for the model.
 - Vertical bars indicate strong individual signals (e.g., a sudden influx of flights).
 - Horizontal bars indicate historical periods that the model found analogous to the current situation.

Through this approach, the system builds political trust by enabling auditing of decisions and proving that ‘the model was looking at the same thing the analysts were looking at’.

3. Operational dashboard – architecture and functionality

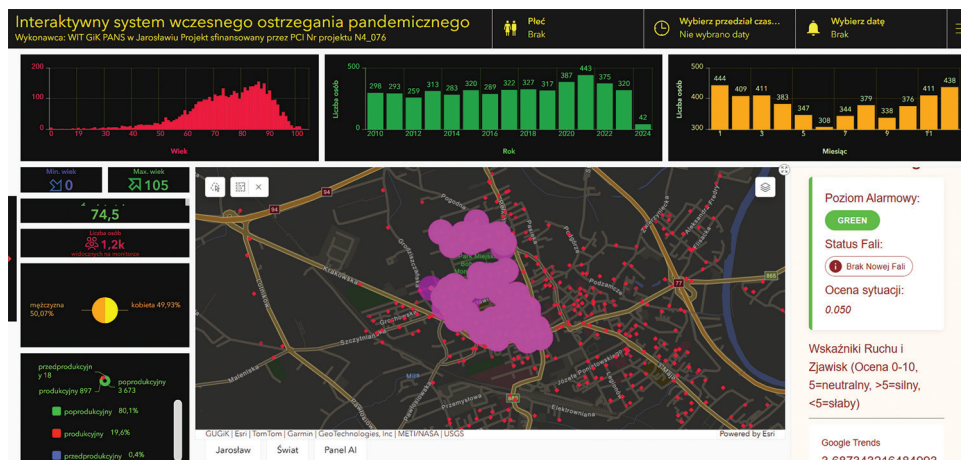
The overarching principle when designing a dashboard ensures that the decision-maker can understand the situation within 30 seconds. This requires avoiding sliders and filters on the main screen in favour of pre-defined messages (colour > number).

3.1. Interface layout

The operational dashboard (ArcGIS) was designed in a “Fixed” layout (a single screen without scrolling), as shown in Figure 3. It consists of the following sections:

1. Header: contains the threat status (e.g., red), the date, and a clear message about the alert level.
2. Alert Panel (left column): lists regions with increasing risk (increasing trend) and an indicator of the number of regions affected by the alert. It answers the question: ‘where does something start?’

3. Main Map (centre): the largest element of the interface. A layer of provinces/counties with risk colour coding.
 - ● Low (monitoring),
 - ● Increasing (preparation),
 - ● High (tests, communication),
 - ● Critical (intervention).
4. Details Panel (bottom – click): activates after selecting a region on the map. Includes a forecast chart (7/14 days), a growth rate indicator, and a mini attention heatmap explaining the reasons for the alert.



Source: Authors' own study

Fig 3. Operational dashboard of the PandemIQ system

3.2. Functional implementation and widgets

A number of specific widgets have been implemented (or are planned) in the PandemIQ system to enhance operational usability:

- Time and Date Selector: allows for historical analysis of waveforms ('From – To' ranges).
- Demographic Filtering: a gender selector (female/male/none) for analyzing incidence rates by group.
- Death Visualization: a serial (bar) chart showing the number of deaths by year (e.g., 2010–2022) for redundancy comparison.
- Matrices and Clusters: alternative methods of visualizing data on a map (density grids or 'heat spot' clusters) for improved readability with high density of point data.

- KPIs: simple counters for ‘Number of people visible on the monitor’ and ‘Average age.’
- These widgets are graphically presented in Figure 3.

3.3. Technical configuration guide (ArcGIS)

The Figure 4 illustrates the steps for implementing a dashboard in an ArcGIS Online/Enterprise environment.



Source: Authors' own study

Fig 4. Steps for implementing a dashboard in the ArcGIS Online/Enterprise environment.

The dashboard implementation process in the ArcGIS Online/Enterprise environment is a seven-step process:

1. Data preparation: it is crucial to join the administrative boundary layer (Shapefile/ GeoJSON) with the pandemic risk table (CSV/Feature Layer) using the unique identifier TERYT.
2. Symbolization: setting the ‘Counts and Amounts’ layer styles and assigning colours (green-red) to the risk level attribute.
3. Configuring Pop-ups: removing technical data, leaving only the region name, risk level, and trend.
4. Building the Dashboard: selecting a fixed layout. Adding an Indicator widget (general status) and a List widget (regions at risk, sorted by risk score in descending order).
5. Interactivity (map actions): configuring an action where clicking a region on the map filters the list and updates the charts in the detailed panel.
6. Automation: powering the feature layer via Python/REST API scripts on a daily basis.
7. Security: restricting access to roles (Ministry of Health, RCB, Voivode), activity logging.

4. Validation on historical data (supplement)

During the system validation process using historical data from 2020–2022 (training: 2020, testing: 2021, validation: 2022), measurable time advantages were achieved compared to traditional methods. The evaluation was based on the lead time, defined by the function:

$$\text{return true_wave_start} - \text{detected_day.}$$

Comparative results are as follows:

1. Traditional method ($R > 1$): 0–3 days of lead.
2. Disease trend analysis: 3–5 days of lead.
3. PandemIQ Hybrid Model: 7–14 days of lead.

The system also demonstrated signal stability (alert persisting for ≥ 3 days), which allowed for the elimination of ‘flickering’ false alarms.



Source: Authors' own study

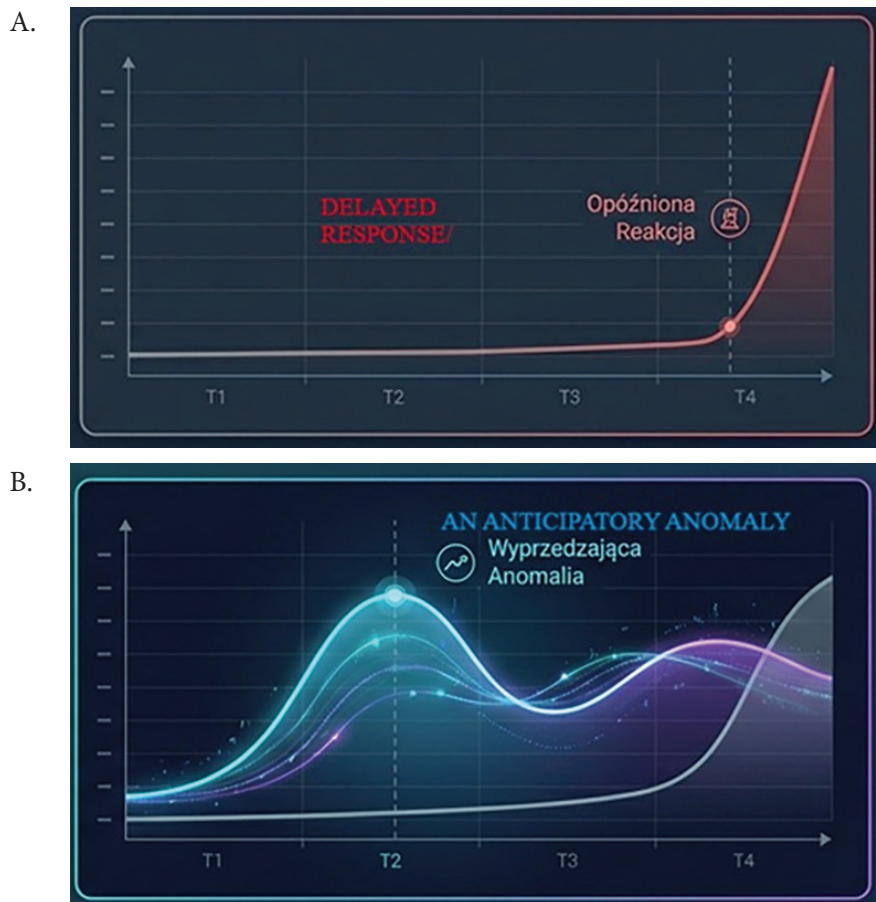
Fig 5. Wave detection

As shown in Figure 5, this provides an average of 7 to 14 days of additional time for a response, allocation of medical resources, and communication with the public, while maintaining a near-zero false alarm rate.

Before medical systems report a problem, society leaves measurable traces of changes in disease incidence. Figure 6 presents graphs illustrating classical and digital epidemiology.

Classical (lagging) epidemiology relies on official medical records and death statistics. ‘Lagging’ means that the system reacts when hospitals are already full. Lead time: 0–3 days.

Digital epidemiology (leading), on the other hand, analyzes ‘digital footprints’: search engine queries, mobile activity, media mentions. ‘Leading’ means that the system detects anomalies before the healthcare system does. Lead time: 7–14 days.



Source: Authors' own study

Fig 6. A. Classical (lagging) epidemiology. B. Digital epidemiology (leading)

5. Discussion and conclusions

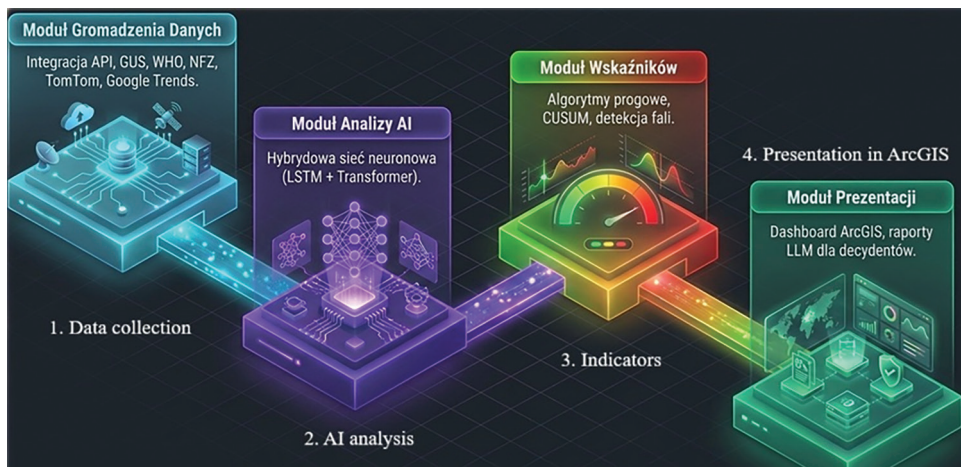
The result is a modular PandemIQ system that collects data, processes it using artificial intelligence, and presents both analytical data and synthetic indicators informing about the human threat status. The PandemIQ system is an example of a practical implementation of interpretable AI in the public sector. Key advantages include:

- early detection of threats with operational advancement,
- transparency through attention mechanisms,
- integration with existing GIS systems and operational dashboards.

The limitation is the need to maintain high-quality input data [Hanh et al. 2026] and regular model validation [Chi et al. 2022] in the evolving epidemic context.

The PandemIQ system consists of four modules:

1. Data collection
2. AI analysis
3. Indicators
4. Presentation in ArcGIS. This is graphically presented in Figure 7.



Source: Authors' own study

Fig 7. Data collection modules in the PandemIQ system

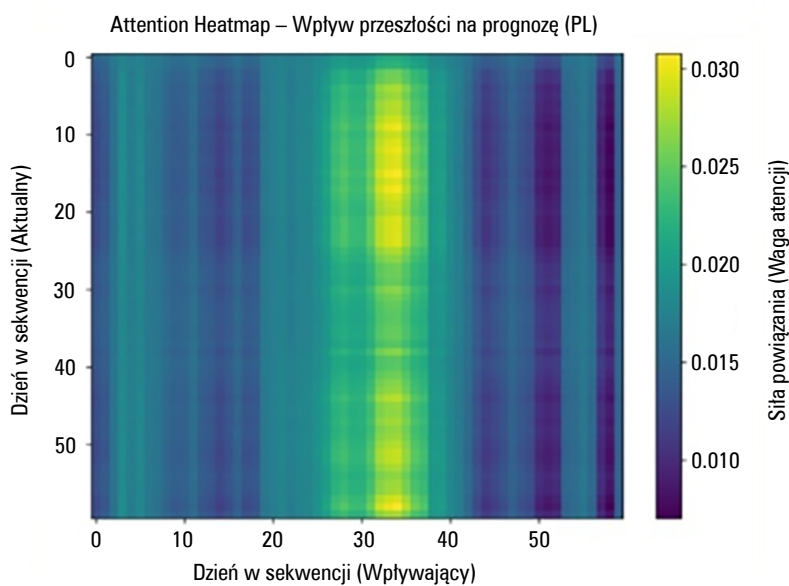
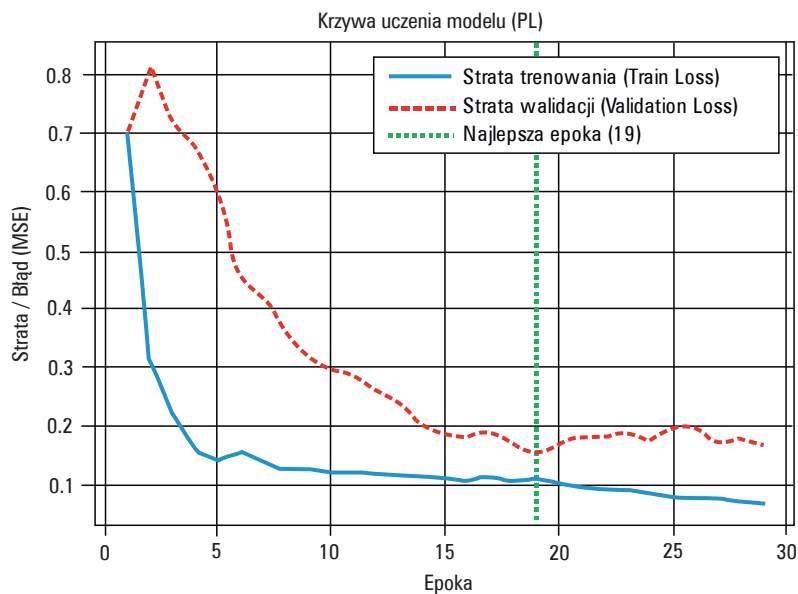
Each of these modules operates autonomously, creating a continuous, automated stream of operational information.

Figure 8 presents the results of network training. The visualization shows the training loss in blue and the validation loss in red. The best epoch is marked in green. Below the network training visualization graph is an attention heatmap, where the current day of the sequence is marked vertically, while the influencing day in the sequence is marked horizontally.

The PandemIQ system analyzes phase 1 to prevent overload in phase 3, as graphically presented in Figure 9.

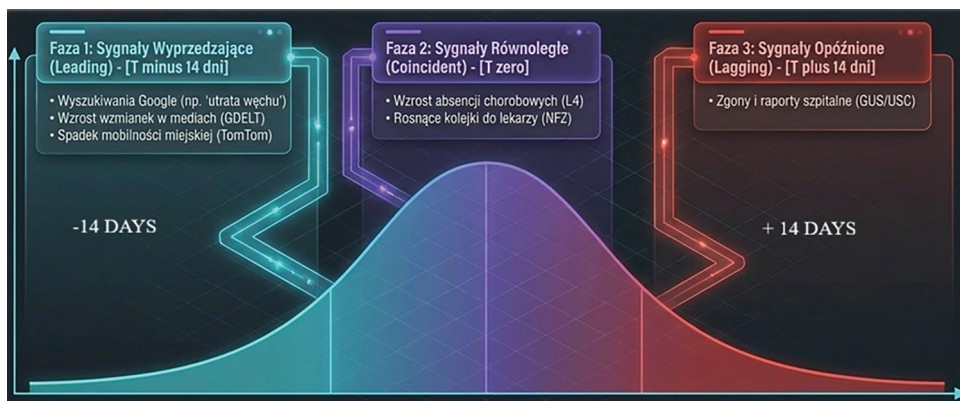
The system was designed in accordance with the requirements of:

- GDPR – no personal data (regional aggregation).
- AI Act – classification as a high-risk decision support system, meeting the requirements of interpretability, documentation, and auditability. The system is classified as 'High-Risk AI – Decision Support,' meeting the requirements of interpretability and documentation.
- KSC – humans always in the decision-making loop, no autonomous decisions. Data is stored in the GOV Cloud environment, with access and generated reports logged.



Source: Authors' own study

Fig 8. Network training visualization



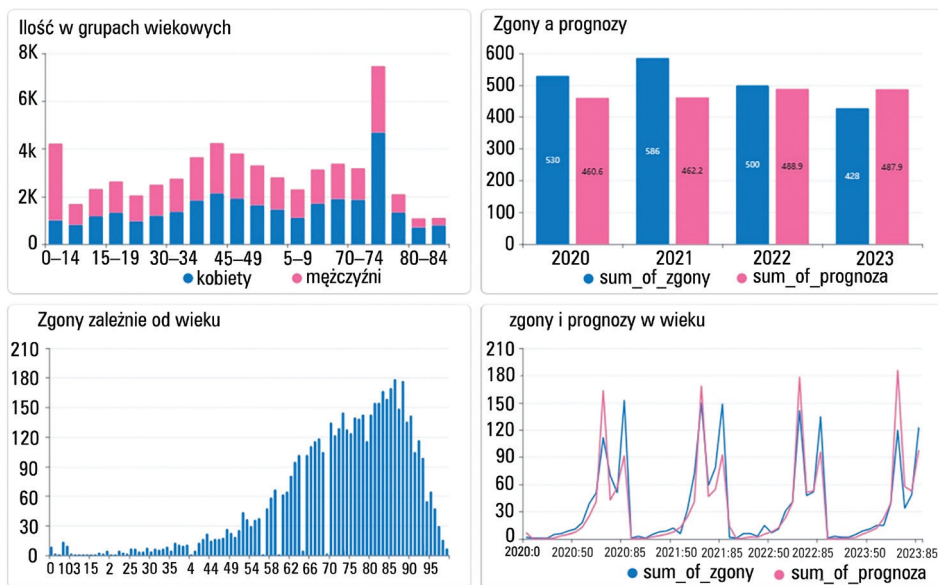
Source: Authors' own study

Fig. 9. PandemIQ system phases

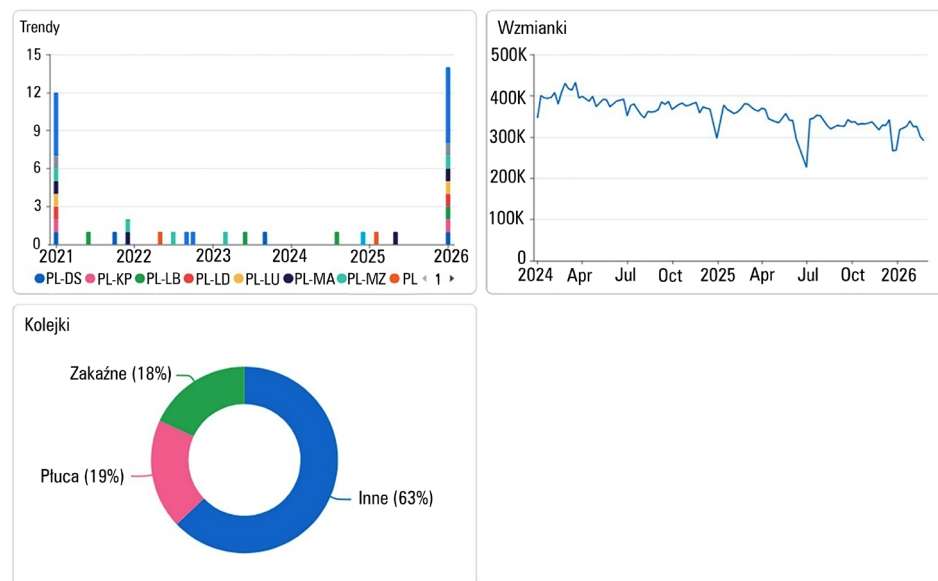
Data presentation in the PandemIQ system is very clear and intuitive. In the data presentation panel, you can select tabs. These include: population, trends and queues, environment, mobility, COVID-19, and correlation with China. All tabs, along with examples, are presented in Figure 10. In the population tab, you can use a chart to present the number of women and men by age group, the number of deaths and forecasts, age-specific mortality, and age-specific deaths and forecasts. In the trends and queues tab, you can display trends, queues, and mentions on a chart. In the environment tab, you can graph weather and pollution data. In the mobility tab, you can graph flights from Western Europe, Poland, and the US-East, as well as car traffic. The most interesting tab, according to the authors, is COVID-19, as it allows you to graph data on COVID-19 and the virus's impact on real estate prices. The final tab is correlation with China. Here we can present the correlation to selected diseases and the correlation of deaths to ECDC diseases using a graph.

DATA PRESENTATION

POPULATION TRENDS AND QUEUES ENVIRONMENT MOBILITY COVID-19 CORRELATION WITH CHINA



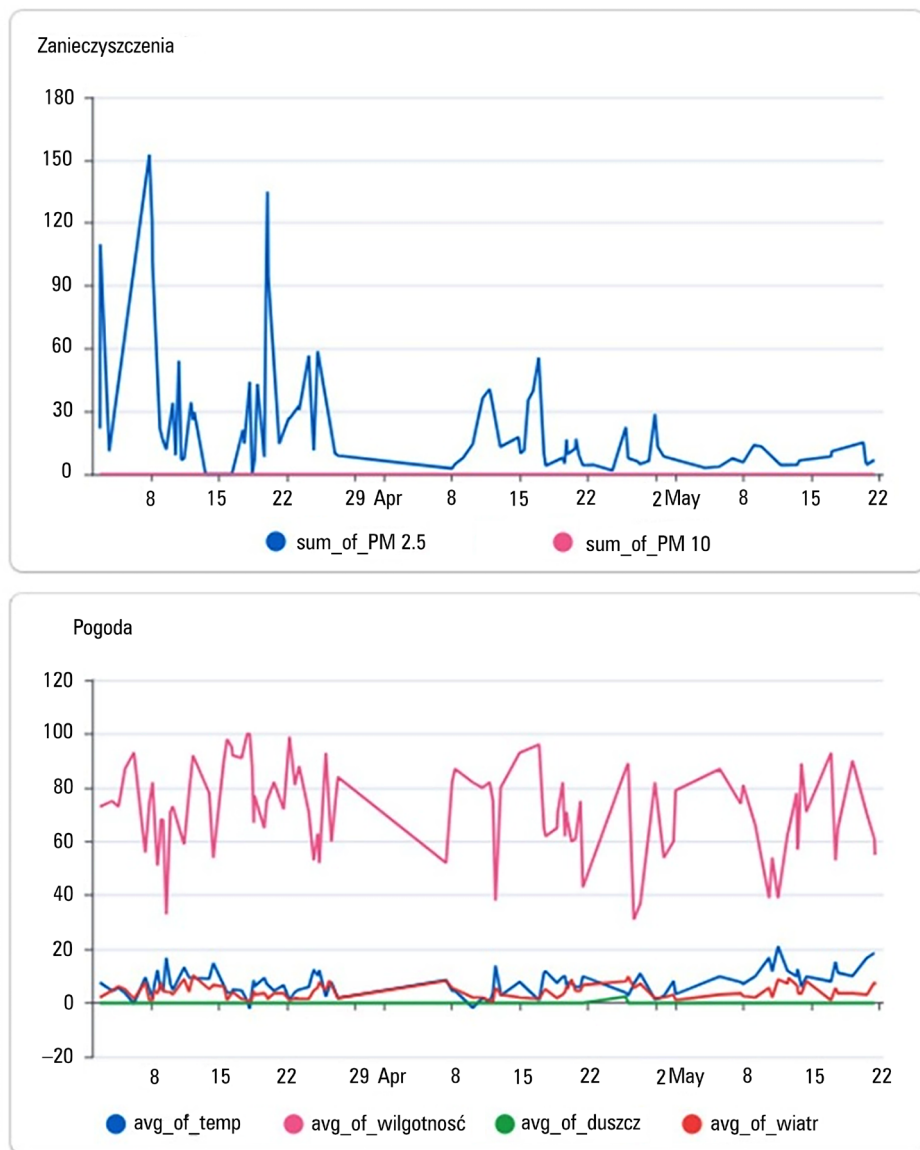
POPULATION TRENDS AND QUEUES ENVIRONMENT MOBILITY COVID-19 CORRELATION WITH CHINA



Source: Authors' own study

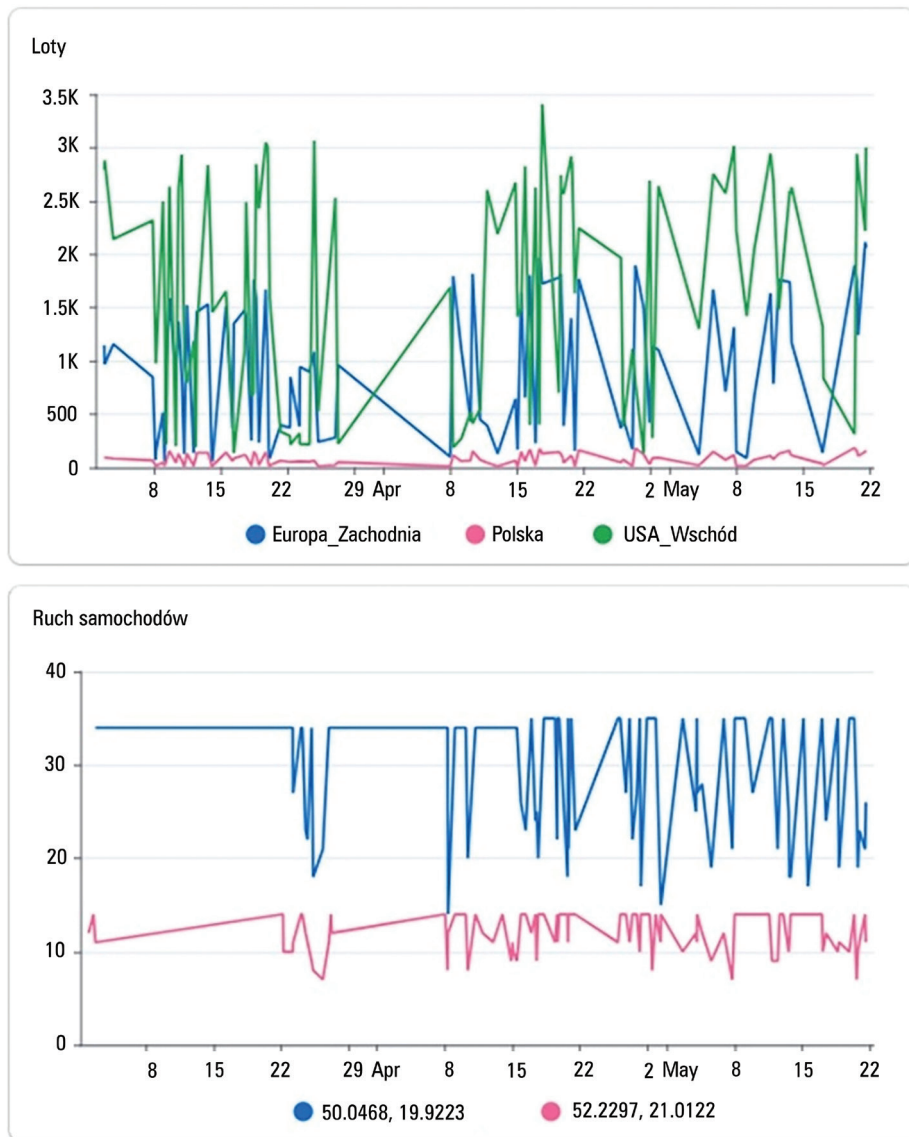
Fig. 10. Data presentation in the PandemIQ system

POPULATION TRENDS AND QUEUES ENVIRONMENT MOBILITY COVID-19 CORRELATION WITH CHINA



Source: Authors' own study

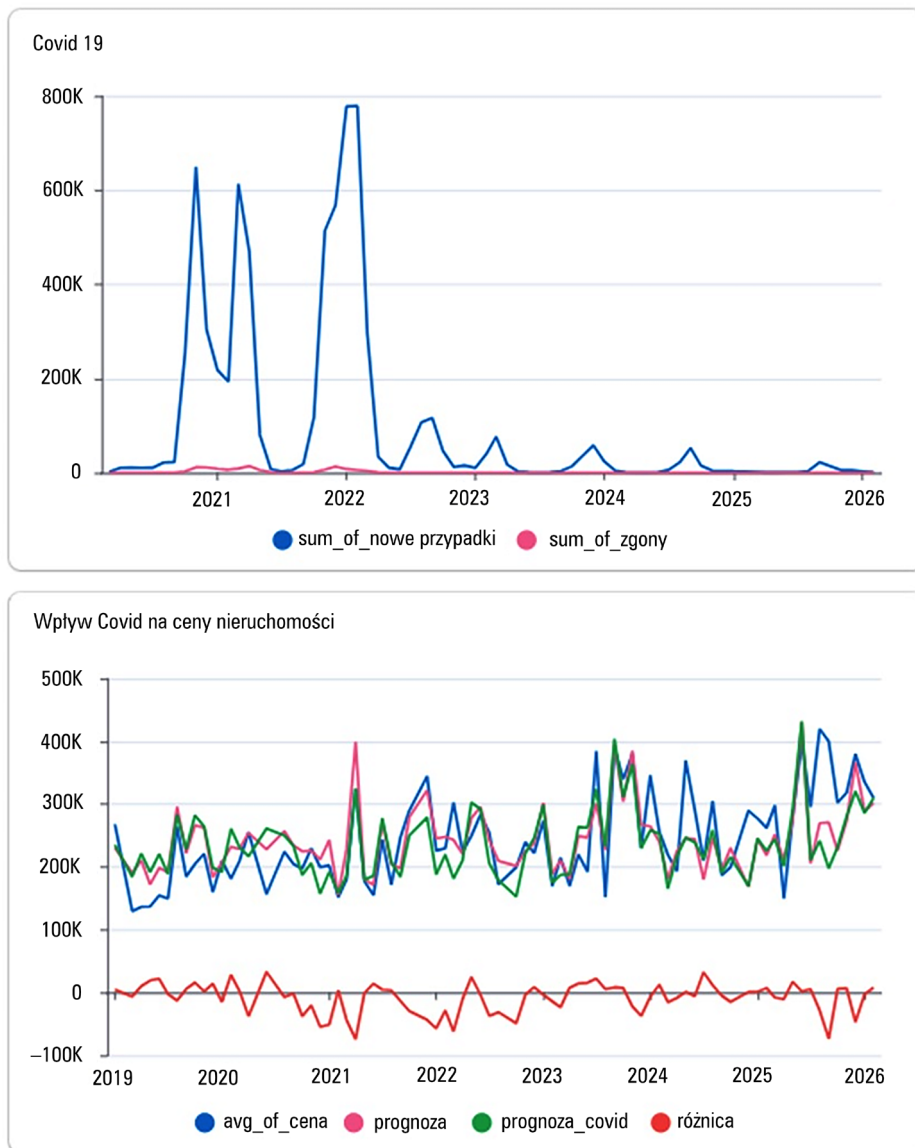
Fig. 10. cd. Data presentation in the PandemIQ system

POPULATION TRENDS AND QUEUES ENVIRONMENT MOBILITY COVID-19 CORRELATION WITH CHINA

Source: Authors' own study

Fig. 10. cd. Data presentation in the PandemIQ system

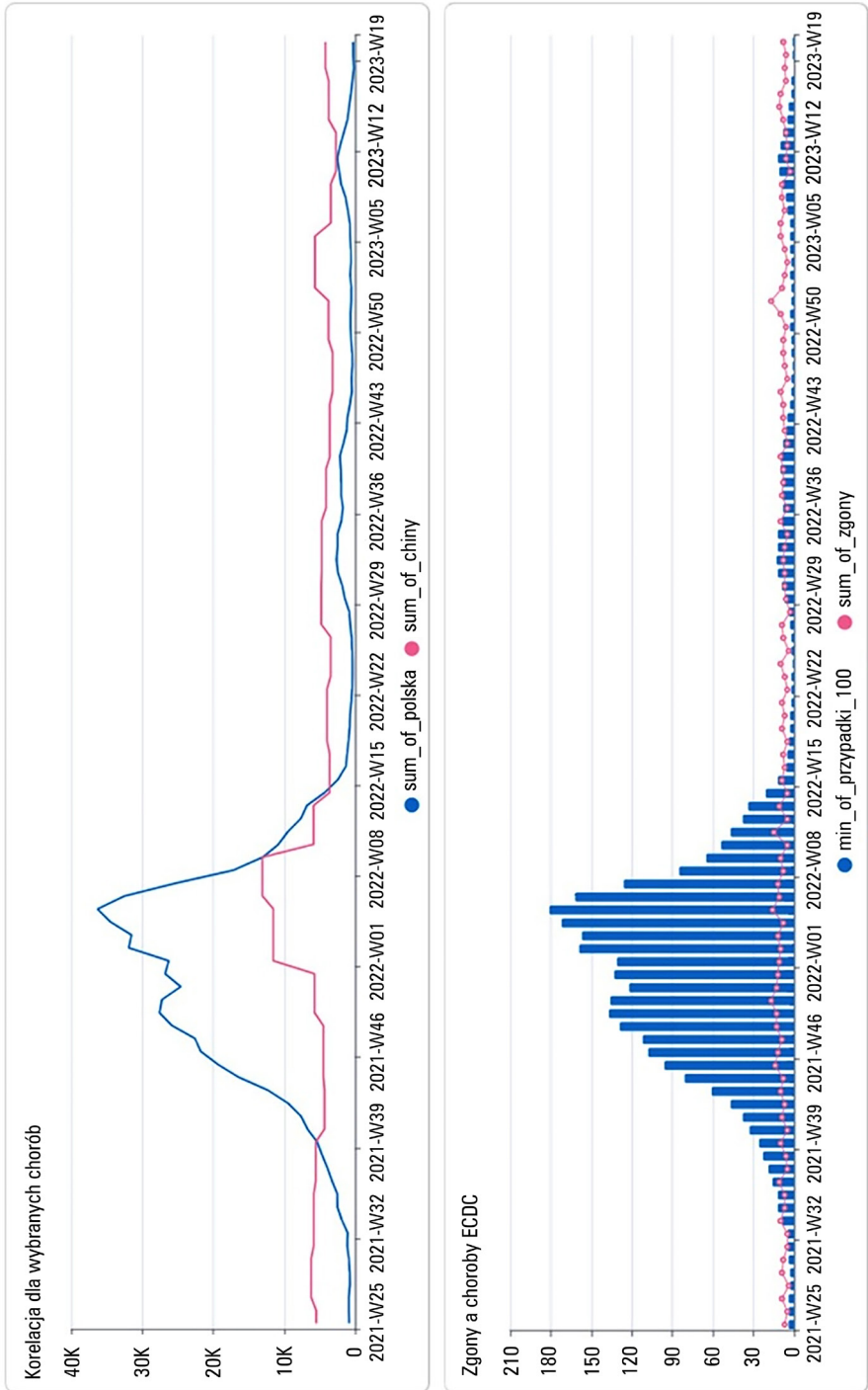
POPULATION TRENDS AND QUEUES ENVIRONMENT MOBILITY COVID-19 CORRELATION WITH CHINA



Source: Authors' own study

Fig. 10. cd. Data presentation in the PandemIQ system

POPULATION TRENDS AND QUEUES ENVIRONMENT MOBILITY COVID-19 CORRELATION WITH CHINA



Source: Authors' own study

Fig. 10. cd. Data presentation in the PandemiQ system

6. Conclusion

PandemIQ is an advanced forecasting system designed to monitor and predict pandemic developments. This tool provides decision-makers with interpretable and practical support for an early response to human health threats. By integrating modern artificial intelligence technologies and GIS mapping (ArcGIS), while ensuring full compliance with applicable legal regulations, the PandemIQ system can provide a comprehensive solution for national and global early warning and crisis management systems.

This scientific publication resulted from the project carried out under the grant programme for R&D works of scientific entities, Call IV, Competition No. 1/2024. Project title: Interactive pandemic early warning system supported by machine learning (AI). Grant agreement number N4_076- co-financed under the project 'Podkarpackie Center for Innovation 2029' implemented under the regional programme European Funds for Podkarpacie 2021–2027, priority: FEPK.01 Competitive and digital economy, measure: FEPK.01.01, Research and development, Type of project: Building the potential of innovation centers Podkarpackie Center for Innovation.

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