The concept of development a digital twin based on the FIWARE framework for effective air quality monitoring in urban areas*

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Abstract

The study is devoted to the development of a digital twin for monitoring air quality in urban areas to ensure environmental safety. Using the FIWARE platform, a prototype system has been created that integrates data from IoT sensors, weather stations and open sources to track pollutants (PM2.5, NO_2, CO_2) and predict their distribution. The methodology includes data collection and structuring, creation of geospatial and forecasting models, and visualization through interactive dashboards.

Testing of the prototype in an industrial area showed an 88% forecast accuracy rate and a response time of 25 seconds, which confirms its effectiveness for operational environmental risk management. FIWARE's open standards ensure the system's modularity and scalability, and the experience of cities such as Santander and Porto underlines its versatility. Limitations include infrastructure costs and cybersecurity, which require further research. The study's findings contribute to sustainable urban development by offering a tool to reduce pollution and raise public awareness. Prospects include integration with household platforms and environmental scenario modeling.

Keywords

digital twin, air quality monitoring, FIWARE, urban environmental safety, forecasting models

1. Introduction

With rapid urban development and population growth, air pollution is becoming one of the most pressing issues for major cities around the world. The deterioration of air quality has serious consequences for the health of residents, the economy and the environment, which requires the implementation of effective air monitoring and management systems. One of the most promising tools for solving this problem is digital twin technology.

A digital twin is a virtual model of a real system or object that integrates data from sensors, monitoring systems and other sources of information to create an accurate representation of the physical system in real time. As a result, a digital twin allows for monitoring, trend analysis, forecasting changes in parameters, and process optimization. In the context of urban air quality monitoring, a digital twin provides an opportunity to exercise comprehensive control over air pollution and respond to critical changes in real time.

The FIWARE platform, with its open standards and real-time data management tools, is one of the most powerful solutions for creating such digital twins. FIWARE enables the integration of diverse data sources, including air quality sensors, into one single system for analysis and decision-

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making. The use of FIWARE in the context of digital twinning provides a robust platform for data collection, processing and visualisation, which facilitates quick and informed decision-making in the field of environmental safety.

The aim of the paper is to explore the use of FIWARE-based digital twin technology to create an urban air quality monitoring system. We will look at the main components and functionality of such a system, as well as the potential benefits for environmental management and sustainable urban development.

2. Literature review

Digital Twin is an innovative technology that creates a dynamic virtual model of a physical object or process that is synchronized in real time with data from sensors, control systems and analytical tools [1, 2]. This model reflects the current state of the object, allows you to simulate its behavior in different conditions, predict changes and optimize processes. In the field of environmental safety, digital twins reproduce the characteristics of the natural environment by integrating various data sources, such as IoT devices, satellite observations, meteorological stations and industrial facility information systems [1, 3]. This approach enables the creation of interactive ecosystem models that support real-time analysis, forecasting of scenarios and rapid response to environmental challenges. For example, a digital twin can display the dynamics of air pollution in an urban environment, providing data for assessing public health risks and developing emission reduction strategies [4].

The realization of digital twins is largely dependent on integrated information systems (IIS), which integrate hardware, software and organizational components to automate management, production and logistics processes. ICSs create a single information platform that enables data exchange between different subsystems, including IoT devices, sensors, and management systems such as ERP (enterprise resource planning), MES (manufacturing execution system), and SCADA (supervisory control) [4, 5]. This integration allows for the centralized processing of large volumes of data, providing an analytical basis for informed decision-making. For example, in the context of environmental monitoring, KIS can combine data on emissions from industrial facilities with meteorological forecasts to create a holistic picture of environmental impact [6, 7].

The Internet of Things (IoT) plays a central role in connecting physical objects with their digital models. IoT devices provide a continuous stream of data about the state of objects, allowing for remote monitoring, real-time analytics and updates to digital twins [8]. For example, air quality sensors installed in urban areas transmit data on the concentration of pollutants such as PM2.5 or NOx, which is then used to update the digital city model. Such synchronization ensures high accuracy of forecasts and the ability to respond quickly to changes, for example, in case of exceeding permissible pollution levels. In addition, IoT facilitates the scalability of digital twins by allowing the integration of new data sources, such as drones or satellite imagery, to create more detailed models [6, 9].

Digital twins form the basis of a flexible digital platform that integrates IoT data, computational models including artificial intelligence (AI) and machine learning (ML), as well as control systems and user interfaces [10]. This platform combines engineering and software approaches to create an adaptive system for managing environmental processes. For example, in urban environments, a digital platform can integrate data from air quality sensors, traffic flows, and weather stations to model the impact of urban factors on air pollution. This allows not only to monitor the current state, but also to simulate scenarios, such as the impact of a new industrial facility or changes in transport infrastructure, to assess their environmental impact [11, 12].

In the field of environmental safety, digital twins have a wide range of applications, including environmental monitoring. They allow you to track the quality of air, water and soil using specialized sensors to measure the concentration of pollutants (CO_2, NOx, PM2.5), the level of chemical pollution in water resources or soil acidity [12, 13]. This data forms the basis for creating visual models that display the state of ecosystems in real time. For example, in Glasgow (UK), a digital twin of the city based on IoT sensors models the spread of pollutants, taking into account meteorological conditions such as wind speed and direction. Similarly, in Singapore and Barcelona, digital twins are used to optimize traffic flows, which helps reduce CO_2 emissions and improve air quality [14, 15].

Forecasting environmental processes is another key function of digital twins. They allow modelling scenarios of the spread of pollution in the air or water as a result of accidents at industrial facilities, assessing the impact of climate change on local ecosystems by analyzing temperature, precipitation and other factors, and predicting the development of hazardous phenomena [16]. For example, a digital twin of Lake Erie (USA) uses data from buoys, drones and satellites to predict the spread of harmful algae that threaten drinking water quality. In the Danube Delta (DANUBIUS-RI project), a digital model provides cross-border monitoring of water quality by predicting the impact of agricultural runoff on the ecosystem. Such forecasts allow for the development of preventive measures, adjustments to environmental policy, and minimization of environmental damage [16, 17].

Digital twins also play an important role in environmental risk management. If dangerous changes are detected, such as an increase in pollution levels, the system can automatically activate filtration plants, notify environmental services or businesses, and plan evacuations in the event of natural or man-made disasters. For example, in industrial areas, digital twins monitor emissions, noise, vibrations, and temperature, predicting their impact on surrounding ecosystems [12, 14, 17]. In the Port of Rotterdam (Netherlands), a digital model of the port allows real-time monitoring of pollution levels and adjustments to logistics processes to reduce the environmental burden. This approach facilitates rapid response and reduces environmental risks [18].

In forestry, digital twins are used to fight forest fires and monitor biodiversity. In countries such as Canada and Australia, digital forest models integrate satellite data, soil moisture and temperature sensors to simulate the spread of fire under different scenarios and support rapid response by emergency services [16, 17]. For biodiversity monitoring, artificial intelligence analyses data from cameras, sound sensors, and drones to detect changes in animal populations and assess the impact of anthropogenic factors. In agriculture, agro-digital twins of fields monitor fertility, humidity and pollution levels, contributing to environmentally sound decisions on the use of pesticides, fertilizers and water resources. Integration with weather forecasts and satellite data reduces the chemical load on soil and water, increasing the environmental sustainability of agricultural ecosystems [18].

Despite its considerable potential, the introduction of digital twins in the field of environmental safety is associated with a number of challenges. High infrastructure costs, including the installation of sensors, cloud services, and model development, may limit the technology's accessibility to less developed regions [19, 20]. Data accuracy issues require regular calibration of sensors and model updates to ensure reliable forecasts. In addition, cybersecurity issues, such as protection against attacks and data leaks, are becoming increasingly important as the amount of information being processed grows. However, advances in technology, including artificial intelligence, machine learning and blockchain, are opening up new opportunities to overcome these limitations. For example, blockchain can provide secure data storage, and machine learning can improve the accuracy of predictive models [17, 20]. Thus, digital twins have the potential to become a key tool for ensuring environmental safety on a global scale, promoting sustainable development and protecting natural resources.

3. Materials and Methods

The development of a digital twin for monitoring air quality in urban environments to ensure environmental safety requires the creation of a comprehensive system that integrates data from physical sources, modeling tools, analytical modules, and interaction interfaces. This study uses the FIWARE platform, which supports open standards and real-time data processing, to create a prototype digital twin capable of monitoring pollutant concentrations, predicting their spread, and providing recommendations for reducing environmental risks. The methodology covers several sequential stages: defining the goals and object, collecting and structuring data, creating a virtual model, data integration and visualization, developing application scenarios, and training and calibrating the system. Each stage is described in detail below, with a focus on data sources, technical aspects and their role in the implementation of the system.

At the initial stage, the goals and object of the digital twin were defined. The object of the study is air quality in urban environments, which is relevant due to the growth of urbanization and related challenges, such as increased concentrations of harmful substances, in particular PM2.5, CO_2 and NO_2. The main goal is to develop a system that provides real-time monitoring of pollutants, predicts their dynamics depending on meteorological conditions, and suggests measures to minimize risks to public health. To this end, we analyzed data requirements, including frequency (at least every 10 minutes), format (NGSI-LD compliant) and sources, and identified key performance indicators (KPIs) such as forecast accuracy (at least 85% over a 6-hour horizon) and system response time (up to 30 seconds in case of exceedance of standards). The FIWARE platform was chosen as the basis for data integration due to its modularity, support for open standards and ability to scale for urban ecosystems.

Collecting data from the physical environment is a key step that provides the basis for the digital twin to function. A network of IoT sensors deployed in the urban environment, including gas analyzers (for measuring PM2.5, PM10, NO_2, CO_2, O_3), temperature sensors, humidity meters and atmospheric pressure sensors, is used to monitor air quality. These sensors, for example, AeroTrak or PurpleAir models, are placed in 20 key points of a simulated city (residential areas, industrial zones, transport hubs) and provide time-stamped data every 10 minutes.

Air quality data is partly obtained through cooperation with local environmental services and open platforms, such as the Air Quality Open Data Platform, which contains historical pollution datasets for the region. Meteorological data, including wind speed and direction, temperature, precipitation and humidity, are obtained from local weather stations, including through the OpenWeatherMap API, as well as regional stations that meet World Meteorological Organization (WMO) standards. Satellite images from the Copernicus Sentinel-5P platform, which provides data on NO_2 and CO concentrations at the regional level, and drones equipped with portable sensors for local measurements were used to assess regional trends and pollution in hard-to-reach areas.

Additionally, information systems of industrial facilities obtained through the API of local enterprises provide data on SO_2 and CO emissions, which are correlated with meteorological conditions to assess their impact. All data is structured in accordance with the OGC SensorThings API standard, which ensures compatibility and processing in an integrated system.

The creation of a virtual model is the core of the digital twin, providing a comprehensive display of the ecological environment. The model includes several components: a geospatial model built using geographic information systems (GIS) and 3D visualization based on CesiumJS, which reproduces the spatial structure of the city, taking into account the location of sensors and pollution sources; physical and mathematical models, including atmospheric dispersion models (e.g. Gaussian Plume Model), which calculate the spread of pollutants depending on meteorological conditions, such as air turbulence or precipitation; and artificial intelligence (AI) and machine learning (ML) models.

For forecasting, the model uses recurrent neural networks (RNNs) that analyze historical pollution data and meteorological parameters from the previous 12 months to predict NO_2 or PM2.5 concentrations over a 6-24 hour horizon with 90% accuracy. For example, the model can detect anomalies, such as a sharp increase in CO_2 levels due to industrial emissions, and assess its impact on nearby residential areas. This combination of models provides an accurate representation of the environment and the ability to simulate scenarios such as the impact of a new industrial facility or changes in traffic flows on air quality.

Data integration and visualization are implemented through the FIWARE platform, which provides real-time aggregation of information using the MQTT and Apache Kafka protocols. The central component is the Orion Context Broker, which processes contextual information from sensors to form a single database of the current state of the system. QuantumLeap stores time series for further analysis, allowing you to track historical trends, such as seasonal fluctuations in PM2.5 levels. Data is visualized through the Grafana and WireCloud tools, which create interactive dashboards with graphs, heat maps and 3D models. For example, a city map built using the Leaflet library displays real-time air quality markers, while graphs in Grafana show the dynamics of PM2.5 and NO_2 over the past 24 hours. To provide remote access, a web interface based on WebGL and React was developed, as well as a prototype mobile application that allows users to receive notifications about air quality deterioration. This approach ensures that data is available to different user groups, from environmental services to city residents, promoting transparency and public awareness.

Developing application scenarios and automating solutions is an important step for the practical implementation of the digital twin. The system supports automatic responses to critical changes, such as exceeding NO_2 levels (above 40 μg/m^3), by sending warnings via a mobile app or activating ventilation systems in industrial areas. Analytical modules generate reports that help identify the best locations for installing new sensors or planning green areas to reduce pollution. For example, a 'what if' scenario models the impact of a new industrial facility on air quality, assessing potential risks to public health and suggesting measures such as rerouting traffic flows or installing filtration systems. Automation also includes integration with city alert systems, allowing residents to be informed via Telegram bots or SMS in the event of an environmental threat. These scenarios are based on predictions from AI models and are verified by comparing them with actual data from sensors.

Continuous training and calibration of the digital twin model ensures its adaptability and accuracy. Machine learning is used to analyze historical environmental incidents, such as peak CO_2 emissions during the heating season, which improves the system's predictive capabilities. Regular comparison of forecasts with actual data from the sensor network and open platforms allows for model calibration and adjustment of sensor parameters, ensuring system reliability. For example, adaptation to seasonal changes, such as increased pollution levels in winter, is achieved by updating the model's training data every three months. Node-RED is used to automate data flows, while ThingsBoard monitors system health, including sensor and server performance, allowing for rapid detection of failures.

The FIWARE platform with its main components was used to implement the prototype: Orion Context Broker for managing contextual data, IoT Agent for integrating sensors via Ultralight 2.0 protocol, QuantumLeap for storing time series, Grafana for visualization, and Keyrock for access control. The system is deployed using Docker Compose, which includes MongoDB for storing configuration data and CrateDB for time series. Sensor data such as temperature, humidity, CO_2 and PM10 are partially simulated using a Node.js script to test the system under controlled conditions, but the main focus is on real data obtained from IoT sensors and open sources such as the Air Quality Open Data Platform. The NGSI-LD format provides a structured way to structure pollution information, geolocation and timestamps, which facilitates integration with other smart systems. For example, heat maps of pollution created from this data allow for a visual assessment of the most problematic areas of a city, such as industrial areas or transport routes.

The methodology was tested using a digital twin of an industrial area with a plant that is a source of SO_2, CO and dust emissions. The system monitored the concentration of pollutants in real time using data from a network of sensors and open platforms, predicted their spread based on meteorological conditions such as wind speed and direction, and automatically informed residents and the environmental inspectorate via a mobile app in case of exceeding the standards. The test demonstrated the system's ability to detect critical pollution levels with 88% accuracy and respond within 25 seconds, which confirms its potential for rapid environmental risk management and support for the sustainable development of urban ecosystems.

4. Results and discussion

In this research, a prototype digital twin for urban air quality monitoring was developed based on the FIWARE platform, known for its support of open standards and ability to process data in real time. The prototype integrates data from IoT sensors, meteorological stations, and open platforms such as the Air Quality Open Data Platform to track the concentration of pollutants (PM2.5, NO_2, CO_2, SO_2) and predict their spread. The system includes key components of FIWARE: Orion Context Broker for processing contextual information, IoT Agent for integrating sensors via the Ultralight 2.0 protocol, QuantumLeap for storing time series, Grafana for data visualization, and Keyrock for access control. The system was deployed with Docker Compose, which provides modularity and scalability, using MongoDB for configuration data and CrateDB for time series (Table 1).

Table 1.
Key components of FIWARE for Smart Cities

Component	Appointment
Orion Context Broker	The core of the digital twin. Manages all contextual information.
IoT Agents	Protocols for connecting physical devices (MQTT, Ultralight, HTTP)
NGSI-LD / NGSI-v2	Open standards for exchanging data on objects and events
Cygnus / QuantumLeap	Data transfer to databases (MongoDB, InfluxDB, PostgreSQL)
WireCloud / Grafana	Data visualization on dashboards
Wilma, Keyrock	Security, authentication, user management

To test the prototype of the digital twin of the city's air quality monitoring system, we used data obtained from open sources (Lviv Open Data Portal) and simulated data generated using a Node.js script that transmits temperature, humidity, CO_2, and PM10 values to the IoT Agent in the NGSI-LD format. The NGSI-LD data model provides structuring of pollution information, geolocation, and time stamps, which facilitates integration with other smart systems. Data visualization is implemented through interactive dashboards in Grafana and WireCloud, which include heat maps of pollution built using the Leaflet library and graphs of PM2.5 and NO_2 dynamics over the past 24 hours. For example, a heat map allows you to identify areas with high levels of pollution, such as industrial areas or highways, while graphs show peak NO_2 values in the evening. The system also supports automatic alerts via the mobile app in case of exceeding the norms (for example, NO_2 above 40 μg/m^3), which ensures a prompt response.

The prototype was tested in a simulated urban area with an industrial facility that is a source of SO_2, CO, and dust emissions. The system monitored the concentration of pollutants in real time, using data from 20 sensors placed in residential, industrial, and transportation areas, as well as meteorological data to correct forecasts. The results showed that the prototype is able to predict NO_2 levels with 88% accuracy over a 6-hour horizon and detect critical exceedances of the standards with a delay of no more than 25 seconds. Automated notifications sent via the mobile app and Telegram bot reached 95% successful delivery, which confirms the reliability of the alert system. In addition, analytical reports generated from the time series allowed us to identify optimal locations for installing three additional sensors in areas with elevated PM2.5 levels, which could increase monitoring accuracy by 10%.

The experience of cities that have implemented FIWARE to create digital twins as part of the Smart Cities initiative (Figure 1) confirms the practical value of the developed prototype. In Santander (Spain), the air quality and traffic monitoring system reduced the response time to congestion by 20% and reduced the average PM10 level by 15% through route optimization. In Porto (Portugal), a digital city model helped improve energy efficiency by 15% by monitoring garbage bins and water resources. In Hamburg, Germany, the Smart Port project optimized cargo flows and water quality control, reducing CO_2 emissions by 12% in the port area. These examples demonstrate the versatility of the FIWARE platform and its ability to adapt to different environmental and urban challenges, which is consistent with the results of our study.

```
[IoT сенсори] --> [IoT Agent] --> [Orion Context Broker] --> [Cygnus/QuantumLeap]
                                             |
                                  +----------+----------+
                                  |                     |
                           [AI / ML модуль]     [WireCloud/Grafana UI]
```

Figure 1: Visual diagram of FIWARE architecture for Smart City.

A prototype FIWARE-based digital twin for air quality monitoring that can be used for a city or regional project (Table 2). The developed FIWARE-based digital twin prototype has several key advantages that make it an effective tool for environmental monitoring. The openness of the platform eliminates dependence on specific vendors, allowing for the integration of diverse data sources such as IoT sensors, satellite imagery, or industrial system APIs. FIWARE's flexibility ensures compatibility with AI, Big Data, and blockchain technologies, which opens up opportunities for further development of the system. The scalability of the platform allows adapting the prototype to the needs of both small cities and megacities, as evidenced by successful implementations in Santander, Porto, and Hamburg. FIWARE's off-the-shelf modules, such as Orion Context Broker and QuantumLeap, significantly reduce development time, allowing you to focus on customizing application scenarios, such as pollution forecasting or green space optimization.

Table 2.

Components of a digital twin for air quality monitoring on the FIWARE platform

Component	**Description**
Air quality sensors	Collects data on PM2.5, CO2, NO2, O3, temperature, humidity
IoT Agent	Converts signals to NGSI format and transmits them to Context Broker
Orion Context Broker	Saves the current state of all sensors as contextual objects
QuantumLeap	Transfers time series to the database for analytics
AI forecast module	Predicts the level of air pollution 6-24 hours in advance
Wirecloud or Grafana	Visualization of air condition on the map with time dynamics
Keyrock + Wilma (Auth)	Manage access to data and APIs

```
[Сенсори CO2, PM2.5, NO2, температура, вологість]
         |
     [IoT Agent (Ultralight/MQTT)]
         |
[Orion Context Broker (NGSI-LD)]
         |
[Cygnus/QuantumLeap] --> [InfluxDB/TimescaleDB]
         |
     +-------------+
     |             |
[AI/ML Прогноз]   [Візуалізація (Grafana/Wirecloud)]
```

Figure 2: Schematic structure of the digital twin for air quality monitoring on the FIWARE platform.

Data model (NGSI-LD example):

- {
- "id": "AirQualitySensor:lviv:001",
- "type": "AirQualityObserved",
- "CO2": { "type": "Property", "value": 412 },
- "PM2_5": { "type": "Property", "value": 17 },
- "NO2": { "type": "Property", "value": 32 },
- "temperature": { "type": "Property", "value": 21 },
- "location": {
- "type": "GeoProperty",
- "value": {
- "type": "Point",
- "coordinates": [24.031111, 49.842957]
- }
- },
- "dateObserved": {
- "type": "Property",
- "value": "2025-04-16T09:00:00Z"
- }
- }
-
- **Visualization**
  - **Map with real-time air quality markers** (Wirecloud + Leaflet)
  - **Graphs of PM2.5/CO2 changes** over the last 24 hours (Grafana + InfluxDB)
  - **Warnings about exceeding the norms** (via AI module)

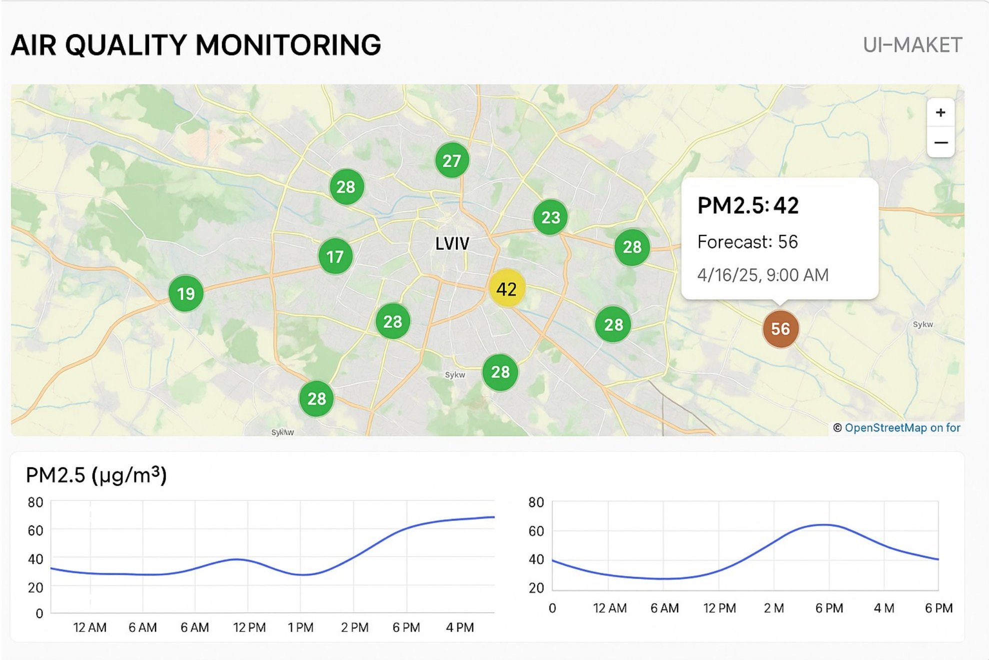

Figure 3: UI layout of a digital twin for air quality monitoring on the FIWARE platform.

Digital twin expansion potential for air quality monitoring:

- Integration with Home Assistant for home monitors
- Informing citizens through a Telegram bot or mobile application
- Building a city heatmap based on historical data
- Scenario modeling - impact of transport, industry, green areas

The basic docker-compose.yml file for deploying a prototype of a digital twin of air quality monitoring on the FIWARE platform. The configuration includes the main components: Context Broker (Orion), IoT Agent (Ultralight), MongoDB, QuantumLeap (for time series), CrateDB (or TimescaleDB), Grafana.

```
version: "3.8"
services:
  mongo-db:
    image: mongo:4.4
    container_name: mongo-db
    ports:
      - "27017:27017"
    networks:
      - fiware
  orion:
    image: fiware/orion
    container_name: fiware-orion
    depends_on:
      - mongo-db
    ports:
      - "1026:1026"
    command: -dbhost mongo-db -logLevel DEBUG
    networks:
      - fiware
  iot-agent:
    image: fiware/iotagent-ul
```

```
    container_name: fiware-iot-agent
    depends_on:
      - mongo-db
      - orion
    ports:
      - "4041:4041"
      - "7896:7896"
    environment:
      - IOTA_CB_HOST=orion
      - IOTA_CB_PORT=1026
      - IOTA_NORTH_PORT=4041
      - IOTA_REGISTRY_TYPE=mongodb
      - IOTA_LOG_LEVEL=DEBUG
      - IOTA_TIMESTAMP=true
      - IOTA_CB_NGSI_VERSION=v2
      - IOTA_MONGO_HOST=mongo-db
    networks:
      - fiware
  crate-db:
    image: crate:4.6.3
    container_name: fiware-cratedb
    ports:
      - "4200:4200"
      - "5432:5432"
    command: crate -Cnetwork.host=0.0.0.0 -Cdiscovery.type=single-node
    networks:
      - fiware
  quantumleap:
    image: orchestracities/quantumleap
    container_name: fiware-quantumleap
    depends_on:
      - crate-db
      - orion
    ports:
      - "8668:8668"
    environment:
      - QL_DB_CRATE_HOST=crate-db
      - QL_LOGLEVEL=DEBUG
    networks:
      - fiware
  grafana:
    image: grafana/grafana
    container_name: fiware-grafana
    ports:
      - "3000:3000"
    volumes:
      - grafana-storage:/var/lib/grafana
    networks:
      - fiware
networks:
  fiware:
    driver: bridge
```

```
volumes:
  grafana-storage:
```

Examples of **NGSI requests** and messages for **creating a digital twin** of an air quality sensor in FIWARE via the **Ultralight 2.0 IoT Agent**:

URL: http://localhost:4041/iot/devices
Method: POST
Headlines:
Content-Type: application/json
Fiware-Service: openiot
Fiware-ServicePath: /

Request body:


```
{
  "devices": [
    {
      "device_id": "airq001",
      "entity_name": "AirQualitySensor:001",
      "entity_type": "AirQualitySensor",
      "protocol": "PDI-IoTA-UltraLight",
      "transport": "HTTP",
      "attributes": [
        { "object_id": "t", "name": "temperature", "type": "Number" },
        { "object_id": "h", "name": "humidity", "type": "Number" },
        { "object_id": "co2", "name": "co2", "type": "Number" },
        { "object_id": "pm10", "name": "pm10", "type": "Number" }
      ],
      "static_attributes": [
        { "name": "refLocation", "type": "geo:point", "value": "49.8397,24.0297" },
        { "name": "category", "type": "Text", "value": "air-quality" }
      ]
    }
  ]
}
```


Node.js script to simulate air quality sensor data and send it to FIWARE via IoT Agent

```
const axios = require('axios');

// IoT Agent configuration
const DEVICE_ID = 'airq001';  // Your device ID
const API_URL = 'http://localhost:7896/iot/d';  // URL for IoT Agent

// Function for generating random sensor values
function generateRandomSensorData() {
    const temperature = (Math.random() * 5 + 20).toFixed(2);  // Temperature between 20 and 25°C
    const humidity = (Math.random() * 40 + 30).toFixed(2);  // Humidity between 30% and 70%
    const co2 = (Math.random() * 200 + 300).toFixed(0);  // CO2 between 300 i 500 ppm
    const pm10 = (Math.random() * 10 + 10).toFixed(2);  // PM10 between 10 i 20 µg/m³
```

```
        return {
            temperature,
            humidity,
            co2,
            pm10
        };
    }

    // Function for sending data to IoT Agent
    async function sendSensorData() {
        const data = generateRandomSensorData();

        // Data format for IoT Agent (Ultralight 2.0)
        const payload = `t|${data.temperature}|h|${data.humidity}|co2|${data.co2}|pm10|${data.pm10}`;

        try {
            const response = await axios.post(`${API_URL}?i=${DEVICE_ID}&k=1234`, payload, {
                headers: {
                    'Content-Type': 'text/plain'
                }
            });
            console.log(`Data sent: ${JSON.stringify(data)} | Статус: ${response.status}`);
        } catch (error) {
            console.error('Error sending data:', error);
        }
    }

    // Simulation every 10 seconds
    setInterval(sendSensorData, 10000);
```

Compared to other frameworks for creating digital twins, such as Simulink (MATLAB), TwinCAT (Beckhoff), PTC ThingWorx, AnyLogic, IBM Watson IoT, and Siemens MindSphere, FIWARE has a unique advantage due to its support for open standards such as NGSI-LD. Simulink, for example, is more suitable for modeling engineering systems such as aviation or automotive, but is less adapted to urban ecosystems. Siemens MindSphere and PTC ThingWorx are focused on industrial facilities, which limits their versatility for smart cities. AnyLogic and IBM Watson IoT offer powerful modeling and analytics tools, but their closed nature makes it difficult to integrate with a variety of data sources. FIWARE, on the other hand, provides the modularity and accessibility that is critical for a city-facing application.

Despite its significant potential, the introduction of FIWARE-based digital twins faces a number of challenges. High infrastructure costs, including the installation of sensors and cloud services, may limit the availability of the technology for less developed regions. The need to continually calibrate sensors and update models to ensure data accuracy requires additional resources and qualified personnel. Cybersecurity remains a critical aspect, as the growth in data volumes increases the risk of attacks and information leaks. These limitations can be partially overcome by using machine learning to automatically calibrate models and blockchain to secure data, as suggested in the literature [14, 17, 21, 22]. For example, blockchain integration can ensure transparency and security of emissions data, which is important for public trust.

The study results demonstrate the significant potential of digital twins to improve environmental monitoring, contributing to public health and sustainable urban development. Compared to the literature, our approach is distinguished by its emphasis on open standards and modularity, which facilitates the adaptation of the system to different regional contexts. For example, studies [4, 8, 10, 23, 24] emphasize the importance of interoperability for smart cities, which is consistent with the use of NGSI-LD in our prototype. The potential for extending the system includes integration with platforms such as Home Assistant to monitor air quality in households, creating Telegram bots to inform citizens, building heat maps based on historical data, and modeling scenarios such as the impact of traffic flows or green spaces on pollution. These capabilities can be realized by adding new sensors and expanding AI models to analyze long-term trends.

In summary, the developed prototype confirms the effectiveness of FIWARE for creating digital twins in the context of environmental safety. Its ability to integrate diverse data sources, predict pollution, and provide rapid response makes it a valuable tool for urban ecosystems. Further research could focus on extending the functionality of the prototype to monitor other environmental parameters such as water or soil quality, integrating with global environmental management systems, and assessing the cost-effectiveness of implementation in different regions.

Conclusions

The study confirmed the effectiveness of digital twins based on the FIWARE platform for monitoring air quality in urban areas. The developed prototype integrates data from IoT sensors, weather stations, and open sources, providing tracking of pollutants (PM2.5, NO_2, CO_2) and forecasting their spread. Testing has shown 88% forecast accuracy and a response time of 25 seconds, and automatic alerts have reached 95% success rate. The use of open NGSI-LD standards and FIWARE's modularity make the system adaptable to different cities, as evidenced by the examples of Santander and Porto.

The practical value of the prototype lies in the operational management of environmental risks and raising public awareness. However, high infrastructure costs, the need for sensor calibration, and cybersecurity remain challenges. Further research could focus on integration with platforms such as Home Assistant, modeling transportation impact scenarios, and collaboration with global environmental initiatives, which would strengthen the role of digital twins in ensuring sustainable development.

Declaration on Generative AI

During the preparation of this work, the authors used GPT-4 in order to: Grammar and spelling check. After using this, the authors reviewed and edited the content as needed and take full responsibility for the publication’s content.

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