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ANALYSIS OF TECHNICAL AND TECHNOLOGICAL SOLUTIONS TO SUPPORT ENVIRONMENTAL MANAGEMENT IN A SMART CITY

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Purpose: The aim of the article is to analyze the trends of contemporary city management and environmental management in the city. The article analyzes the technical and technological tools that can support environmental management in the city against the background of problems related to atmospheric air pollution. Tools for improving social communication in order to increase the comfort of life of city residents were also analyzed. The world literature searched for solutions that could be implemented to the conditions prevailing in Poland, where many urban agglomerations have a carpet structure. In the carpet structure, cities are located close to industrial areas, which significantly affect air pollution in inhabited areas.
Design/methodology/approach: The article analyzes world literature on trends in urban environment management and reports on new technical and technological solutions that support environmental management in the city, especially in the context of polluted air. Foreign solutions were analyzed in search of new solutions to the problems of polluted air in the country (in Poland).
Findings: The article presents technical solutions described in the world literature in the field of monitoring the natural environment and improving communication between city authorities and residents in order to improve their quality of life. Then, an analysis of the possibilities of using new technical solutions supporting the management of the natural environment in the city in Polish conditions was made.
Originality/value: As a result of the analyses, examples of technical solutions were found that could support the management of the natural environment in the city, taking into account the specificity of cities located in the center of agglomerations, which is typical of most Polish cities. Tools were also indicated that could improve communication between city authorities and residents in order to improve their quality of life in the city.
Keywords: environmental management, smart city, urban environment monitoring, air monitoring, ICT solutions.
Category of the paper: literature analysis, review article.

1. Introduction

Globalization, urbanization and the introduction of modern technologies into everyday life, as well as maintaining care for existing resources, mean that the development of urban areas depends on new factors. These include advanced technologies, territorial capital, and tangible and intangible resources that determine the functioning of a given area (Stawasz, Sikora-Fernandez, 2016). This means the need for a comprehensive, integrated approach to city management, based on the existing economic, social, spatial-environmental and institutional potential, with the participation of advanced information and communication technologies (Avveduto et al., 2017, Bacco et al., 2017, Dutta et al., 2017, Szafraniec, 2017).

The above-mentioned activities occur in the process of creating smart cities. World rankings of developed cities are being created, taking into account various criteria, such as: human capital, social cohesion, economy, environment, management, urban planning, internationalization, transport and mobility (Jonek-Kowalska, Wolniak, 2019). The list of the prestigious Forbes magazine, published in 2018, includes the world's largest metropolises as examples of smart cities and assessed according to the above-mentioned criteria. The world leaders include: New York, London, Paris, Tokyo, Reykjavik, Singapore, Seoul, Toronto, Hong Kong and Amsterdam (https://www.forbes.com/…). In Poland, smart cities include: Warsaw, Wrocław, Opole, Gdańsk, Rzeszów, Katowice, Kraków and others, which are large agglomerations or regional capitals (Sikora-Fernandez, 2018). Currently, the very large role of cities in the social and economic functioning of economies means that they have a huge impact on the lives of residents and the natural environment (Jonek-Kowalska, 2018, Pichlak, 2018). Due to the continuous increase in the number of residents of large cities at the expense of rural regions, it is necessary to provide city residents with safety and comfort of life.

In 2014, the International Organization for Standardization published the ISO 37120 standard as a tool for measuring the quality of life of city residents. Thanks to the standard (PN-ISO 37120, 2015), it is possible to provide a uniform method for assessing the functioning of cities, their involvement in the services provided to residents (Fijałkowska, Aldea 2017, Komsta, 2016; Midor, Płaza, 2020). The standard defines 100 indicators along with the adopted methodology for calculating them, which can be used by cities of different sizes to measure and control the level of their development from the social, economic and environmental point of view (Wolniak, 2019). The indicators are grouped into 17 thematic areas concerning aspects of the city's functioning. The following areas were distinguished (PN-ISO 37120:2015): economy, education, energy, environment, finance, crisis management, local government bodies, recreation, safety, solid waste, telecommunications, innovations, transport, urban planning, sewage management, water and sewage management. In order to use the standard in cities to report a different range of data, five levels of certification were defined in the standard, which depend on how many of the listed indicators are subject to monitoring in a given city (Wolniak, 2019).

The subject matter discussed in the article is becoming an increasingly important problem in the face of the effects of civilization development, which often leads to the degradation of the natural environment (including that in densely populated urban areas) and causes increasing traffic. The development of technology for sustainable urban development is a necessity to improve the comfort of life of its inhabitants. The article attempts to analyze available technical and technological solutions that could support city management and improve the quality of life of their inhabitants.

2. The level of intelligence in cities and the management of the natural environment of cities

Various sets of principles for creating smart cities can be found in the literature on the subject (Albino et al., 2015; Kaźmierczak, 2019). The most concise principles are presented in (http://www.masabi.com/…), where four rules for creating a smart urban space for a city treated as an entity are proposed. The recommendations are as follows:

- Smart cities should be experience-oriented – citizens receive the necessary experience or service in the urban space.
- Smart cities should be oriented towards necessary practical solutions – the city uses knowledge from the past and applies technology adequate to solve specific problems.
- Smart cities should function on the basis of full digitization of all services, especially infrastructure – optimizing services takes into account digitally excluded people.
- Smart city services and infrastructure are seamlessly connected – city infrastructure and service providers share data with residents via mobile access and use good external practices.

The concept of smart city development also distinguishes three different levels of urban space intelligence development (www.smartcitieslibrary.com/…). At each level (1.0, 2.0, 3.0) of urban intelligence development, the composition of stakeholders is the same and includes: technology providers, city managers – city administration and city residents. However, at different levels of advancement of the intelligence of urban space, a different leader emerges (Kaźmierczak, 2019).

At the Smart City 1.0 level, the role of the project leader falls to a company from the ICT sector, which offers a specific technical and technological solution to be implemented in the smart city space. For this reason, the 1.0 level of city intelligence is referred to as technology-driven. On the other hand, at the Smart City 2.0 level, ICT companies provide technical or technological solutions according to the requirements (expectations) of the administrators of the urban space, who play the role of a leader and shape the vision of the future of the smart city. This level is called the Technology Enabled project. Finally, at the Smart City 3.0 level, a project called Citizen co-creation appears, in which the role of an equal partner for the city authorities in creating the smart city space is played by its residents (Rożałowska, 2016; Ignac-Nowicka et al., 2019, www.smartcitieslibrary.com/…).

In the pursuit of creating a friendly city, one of the most important factors is taking into account the needs of its residents and their opinions on the quality of life in the city (Ignac-Nowicka, 2020, 2024), as well as strengthening social activities, which leads to building social capital, especially in the case of projects at the Smart City 3.0 level (Stawasz, Sikora-Fernandez, 2016, Ignac-Nowicka, 2018a, 2019). A friendly (clean) natural environment in the city is one of the most important and basic needs of its residents. Proper management of the natural environment seems to be a basic action in the sustainable development of the city.

3. Directions of development of natural environment management in a smart city

Monitoring the environment in smart cities is a key element of sustainable urban management. It involves using modern technologies to constantly monitor the quality of air, water, soil and other parameters that affect the health of residents and the condition of the urban ecosystem. In detail, it can be said that environmental management in the context of a smart city covers the following areas (Buczaj, Michalak, 2018, Ignac-Nowicka et al., 2020, Prawelska-Skrzypek, Blecharczyk, 2022; Bacco et al., 2022):

- Waste management - the use of advanced technologies to monitor and optimize the collection and processing of municipal waste.
- Green infrastructure - creating gardens on the roofs of buildings (green roofs), creating living wall installations and developing urban agriculture (urban farming) to improve air quality and microclimate.
- Environmental monitoring - implementation of systems monitoring air, water and soil pollution, which allows for ongoing response to ecological threats.
- Energy efficiency - the use of intelligent energy management systems in buildings and urban infrastructure to reduce energy consumption and greenhouse gas emissions.
- Water resources management - implementation of technologies to monitor and optimize water consumption and rainwater retention and recycling systems.
- Urban mobility - promoting ecological means of transport, such as city bikes or electric vehicles, and the development of intelligent traffic management systems.

In smart cities, waste management is based on the use of modern technologies, such as the Internet of Things (IoT), IT systems and data analytics, to optimize the processes of waste collection, segregation and disposal. The aim of these activities is to minimize the negative impact on the environment and increase operational efficiency. Examples of solutions include (Bondar et al., 2023):

- Smart waste containers - equipped with sensors monitoring the fill level, which allows for the optimization of collection routes and reduction of transport costs.
- Waste identification systems - RFID technologies enable tracking and identification of waste, which supports recycling and disposal processes.
- Analytical platforms - analysis of data collected from various sources allows for forecasting the amount of waste generated and planning preventive measures.

Green infrastructure in smart cities is a system of interconnected green areas, such as parks, gardens, green roofs and walls, which integrate natural elements with urban infrastructure. The aim of their creation is to improve the quality of life of residents, increase biodiversity and adapt to climate change. Examples of solutions in this area include the creation of (Szymańska, 2023):

- Green roofs and walls, which reduce the urban heat island effect, improve building insulation and increase the biologically active surface.
- Pocket parks, i.e. small green areas in densely built-up urban areas, which provide places for recreation and improve the microclimate.
- Rainwater retention systems by using green spaces to collect and filter rainwater, which reduces the risk of flooding and relieves the sewage system.

Monitoring the environment in a smart city involves the continuous collection and analysis of data on the quality of air, water, soil and noise levels. Sensor networks, drones and satellite technologies are used for this purpose, which allows for a quick response to ecological threats and making data-based decisions. An example is the creation of a network of air quality sensors that monitor pollutant concentrations and provide information to city residents about the current state of the air. Another example is the use of noise monitoring systems, which allows for the identification of sources of excessive noise and support the planning of reduction measures. In turn, the analysis of satellite data allows for the assessment of changes in land cover, the identification of illegal landfills or monitoring the health of urban vegetation (Bacco et al., 2022).

Energy efficiency is also very important in smart cities, which refers to the optimization of energy consumption in buildings, transport and urban infrastructure through the use of modern technologies and intelligent management systems. The aim of such efforts is to reduce greenhouse gas emissions, reduce operating costs and increase the energy independence of the city. Solutions include (Olszewski, Gotlib, 2023):

- Intelligent building management systems (BMS) - automate lighting, heating and air conditioning control based on the actual needs and presence of users.
- Intelligent energy networks (smart grids) - integrate renewable energy sources, energy storage and dynamic demand management, which increases the stability and efficiency of the energy system.
- LED street lighting with motion sensors - reduces energy consumption by adjusting the intensity of lighting to actual needs.

In the context of smart cities, water resource management includes monitoring and optimizing water consumption, controlling the quality of surface and groundwater, and implementing intelligent water retention and recycling systems to minimize losses, improve distribution efficiency, and provide residents with clean water. Technical solutions in this area include (Orłowski, Rosińska, 2018; Zhu, Zhang, 2023):

- Smart water meters that allow for real-time monitoring of water consumption and leak detection.
- Rainwater management systems that use GIS and IoT technologies to optimize the use of rainwater and prevent flooding.
- Modern filtration technologies for water purification and reuse that allow for the recovery of gray water for economic and industrial purposes.

Sustainable transport in smart cities aims to reduce CO_2 emissions, reduce traffic jams and improve the mobility of residents through the integration of modern technologies and transport systems. An important idea is the development of alternative means of transport that reduce the number of cars in cities (city bikes) and the development of electromobility. A specific solution is the optimization of bus and tram routes based on traffic data - AI-controlled public transport (Geels, Schot, 2023).

In addition, smart cities aim to engage residents in decisions regarding environmental protection through digital platforms, mobile applications and educational campaigns. Digital social participation and environmental education can use city applications (tools for reporting environmental problems, e.g. illegal dumps or sewage failures), programs rewarding ecological habits (e.g. waste segregation, use of public transport) and open data platforms with access to environmental information and statistics related to air quality or energy consumption (Arnstein, 2023).

Environmental management in smart cities covers many aspects, from waste management, through environmental monitoring, water management, transport, to environmental education and social participation. IoT, AI, ICT, GIS and big data technologies play a key role in achieving goals related to sustainable development and improving the quality of life of residents (Strzelecka et al., 2017, Stawiarska, Sobczak, 2020).

4. Technical and technological solutions for monitoring air quality in the city

In most large and medium-sized Polish cities, especially in winter, the permissible air pollution standards are exceeded (Kaczmarczyk et al., 2015, Ignac-Nowicka, 2018a, 2018b). The World Health Organization considers atmospheric air pollution to be the greatest health hazard, which increases the risk of developing lung and/or heart diseases, as well as many others (Soussilane et al., 2017). Gaseous and particulate anthropogenic pollution as a result of human economic activity comes mainly from the combustion of coal, liquid fuels and gases, as well as mechanical or thermal processing of natural resources (Kaczmarczyk et al., 2015). In such a situation, an important goal of urban development is to improve environmental conditions and their control, especially air quality (Rossi, Tosato, 2017).

Protection and monitoring of air quality in cities is based on the implementation of various technical and technological solutions. Currently, attempts are being made to introduce integrated technologies to manage air quality in cities, such as: data collection by unmanned aerial vehicles supported by IoT, the use of Information and Communications Technology (ICT), complex event processing (CEP), and many others.

An interesting application is the use of IoT and drone technology. Integration of the Internet of Things (IoT) with drones enables the creation of mobile monitoring platforms that can collect data from hard-to-reach urban areas. This approach allows for obtaining more detailed and spatially differentiated information on air pollution. The publication (Hu et al., 2018) presents a real-time, detailed and energy-efficient air quality monitoring system based on aerial and ground measurements. The architecture of this system consists of four layers: measurement layer for data collection, transmission layer for enabling bidirectional communication, processing layer for analyzing and processing data, and presentation layer for providing graphical interface for users. In the implementation, three main techniques are studied, given by data processing, implementation strategy and power control. For data processing, spatial matching and short-term forecasting are performed to eliminate the influences of incomplete measurements and data transmission delay. Implementation strategies of ground and airborne measurements are studied to improve the quality of collected data. Power control is further considered to balance power consumption and data accuracy. The solution has been operating at Peking University and Xidian University since February 2018 (Hu et al., 2018).

Another example is an innovative, multidisciplinary and cost-effective ecosystem of ICT (Information and Communications Technology) solutions that enables the collection, processing and distribution of geo-referenced information on the impact of pollutants and microclimatic conditions on the quality of life in smart cities. This system was developed and experimentally evaluated within the framework of the Smart Healthy Environment research project, co-financed by the Tuscany Region (Italy). The system developed an innovative monitoring network, consisting of fixed and mobile sensor nodes, that provide comparable measurements in stationary and mobile conditions (Bacco et al., 2022). In addition, the sensor data were enriched with data generated by citizens using a dedicated mobile application, using the participatory sensing paradigms of the subjects themselves, i.e. citizens (Bielecka-Prus, 2013) and mobile social networks.

Another example of a technological solution for monitoring air quality is the use of Complex Event Processing (CEP) based on rules and SPARQL queries (Kumar et al., 2024). The use of advanced CEP analytical systems enables real-time analysis of data, e.g. on air quality. In turn, SPARQL queries are used for: searching for information in knowledge bases, processing data in the semantic web, integrating various data sources in the RDF (Resource Description Framework) format. The Semantic Web is an extension of the traditional www network that allows for more intelligent and automated processing of data thanks to their unambiguous description and mutual connections. It is based on a structure in which information is not only presented, but also understandable to machines, which allows for better analysis and integration and the use of artificial intelligence. On the other hand, the RDF format combines data resources into RDF triples, which have the form: subject - predicate - object (e.g.: for testing air quality in a given area, the connection of three elements: air composition (quality), tested area, cause of pollution, e.g.: burning tires). The authors of the publication (Kumar et al., 2024) from the Indian Institute of Information Technology in Allahabad (India) used CEP analytical systems to collect a data set from the Central Pollution Control Board (CPCB) in India and use this data to test the implementation of CEP systems for monitoring air quality in a smart city.

In Poland, a network of ground sensors is used to monitor air quality, data is processed (e.g. in the cloud) and presented in the form of, for example, visual (pollution maps) and alerts (SMS messages) about the air quality in a given area in appropriate applications (including mobile ones), which are available to city residents. The installation of a network of sensors allows for ongoing monitoring of atmospheric pollutant concentrations, such as PM10 and PM2.5 suspended dust, nitrogen dioxide (NO_2) or sulfur dioxide (SO_2). This data is crucial for informing residents about the current state of the air and taking intervention measures. Actions towards the fight for clean air are carried out in Poland, among others, through the development of the Air Quality Monitoring System (www.gov.pl/web/gios/…). Currently, air quality measurements are carried out in Poland at 1,782 measurement stations, including 1022 automatic stations (57% of all stations) and 760 manual stations (43% of all stations). The largest number of measurement stations operating within the State Environmental Monitoring are located in the Silesian Voivodeship (200), Kuyavian-Pomeranian Voivodeship (169), Lower Silesian Voivodeship (162), Lesser Poland Voivodeship (161) and Mazovia Voivodeship (150), in areas with high concentrations of air pollutants (https://powietrze.gios.gov.pl/pjp/…).

The fewest stations are located in the Opole province, where in 2025 air quality monitoring was expanded to 62 locations, which was another action aimed at fighting for clean air (www.opole.pl/dla-mieszkanca/…). In order to obtain information, among others, on the spatial distribution of concentrations of individual pollutants, measurements can be supplemented with the results of mathematical modeling of the spread of pollutants (pollution forecasts). Data from measurement stations are collected in the national database JPOAT3.0 of the Chief Inspectorate for Environmental Protection (https://powietrze.gios.gov.pl/pjp/maps/modeling).

5. Summary and conclusions

Currently, many new technical and technological solutions are being introduced in the world to manage cities and the natural environment in the city, including:

- GIS technology to track pollution in a given area.
- Use of drones to monitor the environment.
- RFID technology, e.g. to track waste.
- Use of the Internet of Things (IoT) – a network of sensors.
- Use of ICT to communicate with city residents.
- Use of complex event processing (CEP) to search and analyze data networks about threats in the natural environment.

The use of these technologies will certainly affect the high development (smart city 3.0) of cities. However, not all cities can currently move towards the use of the most advanced technologies for managing the natural environment in the city. However, in order to improve air quality, it is possible and necessary to expand activities to many areas of action within cities, such as: modernization of heating systems, increasing green areas in urban space, limiting car traffic with combustion engines and ecological education of residents, in particular regarding the combustion of solid fuels in furnaces. If we want to breathe clean air, even the best actions in only one field will not help in the fight against smog, which is why it is necessary to act comprehensively in every area.

Analyzing the technical and technological solutions currently used in the world, it can be seen that some of them have already been implemented in Polish cities, and the further development of these applications will probably concern the dissemination of certain environmental control standards throughout Poland. Drones are successfully used in many Polish cities to monitor the environment and detect illegal emitters of air pollution. The GIS, RFID, Internet of Things (IoT) technologies analyzed in the article, or the use of ICT for communication with city residents are solutions that can be used in Polish cities. The only limitation may be the financial sphere, and therefore the too small range of the solutions used.

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