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AN OVERVIEW OF THE CURRENT STATE AND FUTURE PROSPECTS OF RESPIRATORY GAS SUPPLY MANAGEMENT SYSTEMS

Abstract. The aim *of the article is to investigate the state and the directions of the development of supply management systems for respiratory gas mixtures that contain oxygen, nitrogen, helium and other gases in varying proportions. This topic is of particular importance at present, given the substantial demand for such systems in hospitals to support patients' vital functions, in aviation, the space sector, during emergency response, and in industrial processes that employ specialised gas mixtures.*

The problem of developing respiratory gas supply management systems came to the fore during COVID-19 pandemic and, amid the current period of Russian military aggression, remains salient. Accordingly, the article highlights issues related to supply logistics in emergencies, when demand for respiratory gas mixtures surges abruptly. It considers opportunities for the design of modular and portable systems that can be rapidly deployed in field conditions.

Respiratory gas supply management systems are undergoing active development in response to growing requirements for safety, efficiency and environmental sustainability, integrating cutting-edge technologies and innovative approaches. Contemporary development trends include the implementation of the Internet of Things (IoT), artificial intelligence (AI), and big data analytics to optimise gas-flow management, anticipate consumption needs, and prevent emergency situations. For example, IoT sensors enable real-time monitoring of pressure, temperature and mixture composition, whereas AI algorithms can predict demand on the basis of operational data.

There are challenges associated with the design and operation of such systems, notably ensuring high-precision dosing, compliance with international standards (ISO, FDA), and reducing energy consumption and the carbon footprint.

An important direction is the development of closed-cycle systems that enable gas reclamation and reuse, thereby reducing costs and supporting environmental sustainability.

Methodology. *To provide a structured analysis of development pathways, assess the current state and outline prospects, the article employs a systems approach to analyse logistics strategies for ensuring timely delivery of oxygen mixtures to hospitals during peak loads. It underpins the need for an interdisciplinary approach involving experts in engineering, medicine, information technology and environmental science; and the importance of international collaboration for knowledge exchange and harmonisation of standards. To assess the current state and define the prospects for respiratory gas supply management systems, we apply a systematic literature review across PubMed, Scopus, Web of Science and Google Scholar over the last five years, covering topics such as open-loop vs closed-loop, gas delivery automation, digital health, and environmental/economic efficiency.*

The scientific novelty. *The article develops and information-logical model of an intelligent system for monitoring and automated control of gas-mixture delivery using digital twins, the adopting of which contributes to improving the quality of healthcare service delivery.*

Conclusion. *In our view, further progress in the development of the respiratory gas supply management systems will depend on the capacity to integrate advanced technologies while ensuring the reliability, accessibility and sustainable development of respiratory gas supply systems on a global scale.*

Key words: *respiratory gas mixture, supply management systems, model, information technology, monitoring, digital twins.*

Валерій МИХАЙЛОВ. ОГЛЯД ПОТОЧНОГО СТАНУ ТА ПЕРСПЕКТИВ СИСТЕМ УПРАВЛІННЯ ПОСТАЧАННЯМ ДИХАЛЬНИХ СУМІШЕЙ

Анотація. Метою статті *є дослідження стану та напрямів розвитку систем управління постачанням дихальних сумішей, що містять кисень, азот, гелій та інші гази в різних пропорціях. Ця проблематика є важливою, особливо зараз, коли існує велика потреба у таких системах в лікарнях для підтримки життєдіяльності пацієнтів, в авіації, космічній галузі, під час ліквідації надзвичайних ситуацій та у промислових процесах, де використовуються спеціалізовані газові суміші.*

Проблема розвитку систем управління постачанням дихальних сумішей актуалізувалась під час пандемії COVID-19, і зараз у період військової агресії росії не втратила свого значення. У зв'язку з чим, у статті висвітлюються проблеми, пов'язані з логістикою постачання в умовах надзвичайних ситуацій, коли попит на дихальні суміші різко зростає. Розглядаються можливості створення модульних та портативних систем, які можна швидко розгортати в польових умовах

Системи управління постачанням дихальних сумішей зазнають активного розвитку, що пов'язано зі зростаючими вимогами до безпеки, ефективності та екологічності, інтегруючи новітні технології та інноваційні підходи. У якості сучасних тенденцій розвитку таких систем можна виділити впровадження Інтернету речей, штучно-

го інтелекту та технологій великих даних для оптимізації управління потоками газів, прогнозування потреб та запобігання аварійним ситуаціям. Так, наприклад, IoT-датчики дозволяють у реальному часі відстежувати тиск, температуру та склад сумішей, а алгоритми штучного інтелекту здатні прогнозувати попит на основі даних про споживання.

Існують виклики, пов'язані з розробкою та експлуатацією систем, зокрема, з забезпеченням високої точності дозування, відповідністю міжнародним стандартам (ISO, FDA), зниженням енергоспоживання та вуглецевого сліду.

Важливим напрямом є розробка систем із замкненим циклом, які дозволяють переробляти та повторно використовувати гази, сприяючи зниженню витрат та екологічному збереженню.

***Методологія.** У статті для забезпечення структурованого аналізу напрямів розвитку систем, оцінки їх сучасного стану та визначення перспектив розвитку використовуються системний підхід для аналізу логістичних стратегій для забезпечення оперативного постачання кисневих сумішей до лікарень під час пікових навантажень. Підкреслюється необхідність міждисциплінарного підходу до розвитку систем управління постачанням дихальних сумішей із залученням фахівців інженерії, медицини, інформаційних технологій та екології; важливість міжнародної співпраці для обміну досвідом та гармонізації стандартів. Для аналізу сучасного стану та визначення перспектив розвитку систем управління дихальними сумішами використовуємо систематичний огляд літератури, що міститься у базах PubMed, Scopus, Web of Science, Google Scholar за останні 5 років за тематикою open-loop vs closed-loop системи, автоматика у подачі газів, digital health, екологічна / економічна ефективність.*

***Наукова новизна.** В статті розроблена інфологічна модель інтелектуальної системи моніторингу та автоматизованого управління подачі газових сумішей з використанням цифрових двійників, використання якої сприяє підвищенню якості надання медичних послуг.*

***Висновки.** Подальший прогрес у сфері розвитку систем управління постачанням дихальних сумішей, на нашу думку, залежить від здатності інтегрувати передові технології із забезпеченням надійності, доступності та сталого розвитку систем постачання дихальних сумішей у глобальному масштабі.*

***Ключові слова:** дихальна суміш, системи управління постачанням, модель, інформаційні технології, моніторинг, цифрові двійники.*

Introduction. The COVID-19 pandemic and Russia's military aggression have foregrounded the development of respiratory gas supply management systems as a highly pressing issue. There is demand for such systems in hospitals to support patients' vital functions, in rescue operations, in a space sector, during emergency response, and in industrial processes that utilise specialised gas mixtures. These systems are responsible for precise dosing, mixing, purification and delivery of gas mixtures to ensure human life support in constrained or controlled environments.

Current state of such systems is characterised by challenges related to technological constraints, integration complexity, and the need to adapt to new requirements for safety, energy efficiency and environmental performance. The principal problem is to ensure stable, precise and safe delivery of gas mixtures under real-life conditions marked by dynamic external changes, individual user needs and stringent reliability demands. Systems must guarantee stable supply with specified parameters of composition, pressure, temperature and humidity in real time, integrate with automated monitoring of human condition (e.g., heart-rate sensors, blood oxygen level) for adaptive control, and minimise energy consumption and environmental impact (particularly for portable or autonomous systems). In addition, they must comply with codified safety standards, considering risks related to gas leaks, pressure fluctuations, equipment failures and diverse operating conditions – from resuscitation units to extreme environments that require rapid response to non-standard situations.

Respiratory gas supply management systems are a key component of modern anaesthesiology, intensive care and surgery. The reliability and accuracy of delivering oxygen, nitrous oxide, volatile agents and other gases directly affect anaesthesia outcomes, patient safety, reduction of side effects and overall treatment efficiency.

Precise dosing is essential to avoid hypoxia, hyperoxia or insufficient anaesthetic depth – an issue that becomes more significant with the grows of minimally invasive and ambulatory procedures.

However, traditional approaches, specifically open-loop systems such as Target-Controlled Infusion (TCI)), while simple to implement, they are often fail to react to rapid physiological changes, leading to potential dosing errors in critical and unstable settings [17, 6]. In response, closed-loop systems have emerged that automatically adjust anaesthetic delivery based on indicators such as BIS or PSI, maintaining the desired level of anaesthesia without direct anaesthetist intervention [17].

For example, the End-tidal Control system (a software solution by GE HealthCare), positively evaluated in the MASTER trial (published in 2024), automatically regulates oxygen and volatile agent concentrations, markedly reducing the need for manual adjustments and contributing to agent savings and lower greenhouse-gas emissions [4]. Research on the Mindray A9 platform likewise showed that automated fresh-gas control reaches the target concentration faster and requires substantially fewer manual interventions [14]. Despite these prospects, barriers remain – complex physiological modelling, high cost, and rigorous certification and regulatory approval that slow widespread clinical adoption of automated systems [17].

The aim of this article is to provide a comprehensive review of the current state of respiratory gas management, from traditional open-loop systems to modern closed-loop solutions and automated platforms – covering technological aspects (e.g., gas-delivery mechanisms, automation, sensors), clinical efficacy and safety, as well as environmental and economic feasibility. We seek to identify key trends and pain points, and define promising directions – AI integration, digital analytics, eco-oriented solutions and the potential for full automation of anaesthesia.

Problem statement. Respiratory gas supply management systems play a key role in ensuring the efficient functioning of modern healthcare facilities, remaining a critically important component of contemporary anaesthesiology, intensive care, and surgery.

In traditional open-loop systems such as Target-Controlled Infusion (TCI), the regulation of anaesthetic delivery is based on a priori pharmacokinetic models and does not respond to real-time physiological changes in the patient, thereby limiting accuracy and safety under unstable clinical conditions [17].

By contrast, modern closed-loop systems and automated platforms demonstrate the potential to enhance control precision, optimise the consumption of oxygen and anaesthetic agents, and reduce risks associated with the human factor. However, issues of clinical acceptability, cost, and regulatory support remain unresolved.

At the same time, several problems persist. In particular, notably the insufficient integration of intelligent control and predictive algorithms; limited implementation of real-time sensor technologies; the lack of comprehensive studies assessing the clinical efficacy and safety of advanced automated systems; environmental changes related to anaesthetic gas emissions and equipment energy consumption; and economic barriers hindering the adoption of advanced technologies in hospitals of different levels. These factors underscore the need for a comprehensive analysis of the current state and development prospects of respiratory gas supply management systems to identify promising directions for their improvement [17, 13].

Clinical trials confirm the advantages of automated systems. For instance, in a randomised study of thoracic surgery, the CLADS system reduced propofol consumption and eliminated the need for frequent manual adjustments [12]. Although closed-loop systems such as CLADS demonstrate clinical benefits, their widespread implementation remains constrained by technological, economic, and regulatory barriers [17].

Challenges also resist in the domains of environmental sustainability (reducing anaesthetic consumption, as many gases are greenhouse gases), economic efficiency, and the use of machine learning and predictive analytics in respiratory gas management.

By integrating data from clinical trials, systematic reviews, and technical innovations, it is possible to form a clear understanding of the current state, existing problems, and promising directions of development, including artificial intelligence (AI), digital analytics, ecological sustainability, and full automation.

Artificial intelligence enables adaptive control of oxygen and anaesthetic dosing by analysing sensor data in real time. Through machine learning algorithms, systems can predict patient gas requirements, automatically select optimal ventilation parameters, reduce the risk of hypoxia or anaesthetic overdose, and lessen the workload on clinicians. Consequently, AI-based closed-loop platforms are already being successfully tested in clinical settings to automate anaesthesia delivery.

Digital analytics is used for processing and analysing large volumes of data from gas sensors, patient monitors, and mechanical ventilation devices. The use of digital analytics allows systems to identify gas-consumption patterns, optimise logistics and supply, and generate predictive models of patient condition or therapy effectiveness. For example, such systems can automatically generate oxygen consumption reports, evaluate adherence to clinical protocols and suggest optimal treatment strategies to clinicians.

Modern development trends prioritise not only efficiency but also environmental safety. The use of medical gases, particularly anaesthetics such as sevoflurane or desflurane, contributes to greenhouse-gas emissions. Environmentally sustainable solutions include gas-mixture recirculation systems, AI-based dosing optimisation to minimise consumption, replacement of harmful gases with safer analogues, and continuous monitoring to reduce hospitals' carbon footprints.

A promising direction involves the creation of intelligent platforms capable of autonomously managing all aspects of respiratory gas delivery, from real-time control of gas concentrations to automated ventilation adjustments and recommendation generation for medical staff. Such automation can significantly reduce human error, lower costs, and make management systems more resilient and reliable.

In most operating theatres and intensive care units, manual adjustment of fresh gas / vaporisers or TCI for intravenous anaesthesia still predominates. These open-loop approaches are highly sensitive to the human factor and fail to account for rapid physiological changes in patients. By contrast, automated and closed-loop systems (e.g. McSleep®, CLADS, iControl-RP) have already demonstrated more accurate maintenance of target anaesthetic parameters and reduced anaesthetic workload, though they continue to face challenges related to sensor/model integration and regulatory compliance [17].

Systematic reviews and meta-analysis of recent years consistently show that automated oxygen titration reduces the need for manual corrections compared with traditional management.

Secondary infrastructure (oxygen, medical air, N_2O, CO_2, vacuum) is regulated by international standards such as ISO 7396-1, which establishes requirements for system design, testing, and commissioning [7]. Recent analytical publications highlight common risks (pressure fluctuations, contamination, and maintenance issues) as well as the importance of third-party audits and digital monitoring to prevent incidents and downtime.

The development of respiratory gas supply management systems encompasses both technological and systemic aspects. The technological aspects relate to the development of new materials, sensors, and control algorithms, whereas the systemic aspects focus on architecture optimization, cybersecurity enhancement, and the creation of universal standards and protocols for respiratory gas management systems.

Scientific relevance of the problem lies in the need to develop new control methods and management algorithms that take into account the complex nature of gas mixtures, their interaction with the human body, and the influence of the external factors such as pressure, temperature, and chemical composition of the environment. Existing systems often face limitations associated with insufficient adaptability, high energy consumption, and the complexity of integration with modern information technologies such as artificial intelligence (AI) or the Internet of Things (IoT).

Practical significance of the problem is determined by the growing demand for automated and intelligent control systems capable of minimizing the human factor, enhancing safety, and optimizing resource use. For example, in the medical field, the improvement of respiratory gas supply systems can substantially increase the efficiency of resuscitation measures and therapy, while in industrial or extreme environments it can ensure operational reliability in critical situations.

Analysis of recent research and publications. Modern studies of respiratory gas supply management systems demonstrate active integration of Internet of Things (IoT) technologies, artificial intelligence (AI), and machine learning (ML) to improve the efficiency, saety, and reliability of such systems.

One of the focal areas involves the implementation of intelligent monitoring and automated control systems that enable real-time tracking of oxygen and other gas-supply parameters, early detection of emergency conditions, and stable equipment operation. The use of sensor networks, AI algorithms, IoT technologies, and digital twins allows precise forecasting of gas consumption and optimisation of resource distribution.

The use of digital twin technology in gas and respiratory systems combines real-time data analytics with advanced modelling capabilities, crating virtual replicas of physical gas-distribution systems. Their application opens new possibilities for testing various operating models of equipment without risk to patients or personnel, facilitating the rapid implementation of innovations into clinical practice. In chronic respiratory medicine, digital twins allow visualisation of patients' breathing functions, supporting therapy personalisation, early diagnosis, and adaptation of treatment approaches to individual needs [5].

A digital twin is a virtual model of physical system, designed to accurately represent the real system in real time, analyse the behaviour, and provide predictive insights through advanced modelling, machine learning, and reasoning for decision-making [10]. In healthcare, a digital twin is a virtual representation of a human being that enables dynamic modelling of potential treatment strategies, monitoring and prediction of health trajectories, and early intervention and prevention based on multiscale modelling of multimodal data related to clinical, molecular, environmental, and social factors. IoT sensors are used to transmit real parameters of the object to a server, where they are processed by a specialised software, and potential situations are simulated using the IT infrastructure.

Continuous communication and information exchange between the physical and virtual worlds make it possible to optimise modelling and machine learning algorithms for analysing and prediction of the real system's future state, thereby optimising performance and accelerating decision-making.

Publications pay considerable attention to energy efficiency and improving the economic performance of respiratory gas supply management systems. Researches explore adaptive controllers, intelligent valves, and diagnostic systems that reduce losses and ensure optimal use of respiratory gas mixtures. Another important topic is standardisation, the integration of digital twins into gas-safety systems, and the development of integrated solutions that meet both medical and industrial requirements [15].

Recently, computer modelling and AI algorithms have been widely applied in disease modelling, target identification, virtual coaching systems, and personalised medicine. The differences and specificities between various virtual models are particularly important in terms of data sources, applications, interactions, and visualisation methods. For instance, virtual models of specific organs are designed using detailed imaging data, while disease models that support precision medicine rely on combining molecular profiling and clinical information.

The article *"Recent advances in medical gas sensing with artificial intelligence – enabled technology"* [3] discusses the use of self-powered sensors, which, owing to energy efficiency and autonomy, enable continuous monitoring of respiratory gas parameters in real time. Integration of artificial intelligence and machine learning into these sensors ensures accurate anomaly detection and timely response to changes in patients' physical conditions.

Medical gases, including oxygen, nitrous oxide, and carbon dioxide, are essential to a wide range of medical treatments, from respiratory therapy to anaesthesia and diagnostics. However, when misused or overexposed, these gases pose health risks. Oxygen is critical for patients with critically low blood oxygen levels. Nitrous oxide, commonly used in dentistry and surgery, serves as an anaesthetic and analgesic. Carbon dioxide is used in minimally invasive procedures to expand body cavities for improved visualisation. Helium mixed with oxygen helps reduce airflow resistance in patients with breathing difficulties. Medical air facilitates respiration without causing hypoxia, and nitrogen is used to power medical devices or preserve biological samples through freezing.

Despite their benefits, strict adherence to proper handling and dosing protocols for medical gases is crucial, as violation pose health risks. Exposure to nitrous oxide may cause neurological and cognitive disorders; cardiovascular diseases and worsening of ischaemic heart disease may be linked to air pollution and particulate matter [19]; some gases, especially those introducing toxic elements such as heavy metals, can promote inflammation and carcinogenesis [1]. Medical gases can affect digestion, contributing to gastrointestinal disorders [9, 11], kidney function, and foetal development during pregnancy [18].

Health risks associated with exposure to medical gases require rigorous risk-management protocols to safeguard patient care and environmental safety, as well as the use of modern monitoring systems for real-time gas concentration management and detection using sensors. Accurate measurement of medical gases is vital in healthcare to prevent gas-related pathologies and ensure the safety of patients and staff.

Medical gas sensors play a key role in monitoring specific biomarkers, in particular, volatile organic compounds (VOCs) in the human body that may indicate various diseases. Today, sensor capabilities are being expanded through AI integration, particularly by applying advanced data processing and pattern recognition. With improved algorithms, artificial intelligence allows sensors to rapidly and accurately analyse large volumes of data, detecting subtle variations that may signal latent health issues.

Recent advances in nanostructured materials and polymers have significantly enhanced medical gas-sensing technologies, improving sensitivity and selectivity. Researches increasingly employ nanomaterials such as nanowires, nanorods, and carbon nanostructures due to their high surface-area-to-volume ratios, promoting better gas adsorption and detection. Nanomaterials exhibit unique electrical, thermal, and optical properties that can be precisely tuned for specific gas-sensing applications [16]. Integration of conductive polymers with nanostructures has proven effective, as such composites can enhance the overall performance of gas sensors by improving response time and stability under diverse environmental conditions [2].

Kharkiv researchers V.O. Harin, D.A. Tkachenko, O.V. Shypul, S.O. Zaklinskyi, O.V. Tryfonov, and S.I. Plankovskyi, in their study *"Development of a Digital Twin for Gas Mixture Tank Filling"*, described the design of a digital twin for the process of cylinder filling with gas mixtures using simulation (ANSYS Fluent, ANSYS Twin Builder) to produce temperature-pressure parameters and ensure precise dosing. They developed examples of digital twins of gas-mixture filling systems using standard elements from the Twin Builder and Modelica libraries [21].

For the safety of airspaces during pandemic, researchers T.I. Zohdi, in the study *"A Digital Twin and Machine Learning Frameworks for Ventilation System Optimisation for Capturing Infectious Disease Respiratory Emissions"*, proposed a framework model that combines digital twin technology and machine learning algorithms. This framework allows the optimal positioning of ventilation devices to capture aerosols such as droplets produced by coughing or sneezing, using rapidly computable models for respiratory emissions [20].

The use of digital twins and ARIMA models made it possible to achieve the highest forecasting accuracy (MAPE, RMSE, R^2), improving maintenance efficiency and gas-supply safety [8].

Main Research materials. Despite the rapid progress in applying artificial intelligence (AI) to medical gas analysis, there remains a significant gap in comprehensive literature reviews that systematically explore this intersection. Current studies are largely focused on the technical aspects of gas sensing and artificial intelligence separately, rather than on their combined application in healthcare settings. This lack of an integrative overview creates an obstacle to understanding the full potential and the challenges of AI integration into medical gas monitoring systems.

The implementation of AI technologies in medical-gas measurement, the enhancement of traditional sensors through advanced data processing and pattern recognition, expands the possibilities for real-time monitoring. Artificial intelligence has improved the ability to detect hazardous gas levels, while advances in nanotechnology have led to the development of cutting-edge materials, such as metal oxides and carbon-based nanomaterials, that increase sensitivity and selectivity. These innovations, combined with AI, support continuous patient monitoring and predictive diagnostics, paving the way for future breakthroughs in medical care.

We intent to emphasise the critical role of artificial lung ventilation devices during pandemic, particularly COVID-19, and the importance of CPAP (Continuous Positive Airway Pressure) devices in addressing the shortage of high-tech medical equipment. CPAP devices, owing to their relatively simplicity, lower cost, and scalability in production, have become an effective solution for supporting patients with spontaneous breathing. Their principle, based on delivering oxygen-air mixture under constant positive pressure through network oxygen pressure and air ejection, enables the required oxygenation without the complex mechanical components typical of conventional mechanical ventilators.

The experience of the COVID-19 pandemic demonstrated that mass production of CPAP devices can be organized more rapidly than that of high-technology ventilators, which require long manufacturing cycles and costly components. For example, in 2020 several countries, including the USA, the UK, and India, actively engaged manufactures to develop simplified CPAP and BiPAP models, and adapted industrial facilities for their production. This helped to partially offset equipment storages during the peak load on healthcare systems.

To automate, control, and stabilise technological processes of gas-mixture delivery in the medical sector, it is proposed to develop an intelligent monitoring and automated control system for gas-mixture supply.

The structure of the intelligent monitoring and automated control system for gas-mixture delivery using digital twins is presented in Table 1.

Table 1

Structure of the intelligent monitoring and automated control system for gas-mixture delivery

Level	Element	Description of Interaction
Sensing level (measurement level)	Sensors of physical parameters: pressure, temperature, concentration, gas-mixture composition, etc.	The collected data are transmitted both to the control system and to the digital twin for real-time modelling of the actual object state.
	Analogue-to-digital converters.	
	Data acquisition modules (DAQ)	
Local control level	Programmable logic controllers or embedded microprocessors	Interaction between the digital twin and the controller enables preliminary testing of virtual parameter-change scenarios.
	Control algorithms	
	Actuating mechanisms (electro-valves, compressors, flow regulators, etc.)	
Monitoring and visualisation level	SCADA system or HMI panel	A 3D model or digital representation of the process displaying current and forecast system states.
	Data-logging module	
	Visualisation subsystem	
Intelligence and analytics level	Analytics module	The digital twin stimulates system operation based on real data, performing virtual experiments and providing optimisation of operating modes.
	AI and machine-learning modules	
	System digital twin	
Communication and integration level	Data-exchange network protocols	Ensure remote analytics and data exchange between the digital twin and system elements; integration with external systems.
	Cloud analytics and remote access	
	Integration with corporate systems	
	Operator-HMI interaction unit	

The level of operator involvement depends on the degree of automation and may vary from direct operational control to supervision and confirmation of AI-generated decisions.

An infological model of the intelligent monitoring and automated control system for gas-mixture delivery has been developed, describing the main information entities of the system, their attributes, relationships, and data flows (Table 2).

Depending on the selected scenario (the system only observes; the system analyses and transmits information to the operator; or the system automatically controls the process), the model may be extended with the "Actuators" entity, which includes the following attributes: mechanism ID, name, action type, state, protocol, and affiliation.

The main infological relationships reflecting data flows within the system include:

– Input data – received from sensors and transmitted to the database and analytics module.
– Analytics – data processing, deviation detection, and forecasting.
– Modelling – synchronisation of the digital twin for scenario testing and action stimulation.
– Control – generation of control signals and their transmission to the automated control system.
– Visualisation – operator or automated system actions initiating a new monitoring cycle.
– Feedback – operator or automated system actions initiating a new monitoring cycle.

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Table 2

Elements of the infological model of an intelligent monitoring and automated control system

Entity	Attribute(s)	Description / Relationship
Monitored object	Name, ID, location, metrics, critical parameters, permissible limits	A process (physical or virtual) or a system being monitored.
Monitoring parameter	Parameter name, ID, unit of measurement, criticality, threshold values, update frequency, logging frequency	Belongs to monitored object.
Sensor / detector / data source	ID, sensor type, accuracy, calibration, specifications / sensor characteristics	Measures monitoring parameters.
Data flow	Timestamp of arrival, protocol, data validity, source, communication channel	Originates from sensors and is stored in the monitoring database.
Monitoring database	Database name, DBMS type, table structure, storage intervals, update intervals	Stores data flows.
Analytics module	Analysis methods, AI, ML, statistics, accuracy, computation interval	Processes data flow, generates decisions, and performs forecasting.
Object digital twin	Process model, simulation parameters, level of detail, scenarios	Mirrors the monitored object and receives data from the analytics module.
Automated control system	Type of control algorithms, response speed, communication protocols	Receives commands from the analytics module or operator and sends signals to actuators.
User interface / HMI / dashboard	Visualisation type, access level, alert models	Interacts with the analytics module, automated control system, and operator.
Operator / user	ID, role, access rights, activity log, measurement log	Interacts with the user interface and adjusts automated control system operations.

To describe information interactions, the following relationships are used:
– Monitored object ↔ Monitoring parameter (1:N);
– Parameter ↔ Sensor (1:N);
– Sensor ↔ Data flow (N:1);
– Analytics module ↔ Digital twin (1:1);
– Analytics module ↔ Automated control system (1:1);
– Automated control system ↔ Monitored object (1:1);
– Operator ↔ User interface (1:1);
– User interface ↔ Analytics module (1:N).

The developed model reflects the interactions between system elements and can be used to standardise the operation of the intelligent monitoring and automated control system.

Conclusions. The problem of developing and monitoring respiratory gas supply management systems is inherently interdisciplinary, involving important scientific tasks such as complex system modelling, development of adaptive control algorithms, and integration of advanced technologies.

The development of an intelligent and automated control system for gas-mixture delivery using digital twins contributes to improving the quality of healthcare services. On a practical level, addressing this issue will enhance the safety, efficiency, and accessibility of technologies across key domains of human activity.

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