ІНФОРМАЦІЙНІ ТЕХНОЛОГІЇ

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THE INTEGRATION OF IOT AND MATHEMATICAL MODELS IN CLIMATE CHANGE MITIGATION

A strategy for using IoT devices to collect real-time environmental data that takes into account the most significant indicators is described. The advantages of using the Internet of Things have also been determined, which makes it possible to monitor the state of the climate in a convenient mode with high accuracy and speed. Because the task of analyzing using mathematical models to optimize energy efficiency, monitor air quality, and strengthen sustainability efforts is complex, it requires the involvement of specific specialists, such as systems analysts, mathematicians, and climatologists. Temperature, humidity and precipitation, among others, are parameters obtained by using Internet of Things devices for analysis. Climate models such as dynamic systems and simple low-order models for studying climate variability are considered, and equations of momentum, thermodynamics, specific humidity, non-primary, hydrostatic and thermodynamics connecting variable states are also described. The use of these equations within the considered models and the values of their parameters are explained, some of which are the result obtained with the help of Internet of Things technologies. It also describes the necessary technologies needed to build an Internet of Things network: microcircuits, sensors, embedded computer, wireless network and protocols.

Climate models of varying degrees of complexity are used to predict climate change and variability on a global and regional scale. Mathematical and climate models are very important for preparing society for the development and implementation of so-called adaptation strategies and measures necessary to reduce the effects of climate change. Adaptation is understood as the process of society getting used to current and predicted changes in the climate system and its impacts. The scientific novelty of the research is determined by the fact that for the first time a review of the integration of IoT and mathematical models for environmental protection was carried out, which made it possible to understand the regularities of the construction of these mathematical models and to reveal the regularities of such integration.

The obtained research results, both theoretically and practically, serve as the basis for further scientific and applied works aimed at improving and improving various aspects of the use of "Internet" devices of things" to collect real-time environmental data and further analyze it using mathematical models to optimize energy efficiency, monitor air quality and strengthen sustainability efforts. The described strategy of using the Internet of Things and mathematical models is important for the life of any person, the work of enterprises and authorities. In the long term, the use of Internet of Things technologies and mathematical models in mitigating the effects of climate change can have a positive impact on the development of the entire human civilization.

Keywords: internet of things; mathematical model; dynamical system; external forcing; governing equation

Introduction. The relevance of the task of integrating IoT and mathematical models in mitigating the consequences of climate change consists of several factors. The first of them is the need to create a strategy for using IoT tools for climate control. The evolution of humanity has caused a negative impact on nature, the extent of which cannot be estimated without the use of modern concepts, one of which is IoT. The Internet of Things is a concept of a network consisting of interconnected physical devices that have built-in transmitters, as well as software that allows the transfer and exchange of data between the physical world and computer systems in automatic mode, using standard communication protocols . IoT-based solutions mainly solve consumer and enterprise problems, however, some important global climate problems can also be solved with the help of IoT technology. The combination of IoT technologies and mathematical models can provide the means to optimize energy efficiency, monitor air quality, and enhance sustainability efforts.

Solving the task of climate monitoring in real time using IoT is described in works [1-5]. It is also proposed to use the Internet of Things as an ecosystem of devices that allow to ensure energy efficiency and safety in works [6,7]. Control of environmental pollution using IoT is mentioned in works [8,9]. Mathematical modeling of climate changes in the context of external ergonomics appears in work [10]. And work [11] describes a computational approach to the mathematical model of climate change using heat and diffusion sources. The impact of climate change and deforestation is mathematically modeled in work [12]. For greater use of IoT in mitigating the effects of climate change, it is necessary to attract large financial and technical resources that can be done by public or private businesses. Examples of the use of the Internet of Things by businesses in Romania to determine the climatic prerequisites for the expansion of the Amurg variety in Transylvania are given in work [13].

Analysis of latest research and problem statement. Formulating a strategy to integrate IoT and mathematical models of climate change mitigation is a complex process that requires the analysis of several different factors. However, before implementing this integration, it is necessary to evaluate it and understand the impact it will have on optimizing energy efficiency, monitoring air quality and strengthening sustainable development efforts in the future.

To form the integration of IoT and mathematical models, it is necessary to first analyze the existing mathematical models of environmental data analysis. This may include an assessment of the problem of modeling climate change processes, based on defined parameters.

The next stage is an assessment of the benefits of using the Internet of Things. It involves analyzing the strengths and weaknesses of this concept to identify possible integration points. After that, a strategy should be formed, which may include the development of technologies to build the Internet of Things that meet the needs of analysis using mathematical models. The first stage is the consideration of climate models as dynamic systems and the analysis of their sensitivity. At this stage, the general appearance of the mathematical model is formulated thanks to a set of three-dimensional nonlinear partial differential equations and a generalized discrete climate model and stochastic climate models, which were first proposed by Hasselman, which must be taken into account for the construction of climate models as dynamic systems.

At the second stage, the response of the climate system to external disturbances is evaluated based on the sensitivity analysis of dynamic systems. The evaluation is based on information from open sources. At the third stage, the sensitivity analysis of the chaotic dynamic system is implemented. At the fourth stage, mathematical models of climate systems based on the main equations (momentum, thermodynamics, precipitation) are considered.

A number of general scientific methods were used to perform the research stages of the integration of IoT and mathematical models for environmental protection, namely: monitoring method: used to collect, systematize and analyze information about mathematical models and the concept of the Internet of Things; comparison method: came in handy when researching the equations of mathematical models and their parameters; method of abstraction: used in the course of research in order to highlight the main concepts and categories; abstract-logical and dialectical methods of scientific knowledge, as well as the method of scientific abstraction, were used in the study to form theoretical generalizations, clarify the conceptual apparatus, and formulate conclusions.

That is why a number of unresolved issues arise in these conditions. The issue of creating a software application based on the integration of IoT and mathematical models, which will make it possible to monitor the state of the climate, optimize energy efficiency and strengthen efforts towards sustainable development, requires additional research.

Presentation of the main material. The first step of this scientific research is the definition of the main mathematical models of climate change and Internet of Things technologies that allow obtaining data for these models.

There are several mathematical models for assessing climate change, the main ones being:

– climate models as dynamical systems and their sensitivity analysis: (climate as a complex dynamical system, climate system sensitivity to external forcing, sensitivity analysis of a chaotic dynamical system);

– governing equations and low-order simple;

– models to study climate variability.

The relationship between the main mathematical models for climate change assessment is shown in fig. 1.

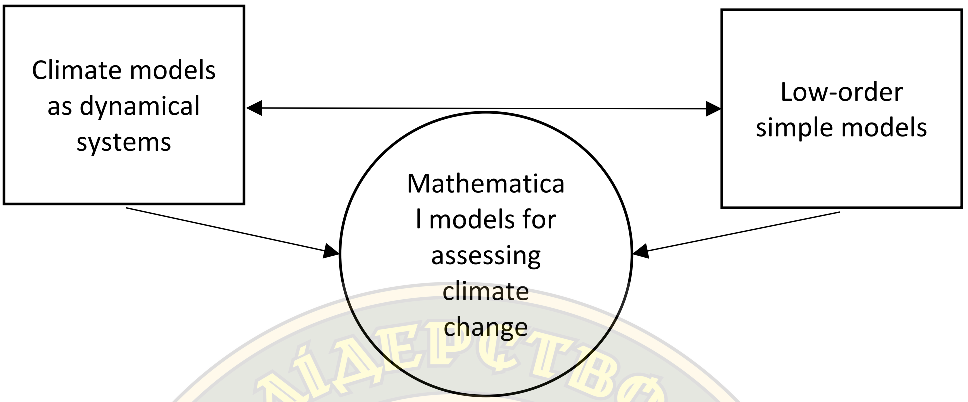

Figure 1 – Mathematical models for climate change assessment

Also, Fig. 1 shows that the use of climate models as dynamical systems and simple low-order models are usually complementary when trying to assess climate change.

Mathematical modeling is the most effective tool for studying climate change and predicting its future state in specific regions and at the global level. Mathematical modeling involves the development of a number of complex mathematical models in which the simulated processes of climate change are presented in the form of a dynamic system and described by a set of ordinary or partial differential equations. These equations are based on the basic laws of physics, such as the laws of conservation of mass, momentum, and energy. Some of the values used in these equations are the result of the work of information systems built on the basis of the Internet of Things concept and using the following technologies:

– a simple, compact technology is needed to identify each object. It is possible to collect and accumulate information about a certain subject only if there is a system of unique identification. Such functionality can be provided using RFID (Radio-Frequency IDentification) chips. They are able to transmit information to reading devices without their own power source. Each chip has an individual number;

– to monitor changes in the state of the element or the surrounding environment, objects must be equipped with sensors;

– an embedded computer) must be used for processing and accumulating data from sensors;

– wireless network technologies (Wi-Fi, Bluetooth) can be used to exchange information between devices;

– optimized and light-weight protocols such as MQTT are used for data transfer. They are based on the principles of publication and subscription where each device (transmitter or sensor) interacts with the program on the server (broker).

Using the concept of the Internet of Things to monitor climate change, through the use of sensors, provides basic values of temperature, humidity, pressure, and others. These parameters are then applied in mathematical models to process optimization and enhance sustainability efforts.

The next step of this scientific research is a review of the main mathematical models of climate change and the equations used to build them.

Ecological Site Classification (ESC) is a web-based decision support system that helps forest managers and planners select tree species that are ecologically suitable for specific sites, rather than selecting a species and trying to modify the site accordingly. Only mathematical modelling can serve as the main tool for studying the Ecological Site Classification. In a formalized form, a model of the ECS is a set of 3D nonlinear differential equations in partial derivatives that generates a deterministic finite-dimensional semi-dynamical system:

$$\frac{dx}{dt} = F(x, \lambda, f), \qquad x \in \{R\}^n,$$
$$x|_{\{t=0\}} = x_0, \; t \geq 0, \tag{1}$$

where x is the vector of state variables characterizing the system state at a given time t, x_0 is a given initial state of a system, n is the dynamical system dimension, $x \in \{R\}^n$ is the m-dimensional parameter vector and f is an external forcing.

Since analytical solutions for the climate system models are commonly not available, we used numerical methods to solve this Equation. The numerical solution of the discrete model equations is only possible with the use of high-performance computers.

A generalized discrete climate model, which is used in computer simulations, can be written in a formal form in the following way:

$$x_k = M_{\{0,k\}}(x_0), \; k = 1, \dots, K, \tag{2}$$

where $M_{\{0,k\}}$ is a nonlinear model operator that propagates state variables from the initial time t_0 to time t_k (this operator indirectly contains model parameters, including external forcing) and K is the number of time steps.

The system of equations of mathematical models that use parameters collected with the help of Internet of Things technologies consists of the following:

– two momentum equations;
– the thermodynamic equation;
– the equation for specific humidity that describes the hydrological cycle;
– the continuity equation;
– hydrostatic equation;
– the equation of state.

The two momentum equations have the following form:

$$\frac{\partial u}{\partial t} + \frac{1}{a\cos\varphi}\left[-\Omega p_S \vartheta \cos\varphi + \frac{\partial}{\partial\lambda}(\Phi + \text{К}) + \frac{RT\partial p_S}{p_S\partial\lambda} + \sigma\frac{\partial u}{\partial\sigma}\right] = F_u,$$
$$\frac{\partial\vartheta}{\partial t} + \Omega p_S u + \frac{1}{a}\left[\frac{\partial}{\partial\varphi}(\Phi + \text{К}) + \frac{RT\partial p_S}{p_S\partial\varphi} + \sigma\frac{\partial\vartheta}{\partial\sigma}\right] = F_\vartheta, \tag{3}$$

The mathematical statement of Newton's second law of motion is called the momentum equation. As momentum is a vector quantity, the momentum equation is a vectorial equation.

The thermodynamic equation is written in the following form:

$$\frac{\partial p_S T}{\partial t} + \frac{1}{a\cos\varphi}\left(\frac{\partial u p_S T}{\partial\lambda} + \frac{\partial\vartheta p_S \cos\varphi\, T}{\partial\varphi}\right) + \frac{\partial\sigma p_S T}{\partial\sigma} -$$
$$-\frac{RT}{C_p\vartheta}\left[p_S\sigma + \sigma\left(\frac{\partial p_S}{\partial t} + \frac{u\partial p_S}{a\cos\varphi\partial\lambda} + \frac{\vartheta\partial p_S}{a\partial\varphi}\right)\right] = p_S(F_T + \epsilon), \tag{4}$$

Thermodynamic equations relate various thermodynamic quantities and physical properties measured in laboratory or industrial processes.

The equation for specific humidity that describes the hydrological cycle is written in the following form:

$$\frac{\partial \mathrm{p_S q}}{\partial \mathrm{t}} + \frac{1}{\mathrm{a}\cos\varphi}\left(\frac{\partial \mathrm{u p_S q}}{\partial \lambda} + \frac{\partial \vartheta \mathrm{p_S} \cos\varphi \mathrm{q}}{\partial \varphi}\right) + \frac{\partial \sigma \mathrm{p_S q}}{\partial \sigma} = \mathrm{p_S}\left[\mathrm{F_q} - (\mathrm{C} - \mathrm{E})\right], \tag{5}$$

Specific humidity is defined as the ratio of air humidity to the absolute water vapor pressure of the air.

The continuity equation is written in the following form:

$$\frac{\partial p_S}{\partial t} + \frac{1}{a\cos\varphi}\int_0^1 \left(\frac{\partial p_S u}{\partial \lambda} + \frac{\partial \vartheta p_S \cos\varphi}{\partial \varphi}\right)\partial\vartheta = 0, \tag{6}$$

The continuity equation is used to describe conservation of atmospheric mass. Conservation means that in an isolated system that parameter remains constant. It’s not created. It’s not destroyed. But it can move around. There are certain parameters (energy, momentum, mass, air, water, ozone, number of atoms, etc.) that must be conserved.

The hydrostatic equation is expressed as:

$$\frac{\partial \Phi}{\partial \vartheta} = -\frac{RT}{\vartheta} \tag{7}$$

The change in pressure with change in altitude is equal to the average air density multiplied by the gravitational constant. The negative sign is due to the fact that pressure decreases with height (usually when plotting a graph, values on the y-axis increase with height, this is the opposite of atmospheric pressure). The quantity on the right side of the equation is the density. Air density is a function of temperature and humidity. An increase in water vapor content and/or an increase in temperature leads to a decrease in density. In very cold air, the air is very dense. Therefore, $\partial\Phi$ / $\partial\vartheta$ is large in cold air (the change in pressure with height is large). This means that in cold air the pressure drops quickly, and the thickness of the cold air mass is small (the atmosphere thins vertically when it is cold). In warm air, the opposite is true, warm air expands and occupies a larger volume. The thickness of warm air and the depth of the atmosphere are greater in a warm air mass. Because warm air has a low density, the change in pressure with height in warm air is less than in cold air.

The thermodynamic equation connecting the state variables is written in the form:

$$p = \rho R T_\vartheta \tag{8}$$

The equation of state establishes a direct relationship between density and pressure, an inverse relationship between density and temperature, and a direct relationship between temperature and pressure.

Here ϑ and u are the meridional and zonal components of the wind; a is the Earths mean radius; $\sigma = d\sigma/dt$ is an analogue of the vertical speed in the σ coordinate system; T is temperature; Φ – geopotential; $\Omega = \zeta + f$ is the absolute vorticity, where ζ is the relative vorticity; f is the Coriolis parameter; K is the kinetic energy; R is the gas constant for dry air; q is the specific humidity; C_p is the specific heat of dry air at constant pressure; T_ϑ is the virtual temperature; and ρ is the air density. The terms F_u and F_ϑ describe the vertical friction and the horizontal diffusion processes; ϵ is the diabatic heating rate; F_T and F_q describe the vertical and horizontal diffusion of heat and water vapor, respectively; and C and E describe the source and sink processes for water vapor, respectively.

The considered equations of mathematical models demonstrate the importance of monitoring climate changes by means of the Internet of Things, as the equations contain parameters that are physical quantities used to denote various climatic phenomena.

The last step of this scientific research was the determination of the climate response time to various factors based on the equation of the two-block EBM model.

It is very important to point out that although the mathematical models developed in various research centers fairly consistently predict warming in the future, the indicators that characterize the response of the climate system to radiation pollution differ significantly from model to model.

Simple linear systems, such as the two-block EBM with additive stochastic forcing, which is parameterized by Gaussian white noise, have proven useful for investigating climate change on time scales ranging from years to decades. These models are able to explain much of the observed climate change on time scales ranging from annual to several decades. The equation of the two-block EBM model has the following form:

$$C\left(\frac{dT}{dt}\right) = -\lambda T - \gamma(T - T_D) + F_S$$
$$C_D\left(\frac{dT_D}{dt}\right) = \gamma(T - T_D), \qquad (9)$$

where C is the effective heat capacity of the upper box, consisting of the atmosphere and the oceanic surface mixed layer and characterized the climate system inertia; λ, which is called the climate feedback parameter, is the proportionality coefficient between the radiative response and the global mean surface temperature (GMST); γ is the deep ocean heat uptake parameter; $C_D$is the effective heat capacity of the deep ocean; and F_S is the stochastic forcing.

The response of the climate to the radiation impact caused by human activity has a wide range of time scales.

For example, the response time of the atmosphere is only a few weeks. The reaction time of a system that includes not only the atmosphere but also the ocean layer is several years, while a system that includes the deep ocean characterized by time scales from decades to centuries and even longer.

Signs of the fundamental nature of the conducted research are that the research results can become the basis for new fundamental, applied works and developments and that the research has a broad theoretical base.

The scientific novelty of the conducted research is determined; the integration of IoT and mathematical models for environmental protection was reviewed for the first time; revealed regularities of building mathematical climate models; patterns of integration of the Internet of Things and mathematical models were revealed.

Conclusions. The integration of the Internet of Things for climate monitoring and real-time environmental data collection provides the necessary parameters for their further use in mathematical models of climate change prediction. Mathematical models of climate change predictions are based on a set of equations that have numerical values and are usually solved by computer because of their complexity.

The use of IoT and mathematical models in the assessment of climate change contributes to the optimization of energy efficiency, monitoring of air quality and strengthening of sustainable development efforts.The use of climate models as dynamical systems and simple low-order models are usually complementary when trying to assess climate change. For detailed modeling of physical, chemical and biological processes in the atmosphere, ocean, land and cryosphere, it is necessary to use the most powerful supercomputers capable of creating a forecast of climate change.

Global and regional climate change projections have a rather high degree of uncertainty for scenarios of greenhouse gas emissions.The effectiveness of the scientific research is confirmed by the fact that with the help of the review of the integration of IoT and mathematical models for environmental protection, for the first time, the regularities of the construction of these mathematical models and their integration with the Internet of Things were revealed.

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ІНТЕГРАЦІЯ IOT ТА МАТЕМАТИЧНИХ МОДЕЛЕЙ У ПОМ’ЯКШЕННЯ НАСЛІДКІВ ЗМІНИ КЛІМАТУ

Описано стратегію використання пристроїв «інтернет речей» для збору даних про навколишнє середовище в реальному часі, що враховує найбільш значущі показники. Також визначено переваги використання інтернет речей, що дає можливість моніторити стан клімату у зручному режимі з високою точністю та швидкістю. Оскільки задача аналізу за допомогою математичних моделей для оптимізації енергоефективності, моніторингу якості повітря та посилення зусиль щодо сталого розвитку складна, то вона потребує залучення окремих спеціалістів, таких як системні аналітики, математики та кліматологи. Отриманими, шляхом використання пристроїв «інтернет речей» параметрами для аналізу є температура, вологість і опади та інші. Розглянуто такі кліматичні моделі як динамічні системи та прості моделі низького порядку для вивчення мінливості клімату, також описані рівняння: імпульсу, термодинаміки, питомої вологості, непервності, гідростатичне та термодинаміки, що з'єднує змінні стану. Пояснено використання цих рівнянь в рамках розглянутих моделей та значення їх параметрів, частина з яких є результатом, що отриманий за допомогою роботи технологій інтернет речей. Також описані необхідні технології, що потрібні для побудови мережі інтернет речей: мікросхеми, сенсори, вбудований комп’ютер, бездротова мережа та протоколи.

Кліматичні моделі різного ступеня складності використовуються для прогнозування зміни клімату та мінливості у глобальному та регіональних масштабах. Математичні і кліматичні моделі дуже важливі для підготовки суспільства до розробки та реалізації так званих стратегій адаптації та заходів, необхідних для зменшення наслідків зміни клімату. Під адаптацією розуміється процес звикання суспільства до поточних і прогнозованих змін кліматичної системи та її впливів. Науковою новизною дослідження визначено те що вперше був проведений огляд інтеграції IoT і математичних моделей для захисту навколишнього середовища, що дозволило зрозуміти закономірності побудови цих математичних моделей і виявити закономірності такої інтеграції.

Отримані результати дослідження, як у теоретичному, так і практичному плані, служать основою для подальших науково-прикладних праць, спрямованих на удосконалення та покращення різних аспектів використання пристроїв «інтернет речей» для збору даних про навколишнє середовище в реальному часі та їх подальшого аналізу за допомогою математичних моделей для оптимізації енергоефективності, моніторингу якості повітря та посилення зусиль щодо сталого розвитку. Описана стратегія використання інтернет речей та математичних моделей є важливою для життя будь-якої людини, роботи підприємств та органів влади. В довготривалій перспективі саме використання технологій «інтернет речей» та математичних моделей у пом’якшенні наслідків зміни клімату може дати позитивний вплив на розвиток всієї людської цивілізації.

Ключові слова: інтернет речей; математична модель; динамічна система; зовнішній вплив; головне рівняння.