UDC 004.9+728.1
DOI: 10.15587/1729-4061.2024.301882

DESIGN OF PROACTIVE MANAGEMENT SYSTEM FOR RESIDENTIAL BUILDINGS BY USING SMART EQUIPMENT

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This study's object is an energy efficiency of residential sector. The work is aimed at solving the task to improve the energy efficiency of the housing sector by devising technical solutions for monitoring and managing energy consumption and microclimate parameters of buildings. The proposed proactive management system for residential buildings consists of multi-sensors measuring CO_2, temperature and humidity, smart meters of heat and electricity consumption, and smart plugs. The equipment is combined into single system through an integration controller with remote user access through an interactive web interface. A feature of the technical solution is the ability to collect, process, visualize, and archive data on the consumption of energy, as well as on the key parameters of the microclimate of residential premises. The advantages of the system are its flexibility due to the possibility of integrating additional devices during operation, as well as the use of standard communication protocols, which enables the interchangeability of component elements. The implementation and testing were carried out under the conditions of a real pilot site. The use of the system in practice confirmed the efficiency and stability of the operation, making it possible to obtain data on the parameters of energy consumption and microclimate and devising recommendations for reducing energy consumption at the pilot site. It was established that the microclimate meets the requirements of the standards (air temperature is about 22 °C while relative humidity does not exceed 60 %). Decrease in energy consumption can be achieved by reducing the temperature of the heat carrier in the absence of residents, as well as by considering the influence of weather conditions. During periods of residents activity, an excess of the permissible level of CO_2 was recorded, therefore, automatic ventilation systems should be provided in the apartments

Keywords: energy efficiency, energy management, residential building, smart equipment, internet of things, energy demand, occupants' well-being

Received date 06.02.2024
Accepted date 08.04.2024
Published date 30.04.2024

How to Cite: *Savytskyi, M., Shekhorkina, S., Bordun, M., Babenko, M., Tsyhankova, S., Spyrydonenkov, V., Savytskyi, O., Rabenseifer, R. (2024). Design of proactive management system for residential buildings by using smart equipment. Eastern-European Journal of Enterprise Technologies, 2 (8 (128)), 16–25. https://doi.org/10.15587/1729-4061.2024.301882*

1. Introduction

Energy consumption by buildings is up to 40 % of global demand, and total greenhouse gas emissions are about 35 % of the total volume. Moreover, the residential and communal sector is characterized by a high percentage of energy losses because of low quality of management [1]. In this context, strategies and tools for improved consumption structure management, planning and implementation of energy saving measures in buildings have significant potential.

Improving energy efficiency throughout the energy chain, from energy production to its distribution and use, is a priority area for the European Union (EU). Rational use of energy is seen as a key aspect of reducing environmental damage, reducing greenhouse gas emissions, increasing energy security, and decreasing utility bills for households.

In 2023, the European Parliament adopted the updated Energy Efficiency Directive (EU) 2023/1791 [2], which provides for a mandatory reduction of energy consumption in the EU by 11.7 % by 2030 (compared to the baseline scenario of 2020). To achieve climate neutrality according

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to the Energy Performance of Buildings Directive [2], from 2028 all new buildings must have zero emissions. According to this document, all existing buildings must meet minimum energy efficiency standards.

Reducing the costs of providing buildings with energy resources can be achieved by applying special engineering and technical solutions to control and optimize energy consumption. One of them is to design energy-efficient building management systems using "intelligent" or smart technologies and the Internet of Things (IoT) concept. IoT devices enable the collection of consumption data, the analysis of which can provide useful information for building management strategies. At the same time, remote control and adjustment of building systems is provided. Instead of the usual passive use, it becomes possible to switch to proactive resource management, which involves tracking energy consumption in real time and early identification of opportunities to optimize the operation of equipment and devices. This improves the efficiency of implementation of energy saving measures.

Based on the above, research into the area of modern energy management systems of residential buildings using smart technologies is extremely relevant.

2. Literature review and problem statement

The authors of paper [3] propose a web application with the possibility of remote access for controlling electrical equipment. The principle of operation of this solution is quite simple – the user can set the operating mode of household appliances at his/her own discretion, which enables control over energy use. However, the developers did not foresee the possibility of collecting and storing data, which imposes a significant limitation on the analysis and forecasting of consumption.

A monitoring system integrated with an intelligent control panel for continuous control of electricity use, automatic registration of the load in the electrical network and recording of consumption data is presented in work [4]. The experimental prototype system consists of an intelligent panel, a local computer network, a database server as a data store, a web server containing a system controller program, and a power monitoring display. The intelligent panel contains a built-in operating system that corresponds to the reading of input signals from connected devices, as well as a meter of electrical quantities that constantly records electricity consumption. The disadvantage of this system is the consideration of only one energy resource, while the vast majority of buildings and structures use different types of energy.

Paper [5] reports the results of the development of technical documentation and a software product for the building's energy management system. The architecture of the program makes it possible to execute automated control over an integrated set of functions in the building, to transmit or receive information from various devices and sensors that are connected to the system (switch drives, motion, temperature and lighting sensors, etc.). The program can be adapted both for intelligent building automation systems according to the general KNX standard, and for proprietary systems controlled by the gateway (Xiaomi or Google Home). However, the authors provide only theoretical provisions regarding the general structure and functionality of the software product, and the next step is to test its beta version.

Work [6] describes the architecture of the energy management model based on full supervisory control and data collection (SCADA). The model consists of a photovoltaic electricity generator, a battery system for energy storage, a smart switchboard, and several connected electrical appliances, some of which are controlled and managed (lighting, air conditioning, operation of smart sockets). Communication in the system takes place using standard Modbus and Konnex protocols. The resulting solution was tested under laboratory conditions, which showed the autonomy of the system's energy supply. However, to confirm the results in practice, it is necessary to scale the experimental model and test it under the conditions of a real building.

An innovative general structure of energy resource management in a community of flexible smart buildings in the presence of local sources of renewable energy is presented by the authors of [7]. The proposed algorithm uses user participation to allow them to select a power consumption profile for a day in advance, and subsequently provides intraday forecast tracking. In practice, the algorithm is fully decentralized using Blockchain technology, which provides a reliable communication environment between participants and provides autonomous monitoring and generation of electricity bills. The simulation results showed that the algorithm promotes the use of locally produced energy, and with a special tariff structure, peak demand can be reduced. The disadvantage of the work is the lack of practical implementation, as well as indirect consideration of the level of comfort of residents.

In study [8], the system of energy management of buildings, taking into account energy, environmental, social and financial constraints, is considered, aimed at increasing energy efficiency, the quality of the internal environment and reducing the impact of buildings on the environment. In addition to taking into account energy consumption, during the development of the energy management system, a method of collecting data on the energy activity of the building's residents and the intensity of energy consumption was proposed. Implementation of the proposed system can be used for predictive analysis of energy consumption in the future.

One of the trends in the field of energy saving optimization is the development of expert analytical tools that will be included in commercial platforms. In particular, in paper [9], the authors investigate the expediency of using new intelligent control methods in modeling and managing the operational characteristics of the building using theories of fuzzy logic. Multi-level intelligent controllers for controlling various building automation components and increasing its energy efficiency are presented, and theoretical modeling of the building's energy management system is performed. The authors of [10] propose a complex algorithm based on fuzzy logic for optimizing the operation of heating, ventilation, and air conditioning systems, as well as predicting future maintenance of the building's main equipment. The basic function of this development is to replace the analysis and interpretation of data performed by humans with software that simulates analytical procedures. To this end, the authors used an array of medium-term energy consumption data. The algorithm of intelligent forecasting was tested on the example of a real building, which made it possible to reveal its limitations. In the event of equipment malfunctions or excessive energy consumption because of human factor in the building, the results of the algorithm differed from the actual values of the building's energy consumption parameters.

A number of studies [11, 12] tackle more sensitive so-called proactive energy management schemes. The goal is to design energy management systems capable of making strategic decisions, taking into account real-time forecasting, planning, and control. The proposed systems are designed for so-called building energy supply microgrids, which can work independently or together with the main power grid and use different energy sources (renewable energy generators, energy storage systems and conventional generators). State-of-the-art advancements include the development of self-adaptive algorithms [13] and the implementation of machine learning tools [14] for automated control and supervision of building systems. The efficiency of such systems depends significantly on uncertainties in the generation of energy from renewable sources (such as solar radiation, wind speed, etc.), demand profiles, efficiency of energy conversion subsystems, etc. A separate problem of this kind of systems is the excessive complexity of the architecture, which leads to the irrationality of use in the case of traditional configurations, which are still characteristic of residential buildings in many European countries and, in particular, in Ukraine.

Our review of technical advancements in the field of energy management of buildings showed that, despite the large number of works, most are limited to theoretical aspects or are aimed at monitoring and managing one energy resource (usually, electricity). The use of any theoretical model requires verification under real conditions. The proposed systems are characterized by the complexity of changing the configuration when it is necessary to add or remove a monitoring element. At the same time, there is no collection of data on the parameters of the microclimate of buildings, which has a significant impact on the behavior of residents and, as a result, on energy consumption. Thus, there is a need for further development of technical solutions for energy management systems of buildings using intelligent technologies and equipment, which would meet the criteria of proactivity, flexibility, taking into account the needs of direct consumers in creating comfortable living conditions, and which would have been tested on a real object.

3. The aim and objectives of the study

The purpose of our study is to devise a technical solution for a flexible system of proactive management of energy consumption and microclimate parameters of residential buildings based on smart equipment and the concept of the Internet of Things (IoT). Testing of the proposed solution under the real conditions of the pilot facility will allow monitoring and analysis of energy resource consumption of various types (electrical and thermal) and microclimate parameters (temperature, humidity and CO_2 level). The obtained data will make it possible to propose potential scenarios for reducing energy costs while ensuring comfortable conditions in the premises. Due to the demonstration of the results, the level of awareness of potential stakeholders regarding the benefits of using the system will be increased.

To achieve the goal, the following tasks were set:

– to design the architecture of an Internet of Things network for the technical solution of the system of proactive management of residential buildings based on smart equipment;

– to test the proposed solution under real conditions of the pilot facility.

4. The study materials and methods

4. 1. Methodological basis of the study

The object of the study is the energy efficiency of the residential sector.

The development and implementation of a proactive management system at the local level of the building will make it possible to obtain objective information about the consumption of heating, ventilation, air conditioning, and household appliances. Real data will make it possible to balance the operation of the building's equipment, and as a result reduce operating costs, while providing the necessary level of comfort for residents. This provision is the working hypothesis of this paper.

Energy consumption can potentially be minimized. Nevertheless, a simple reduction of the energy consumption of the building will not make sense if, at the same time, comfortable parameters of the microclimate of the premises are not provided. In the absence of comfort, people are inclined to take measures to increase it, which can negate measures to save energy for heating, cooling, lighting, and household needs. The use of a proactive management system should contribute to a more rational consumption of electrical and thermal energy while meeting the requirements for the quality of the microclimate of the premises. Air environment factors such as temperature, humidity, and air quality (CO_2 carbon dioxide concentration) are most important for the feeling of comfort. Recommended parameters of comfortable conditions of the microclimate of residential buildings for the normal well-being of people according to the state standards of Ukraine [DSTU B EN 15251 (EN 15251:2007), DBN B.2.2-15, DBN B.2.6-31, DBN B.2.5-67] [15–20] are given in Tables 1–3.

Table 1

Recommended indoor temperature for residential buildings

Type of room	DSTU B EN 15251 (EN 15251:2007) [15]	DBN B.2.2-15 [16]	DBN B.2.6-31 [17]	DBN B.2.5-67 [18]
Bedrooms	20 °C (winter) 26 °C (summer)	22±2 °C	20 °C	22±2 °C
Kitchen, living room		19.5±3 °C		19.5±3 °C
Bathroom		25±1,5 °C		25±1,5 °C
Toilet		22±2 °C		25±1,5 °C
Corridors	16 °C (winter)	19.5±3 °C		19.5±3 °C

Table 2

Recommended relative humidity in residential buildings

DSTU B EN 15251 (EN 15251:2007) [15]	DBN B.2.5-67 [18]	DBN B.2.2-15 [16]	DBN B.2.6-31 [17]
60 % (limit value for dehumidification) 25 % (limit value for humidification)		55 %	

Table 3

Recommended level of CO_2 concentration in the indoor air of residential buildings

DSTU B EN 15251 (EN 15251:2007) [15]	DBN B.2.5-67 [18]
400–600 ppm	

The system of proactive management of residential buildings, which is being developed, must meet the following requirements:

– the possibility of constant monitoring and control of environmental parameters in the premises;

– receiving and processing data in real time;

– accumulation and transfer of information to the cloud service;

– management of energy consumption to reduce energy costs;

– ensuring the comfort of residents.

At the same time, the building management system should be flexible in its structure, i.e., provide the possibility of changing the configuration during operation and provide for the security of the received data.

The basis of the technical solution, which is developed within the scope of this work, is the intelligent system of a smart house. The structural unit of the system is physical devices ("things"), which collectively form the Internet of Things (IoT) network. Connecting physical devices to the network and transferring data is enabled by a communication protocol. The chosen protocol provides standardized communication between devices on the network, ensuring interoperability and seamless data transfer. A system integrator with the appropriate software is responsible for receiving, storing, and processing the data generated by the devices. The user interface makes it possible to visualize monitoring parameters and manage and optimize the operation of equipment, household appliances, and systems in real time. As a result, a single multi-level structure of monitoring and management of energy consumption and microclimate parameters of a residential building will be obtained.

The main assumption is the prerequisite for the proper use of the developed proactive management system by the residents of the house, that is, the installation of smart sensors according to the purpose at the agreed points within the premises and uninterrupted data transmission.

4. 2. Pilot facility for implementation of results

The research was conducted within the framework of the PRECEPT project [19] at the pilot facility – the Panorama residential complex (Fig. 1).

The Panorama complex is located in the city of Dnipro, the central part of Ukraine. According to the region, the climatic conditions for heating systems are characterized by the following indicators:

– the average temperature of the coldest five days is –24 °C;

– the average temperature of the outside air during the heating period (from October 15 to April 15) is –0.2 °C;

– duration of the heating period is 175 days.

The complex consists of five apartment buildings, including two 19-story and three 24-story buildings (commissioned in 2017). Apartments in the complex contain different numbers of rooms of different sizes, with different numbers of residents. The complex consists of 1,008 one-, two-, and three-room apartments with a 3-story parking lot. The area of the apartments is from 46.3 to 121 m^2 with the possibility of free planning. The supporting structures of the buildings are made of reinforced concrete. External walls are aerated concrete blocks insulated with mineral wool. Windows are double-glazed units with a heat transfer coefficient from 0.85 to 2.42 W/m^2K (depending on the size and number of window panels). Technical solutions for the buildings at the complex include ventilated energy-saving facades, energy-saving panoramic glazing, individual gas boiler rooms, elevators, fire alarms, smoke removal and fire extinguishing systems.

Fig. 1. Pilot object — Panorama residential complex

As the data from the sensors will be continuously transmitted in real time, this will potentially lead to the formation of a large amount of data. In view of this, to simplify the further analysis within the scope of this work, typical apartments with an area of 120 m^2 were chosen for the installation of smart equipment.

Available utilities and amenities in typical apartments include electricity, heating, and water. In addition, each apartment has a TV, refrigerator, water heater, microwave oven, dishwasher, washing machine, and dryer. Accordingly, each apartment has different levels of consumption of resources: electricity; hot water for hot water supply; hot water for heating systems; cold water. Hot water supply and heating is provided centrally by a gas boiler room on the roof of the building. The cooling system includes individual electric air conditioners.

5. Results of research on the system of proactive management of residential buildings based on smart equipment

5. 1. Architecture of the Internet of Things network for the technical solution of the proactive management system of residential buildings based on smart equipment

The technical solution of the system for proactive management of apartments in the residential complex provides monitoring and management of heat and electricity consumption, microclimate parameters (temperature and humidity), and air quality (carbon dioxide level).

Within each apartment selected for implementation, it is planned to install the following smart equipment:

– smart meter of electricity consumption (installed in the floor distribution cabinet);

– smart heat energy consumption meter (installed in the heat meter chamber);

– wireless multisensors in bedrooms for measuring temperature and air humidity;

– a wireless multi-sensor in the common room (combined kitchen, living room and recreation area) for measuring temperature, air humidity, and CO_2 level;

– smart sockets with a power monitoring function for measuring and managing the electricity consumption of household appliances (refrigerator, boiler, and circulation pump).

The scheme for installing smart equipment in a typical apartment of a residential complex is shown in Fig. 2.

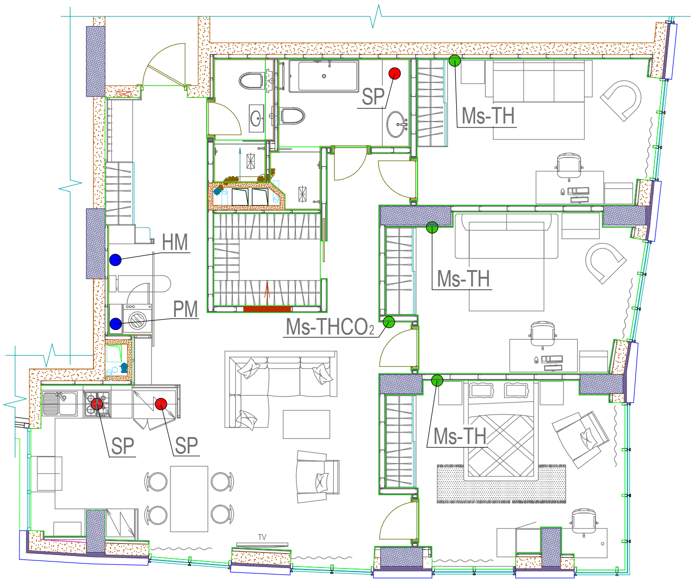

Fig. 2. Scheme for installing smart equipment in a typical apartment in a residential complex: PM – smart electricity consumption meter; HM – smart heat energy consumption meter; Ms-TH – multi-sensor of air temperature and humidity; Ms-THCO$_2$ – multisensor of temperature, air humidity, and CO$_2$ level; SP – smart outlet

The principle of interaction among the system components is as follows. Multi-sensors measuring CO$_2$, temperature, and humidity in the room are represented by 7bit AirPoint-Q air parameter monitoring modules, which transmit the received data via the LoRa radio channel (frequency 868 MHz, power 25 mW). The system uses a 7bit AirGate wireless communication gateway to receive data from the monitoring module. This module receives and forwards the monitoring data acquired over the radio channel to the upper-level system using the MQTT network protocol via a local network or the Internet in transparent bridge mode. 7bit AirPoint/AirGate modules have small dimensions (70×70 mm) and a neat appearance, which makes it possible to harmoniously integrate the devices into the general interior of the room.

Monitoring of heat and electricity consumption is implemented using smart meters with built-in data transmission interfaces using the Modbus RTU (RS-485)/Mbus communication protocol via serial communication lines. Data reading by the upper-level device via RS-485 occurs directly, and a 7bit USB-Mbus converter is used for Mbus.

Smart sockets connect to the control system via IEEE 802.11n (Wi-Fi).

All data collection modules and smart sockets are combined into one system using an integration controller. The real-time controller provides data collection on monitoring parameters, their processing, visualization, and archiving, as well as remote user access to the received information. In addition, the integration controller exports data for analytics or energy management systems via the MQTT protocol or using an API. In the proposed solution, the WebHMI hardware device was used, which is a full-fledged SCADA system with a built-in web server [20]. The controller has built-in support for most popular industrial data exchange protocols, and also makes it possible to easily add non-standard devices using the "Custom protocol" function. The "Multi-protocol" function makes it possible to connect devices with different communication protocols to one bus and provides the user with practically unlimited communication options through the built-in RS-485, USB, Ethernet LAN, and WAN ports.

The schematic diagram of the technical solution for the system of proactive management of residential buildings based on smart equipment is shown in Fig. 3.

The collected data are grouped and converted into the required format using the Lua scripting language built into WebHMI, and then sent via the MQTT protocol to the analytics system (Fig. 4).

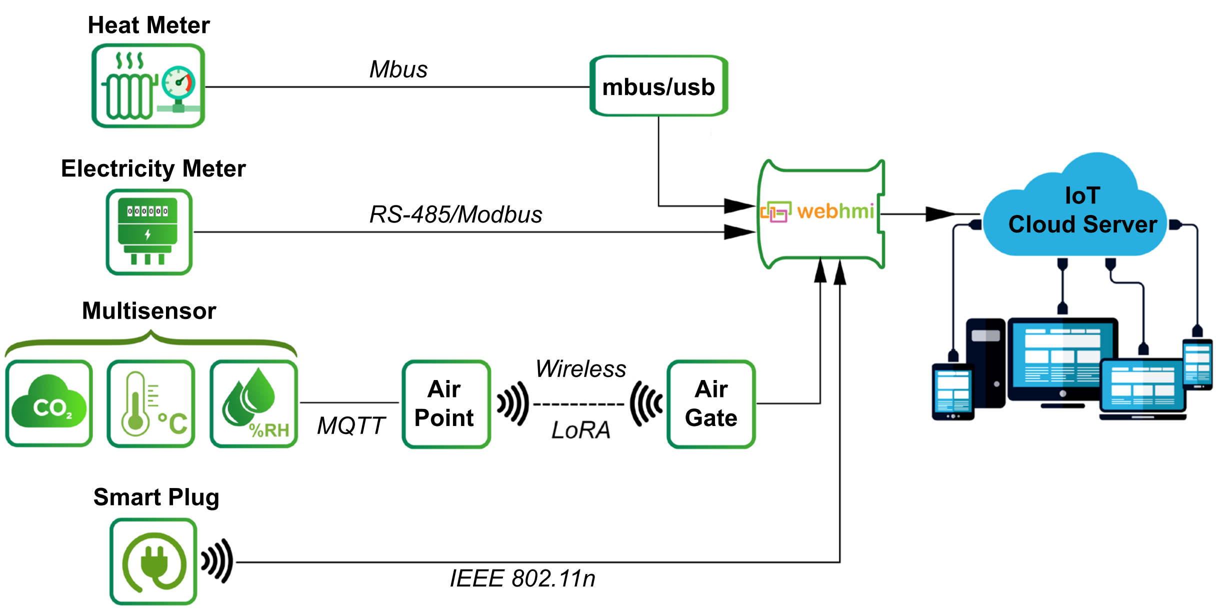

Fig. 3. Schematic diagram of the technical solution for the proactive management system of residential buildings based on smart equipment

User interaction with the proactive management system takes place over the network through the WebHMI web interface. This applies to both the use of the system and its configuration. The user configures pages in "Drag&Drop" mode, clicks "Save changes", and immediately sees the result of his/her actions. Thus, all possible functionalities can be developed using embedded software using a web browser. If necessary, any changes can be made in the project promptly. Working with the software resembles working in a personal web application cabinet. Owing to the flexible role and user management mechanism, the system can be used by many users at the same time, but everyone will see only the authorized parts of the system. Access to the personal account is carried out by logging in through a browser to WebHMI (both on the local network and remotely via VPN) using a login and password (Fig. 5). For access, one can use any electronic device with access to the Internet (computer, laptop, tablet, or smartphone). The general view of the start page of the user's personal account of the system for proactive management of residential buildings based on smart equipment is shown in Fig. 6.

Fig. 6. General view of the start page of the personal account of the user of the proactive management system of residential buildings based on smart equipment

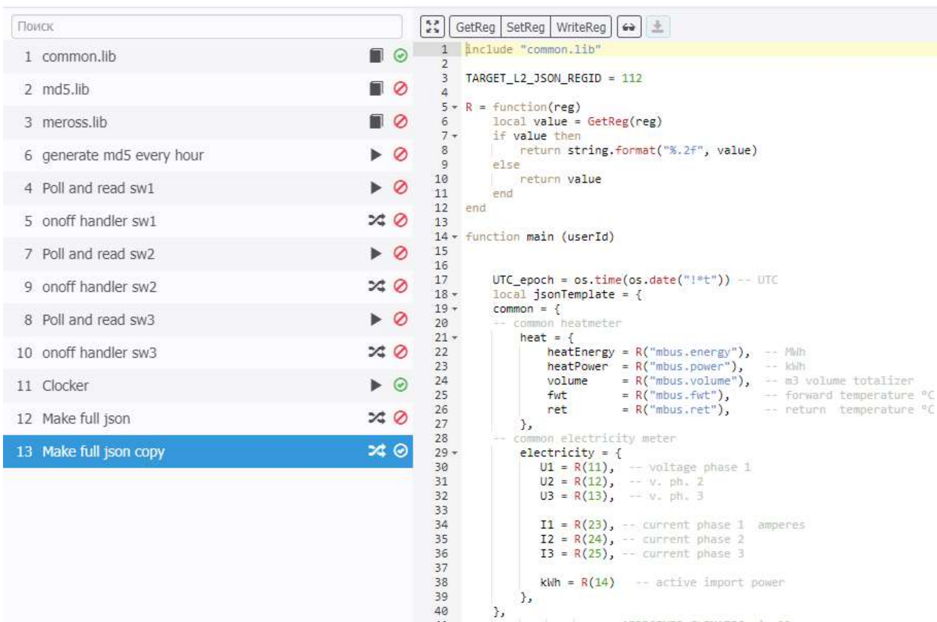

Fig. 4. Data collection and processing script

As can be seen from Fig. 6, the interface of the personal office is intuitive for the user, it displays the general scheme of the premises of the apartment with installed smart equipment and the performance indicators of household appliances connected to the system.

5. 2. Results of testing the proposed solution under real conditions of the pilot facility

As a result of testing the proposed technical solution for the proactive management system of residential buildings based on smart equipment, arrays of data on daily energy consumption and changes in the microclimate parameters of the premises were obtained.

Fig. 5. User authorization page in the proactive management system

In order to illustrate and analyze the monitoring data, the corresponding plots, typical for the working day and for the weekend, were built for the following parameters:

– current consumption from smart sockets (Fig. 7);
– change of heating capacity (Fig. 8);
– room temperature (Fig. 9);
– relative humidity in the premises (Fig. 10);
– the CO_2 level in the common room (Fig. 11).

It should be noted that, as monitoring showed, the operation of the circulation pump is continuous and characterized by a constant power value of $P\approx6$ W. In view of this, the plot of change in the electric current consumption from smart sockets (Fig. 7) shows data only for the refrigerator and water heater.

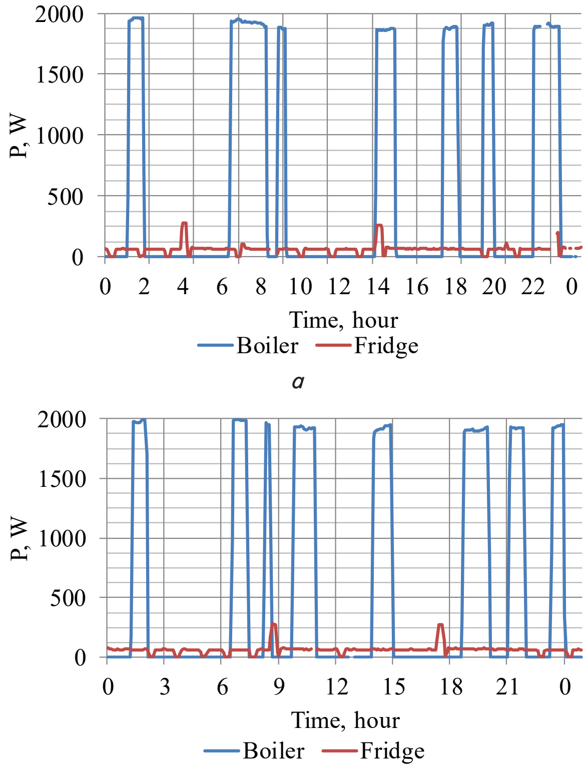

Fig. 7. Change in electric current consumption from smart sockets (P, W): *a* – working day; *b* – day off

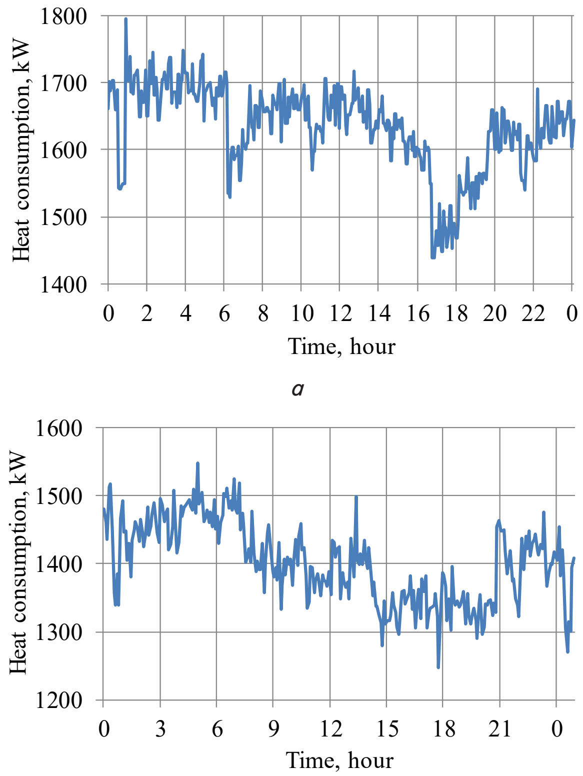

Fig. 8. Change in heating capacity: *a* – working day; *b* – day off

Plots in Fig. 7–11 confirm that monitoring data is collected, archived, and transmitted to the analytics system continuously. The system makes it possible to display and analyze the power of electric current consumption, heating power, temperature, CO_2 concentration, and relative humidity both within the selected period and in general during the test.

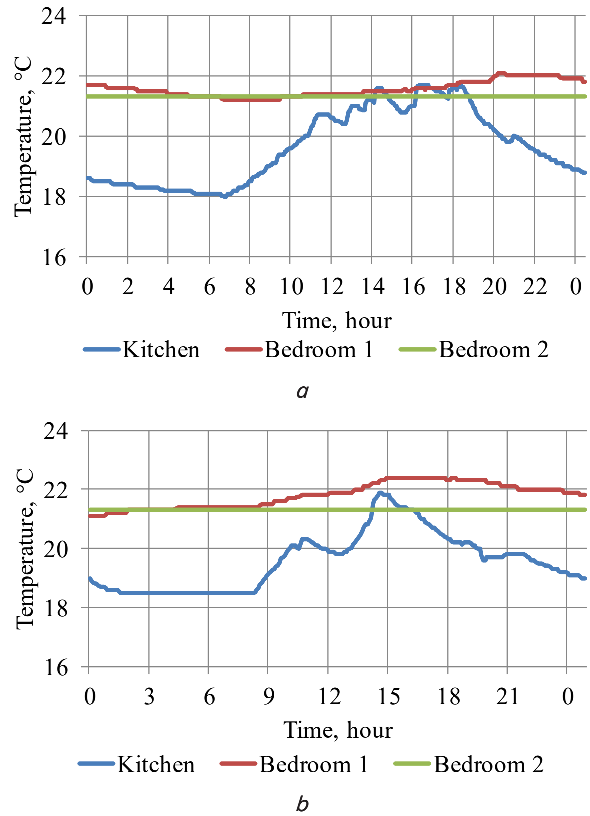

Fig. 9. Indoor air temperature: *a* – working day; *b* – day off

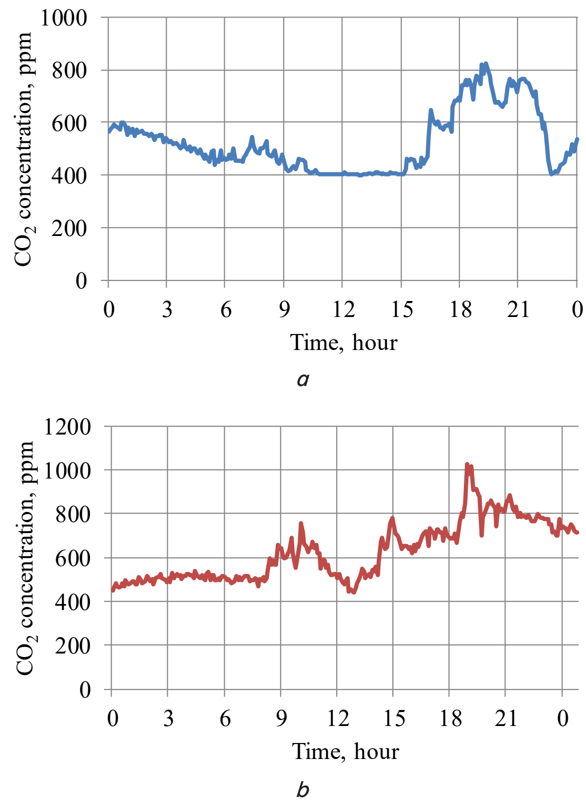

Fig. 10. CO_2 concentration in the common area: *a* – working day; *b* – day off

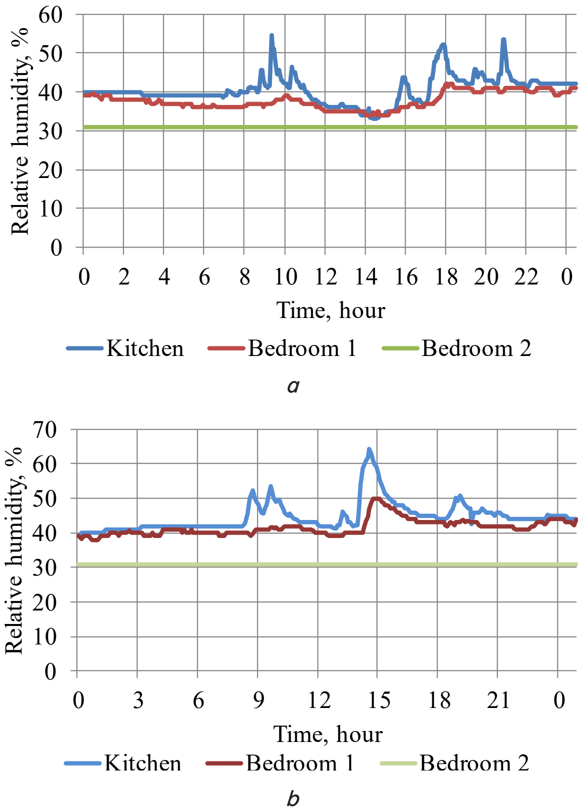

Fig. 11. Relative humidity in the premises: *a* — working day; *b* — day off

The user accesses their energy consumption through a visual representation together with the internal conditions of the residence (temperature, humidity, CO_2). It is possible to check and monitor the consumption by looking at an overview consisting of an easy-to-understand consumption summary. The user can choose different levels of detail (day, week, month, or arbitrary periods) to check, navigate consumption for different periods by choosing the start and end dates and times.

6. Discussion of results of investigating the system of proactive management of residential buildings

The proposed proactive residential building management system consists of CO_2, temperature and humidity multi-sensors, smart heat and electricity consumption meters, and smart sockets (Fig. 3). The equipment is combined into one system through an integration controller with remote user access through an interactive web interface (Fig. 6). A feature of the technical solution is the ability to collect, process, visualize and archive data on energy consumption and, at the same time, on the key parameters of the microclimate of residential premises.

Unlike the existing ones, the system collects and processes data not only on the consumption of electrical and thermal energy but also on the key parameters of the microclimate of residential premises (temperature, humidity, and carbon dioxide level). This makes it possible to monitor and manage energy consumption and at the same time ensure the necessary level of comfort for residents.

The advantages of the system are its flexibility, that is, the possibility of integrating additional devices during operation and using standard work protocols, which enables interchangeability of constituent elements, as well as the use of elements in its architecture that are based on standard work protocols. Thus, if necessary, it is possible to expand or deepen the system by integrating additional devices (sensors, smart equipment) for more precise monitoring, and combining the same systems, for example, several apartments or houses to scale the solution. All elements of the system have the same manufacturing and operation protocols as elements from more well-known brands, such as Siemens or Schneider, so they are interchangeable. Installed elements of the system (devices and sensors) have a long availability period, that is, any component of the system is produced by manufacturers for a long time (10 or more years). Therefore, if necessary, even after 5 years, one element can be replaced with another. For example, the controller installed in the proposed system has been produced since 2012 and its production will continue in the near future.

The results of testing the proposed technical solution of the proactive management system of residential buildings based on smart equipment and the concept of the Internet of Things (IoT) showed the stability of operation. Data on energy consumption, microclimate, and air quality parameters were transferred to the analytics system without interruption. Users can get data both on aggregate energy consumption and separately for each device. Disaggregated information about consumption is provided to the user in a user-friendly form (for example, in a detailed visualization of energy consumption).

If we analyze the plots in Fig. 9–11, it can be noted that the measured microclimate parameters (air temperature, relative humidity, and CO_2 level) are mostly within the limits of regulatory requirements. In this way, a comfortable stay of residents in the premises is ensured.

Analyzing the plots of air temperature changes in the premises, the following can be noted. On working days, the numerical values of the air temperature in the bedrooms are at the level of 22 °C during the day. The air temperature in the kitchen is at the level of 18 °C during the dark period of the day from 22:00 to 08:00. After 8:00, the air temperature starts to rise. The peak temperature rise occurs at 14:00–16:00 hours, after which the temperature begins to gradually decrease and reaches 18 °C by 22:00. A similar situation is observed on weekends. Based on this, it can be concluded that the constant temperature in the bedrooms is maintained by the space heating system. The increase in temperature in the kitchen is likely to be influenced by external factors such as solar heat gain through transparent enclosing structures. This is indicated by the similarity of the temperature plots on different days (working days – when a person is not in the room, weekends – when, on the contrary, a person is present in the room) and the location of the building relative to the cardinal points. It is also possible to see on the plot of consumption of heat carriers that during the specified period, the supply of heat to the premises decreases. An increase in the level of CO_2 and relative humidity in the room occurs only after 15:00. This indicates that since that time the residents have been in the premises and are engaged in certain activities. Until 15:00, the level of CO_2 in the room on working days is stable at the level of 400 ppm.

The influence of such factors as the presence or activity of a person in the premises on the increase in temperature in the premises is insignificant. This is indicated by the temperature plot in the rooms of bedroom 1, where temperature fluctuations are noted only within 1 °C.

Based on the above, the following recommendations can be made to reduce energy consumption for the pilot facility. To reduce energy consumption during the operation of the pilot facility, the following external factors must be taken into account: solar heat input and habits (periods of active activity, absence, etc.) of the occupants of the premises. It is not necessary to maintain the temperature in the premises at the level of 22 °C during the time when the residents are not in the premises (working time period). Weather conditions should also be taken into account when adjusting the heat supply to the room. If the weather is clear, the solar heat input significantly increases the temperature in the premises by approximately 4 °C, which makes it possible to reduce the consumption of heat carriers in the specified period of time.

The level of CO_2 in the premises reaches 800 ppm on working days from 17:00 to 22:00. During the day on the weekend, CO_2 is at the level of 700–800 ppm and even reaches the mark of 1000 ppm during a separate period of time. In view of this, automatic ventilation systems should be provided in the premises of the pilot facility to provide fresh supply air during periods of active activity of residents.

The limitation of the technical solution, which is tested under the conditions of the pilot facility, is the ability to only monitor and collect data on heat and electricity consumption, as well as microclimate parameters (temperature, humidity, and air quality). For example, in its current state, the system cannot independently lower the temperature in the room when there is no one in the room. Nevertheless, interactive visualization of electrical and thermal energy and microclimate indicators encourage the user to proactive behavior. Apartment owners can independently adjust the parameters of the microclimate, relying on the monitoring data provided by the system.

The disadvantage of the proposed system is the significant influence of the habits and behavior of residents as potential users on the effectiveness of its application. A person may forget to turn off this or that household appliance, change the connection point of smart equipment. For example, we have to monitor the boiler, and connect a hair dryer or an iron to the smart outlet, etc. It is assumed that minimization of this impact will be achieved through residents' awareness of the possible benefit. The desire to reduce utility costs will encourage a conscious attitude to energy saving problems.

The next stage of research is the implementation of the developed system within the framework of the PRECEPT international grant [21]. The proposed solution will be integrated into the Pred(scr)ictive and Proactive Building Management System (PP-BMS). PP-BMS uses the analysis of monitoring data and machine learning algorithms taking into account external variables (weather forecast, presence of people in the premises). The joint work of the two systems will be aimed at automating the regulation of energy consumption and optimizing the internal environment. In practice, after analyzing the received data, the PP-BMS system will devise scenarios for improving microclimate conditions and reducing energy consumption. The user receives a notification with an action suggestion to manually perform an action to save energy/increase the level of comfort. The offer is adapted to the specific context based on the sensor data, the user profile and the behavior detected by the user. PP-BMS will send action suggestions that will be displayed to the user via a notification widget, the suggested action may contain the underlying motivation for the suggested action.

7. Conclusions

1. The architecture of the Internet of Things network was developed for the technical solution of the proactive management system of residential buildings based on smart equipment. The solution consists of multi-sensors measuring CO_2, temperature and humidity in the room, smart meters of heat and electricity consumption, and smart sockets, which are combined into one system with the help of an integration controller. The real-time system provides data collection on monitoring parameters, their processing, visualization, and archiving, as well as remote user access to the received information through an interactive web interface.

2. The results of testing the proposed technical solution under the conditions of the pilot facility showed the stability of operation and uninterrupted transmission of data on parameters of energy consumption, microclimate, and air quality to the analytics system. Our analysis of the obtained arrays of data on the daily consumption of energy resources and changes in microclimate parameters made it possible to propose recommendations for reducing energy consumption for the pilot facility. The air temperature and relative humidity are at an appropriate level, within the regulatory requirements, but there is no need to maintain the temperature in the premises at the level of 22 °C when the occupants are not in the premises (working time period). To reduce energy consumption during the operation of the pilot facility, the following external factors must be taken into account: solar heat input and habits (periods of active activity, absence, etc.) of residents. Weather conditions should also be taken into account when adjusting the heat supply to the room. During periods of active activity of the residents of the pilot facility (from 17:00 to 22:00 on working days and during the day on weekends), the level of CO_2 in the premises is 700–800 ppm and even in a separate period of time it reaches 1000 ppm. With this in mind, automatic ventilation systems should be provided in the premises to ensure fresh supply air.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The work was carried out within the framework of the project "PRECEPT – A novel decentralized edge-enabled PREsCriptivE and ProacTive framework for increased energy efficiency and well-being in residential buildings", financed by the EU program HORIZON2020, Grant agreement 958284.

Data availability

The manuscript has associated data in the data warehouse.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

The authors express their gratitude for the technical support from the team of DDS LLC (Distributed Data Systems, LLC webhmi.com.ua) – a Ukrainian developer of hardware and software solutions for monitoring and managing production and equipment based on the concept of industry 4.0 and IoT.

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