ANALYSIS OF THE PERFORMANCE OF AN IOT SYSTEM APPLIED TO THE THERMAL MANAGEMENT OF MODERN HOMES

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ABSTRACT: The paper presents an analysis of the implementation of an IoT system designed to improve thermal energy consumption efficiency in a 64 m² residential apartment located in the Petroșani depression. The main objective was to optimize thermal comfort and reduce heating costs by automating temperature control according to both indoor and outdoor conditions. The system consists of temperature sensors installed in each room, thermal actuators mounted on the radiators, and a gas-fired boiler controlled via a dry-contact relay. The control logic is based on virtual thermostats configured in the Home Assistant interface, which automatically adjust the operation of the boiler and actuators while considering occupant presence and the daily schedule. The results obtained led to a significant reduction in energy losses and an increase in thermal comfort.

KEY WORDS: IoT (Internet of Things), Machine Learning, Energy Efficiency, Industrial Sensors.

1. INTRODUCTION

The energy efficiency of residential buildings represents one of the main priorities of European sustainability policies. The residential sector is responsible for a significant share of total energy consumption and greenhouse gas emissions, and reducing heat losses is essential for the energy transition. In this context, Internet of Things (IoT) technologies enable real-time monitoring and control of heating systems, transforming homes into intelligent environments capable of managing their own comfort and energy consumption.

This paper analyzes the implementation of an IoT-based thermal automation system in a 64 m² residential apartment located in the Petroșani depression, equipped with temperature sensors, thermal actuators, and a gas boiler controlled through Home Assistant. The study highlights how data collection and processing contribute to reducing energy consumption, maintaining comfort, and lowering monthly costs. Additionally, the influences of outdoor temperatures, the thermal behavior of indoor spaces, and the direct economic benefits resulting from automation are examined [6], [8], [11].

The main purpose of this research is to optimize thermal energy consumption in a residential dwelling through the implementation of an IoT system for intelligent temperature monitoring and control. The paper aims to demonstrate that integrating temperature, presence, and window sensors together with automatically controlled thermal actuators can lead to a significant reduction in energy losses and an improvement in thermal comfort indicators.

Among the parameters that ensure thermal comfort, only temperature values were considered, without taking into account relative humidity or air circulation velocity [9], [13], [19], [20].

To achieve this purpose, the following specific objectives were established:

- Analysis of the architecture and hardware components used in the implemented IoT system;
- Definition of the distributed thermal control algorithm and operational logic within the Home Assistant platform;
- Evaluation of the system’s performance based on real temperature and energy consumption data;
- Determination of the correlation between outdoor climatic conditions and indoor thermal comfort;
- Estimation of the system’s economic impact by comparing energy consumption with conventional heating solutions;

By achieving these objectives, the research contributes to strengthening the smart building concept and deve loping sustainable solutions in the field of residential energy efficiency [2], [4], [10].

2. DESCRIPTION OF THE IOT SYSTEM IMPLEMENTED

The studied apartment has a usable area of 64 m², is fully thermally insulated on the exterior, and includes two bedrooms, a living room, a kitchen, a bathroom, two terraces, and a balcony. The dwelling is located on the first floor of a building with a basement and four above-ground levels; above it there is an unoccupied apartment, while below it there is a similar apartment with a smaller surface, without terraces and with one bedroom. This configuration influences the thermal balance: heat losses through the ceiling are moderate, while the thermal contribution from the lower apartment helps stabilize the indoor temperature.

The automation system is implemented entirely on the Home Assistant platform, using Zigbee communication, and relies on a set of Sonoff-brand devices, which ensure interoperability and network stability [12], [15], [17], [24].

The main components used to build the IoT system are presented in Table 1, where the models, functions, and power supply specifics of each device are detailed [16].

It can be observed that the NSPanel Pro 120 is the central element of the system, coordinating communication between the sensors, actuators, and the thermal boiler through the Home Assistant platform.

Table 1. IoT Devices Used in the Thermal Automation System

Equipment Type	Model/Manufacturer	Main Function	Power Supply
Human presence sensors	SNZB-06P (Sonoff)	Detects motion and presence	3V DC (CR2450)
Temperature and humidity sensors	SNZB-02D (Sonoff)	Measures ambient temperature and humidity	3V DC (CR2477)
Window / door sensors	SNZB-04P (Sonoff)	Detects window opening and stop heating	3V DC (CR2450)
Dry contact relay	THR320D (Sonoff)	Controls boiler ON/OFF	230V AC
Thermal actuator modules	ZBMINI R2 (Sonoff)	Controls thermal actuators	230V AC
Thermal actuators	ZL-2041 (2-wire, 230V AC)	Regulates radiator flow	230V AC
Control panel	NSPanel Pro 120	Zigbee console + Wi-Fi	230V AC

The system operates as follows: each room is equipped with a temperature sensor and a presence sensor (except for the bathroom, which is fitted only with a temperature sensor). When presence is detected and the temperature drops below the defined setpoint, the ZBMINI R2 module activates the ZL-2041 thermal actuator, which opens the radiator in the respective room [3], [14], [21], [23].

If the set temperature is reached or a window is opened (signaled by the SNZB-04P sensor), the system automatically closes the actuator and disables the heating request for that zone. The gas boiler is controlled via the THR320D relay, which receives commands from the NSPanel Pro 120 and Home Assistant, ensuring that it turns on only when there is at least one active heating demand.

This decentralized architecture, based on zonal control and presence detection, provides high thermal efficiency by reducing energy waste in unoccupied rooms while maintaining stable thermal comfort in actively used spaces [1], [5].

For example, the set temperature in the kitchen is 21°C, while the bedrooms are maintained at 22°C for optimal nighttime comfort. When the occupants are away, the overall temperature automatically drops to 18°C, returning to comfort levels upon presence detection—achieved either through the human presence sensors installed in each room or through geofencing. In the bathroom, the radiator is not fitted with a thermal actuator, being considered the "end of line" of the heating circuit to allow the boiler to circulate the heating medium properly [7], [25], [26].

Observations made during October 2025 showed that the radiator in the kitchen activates very rarely due to the thermal contribution generated by cooking activities; the average temperature in this space remained between 22–23°C without the need for frequent heating.

The analysis of the monthly consumption indicated high efficiency: throughout the month of October, characterized by low outdoor temperatures, the total gas consumption remained below 100 m³, confirming the performance of the automatic regulation system [18], [22].

3. OPERATING PRINCIPLE AND CONTROL ALGORITHM

The IoT system operates on the principle of zone-based distributed control. Each room is assigned a virtual thermostat that compares the measured temperature with the defined setpoint. When the temperature drops below the comfort threshold, the thermal actuator of the corresponding radiator opens, and Home Assistant activates the boiler's control relay.

The boiler operates only when at least one radiator is open, thus avoiding unnecessary start-ups. Once the set temperature is reached, the actuators gradually close, and the boiler stops automatically. The system uses a thermal hysteresis of ±0.2°C to maintain temperature stability and prevent frequent start/stop cycles. The general schematic of the thermal control system—highlighting the connections between sensors, actuators, the NSPanel Pro, and the Home Assistant platform—is shown in Figure 1. This representation emphasizes the bidirectional flow of data and decision-making, which is characteristic of a distributed IoT architecture.

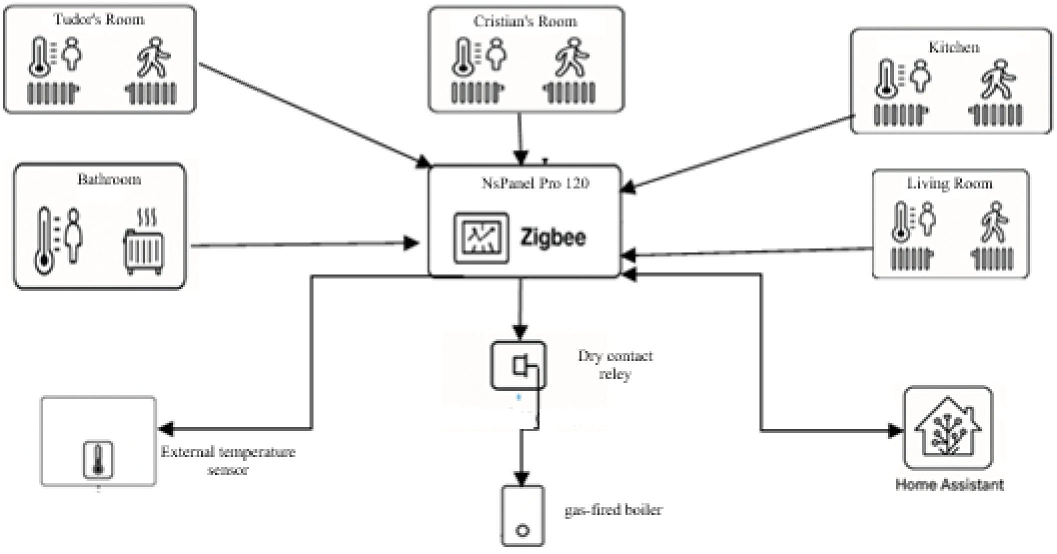

Figure 1. Block Diagram of the IoT Thermal Control System

- Temperature Sensor – measures the ambient temperature and sends the data to the Zigbee control panel.
- Presence Sensor – detects movement and room occupancy, enabling automatic heating adjustment.
- Thermal Actuator – mounted on the radiator, it controls the flow of the heating medium according to the received commands.
- Zigbee Control Panel – the central communication unit that connects all sensors and actuators, displays system information, and sends commands to Home Assistant via Wi-Fi. It also controls the boiler's dry-contact relay.
- Dry-Contact Relay – the electrical interface between the control panel and the gas boiler, used to turn the boiler ON/OFF without transferring voltage.
- Gas-fired Boiler – the thermal energy source of the heating system, electronically controlled by the NSPanel Pro through the dry-contact relay.
- External Temperature Sensor – monitors outdoor temperature and enables automatic weather compensation.
- Home Assistant – the automation software platform that manages virtual thermostats, analyzes data received from the control panel, and optimizes system operation for comfort and energy efficiency.

This logic enables precise control, reducing energy losses caused by overheating.
The system includes additional functions such as: "away mode" (automatically lowering the temperature to 18°C), "night mode," and geofencing (restoring normal temperatures when the user approaches the home).
The general operating algorithm can be described as follows:

1. Data collection from sensors (temperature in each room).
2. Comparison with the set values (setpoints).
3. Local decision-making: pening/closing the actuator.
4. Aggregating commands at the boiler level: activation only if there is at least one active heating request.

5. Continuous state updating and user preference learning (automatic adjustment of schedules).

Through this approach, each room becomes an independent thermal zone, eliminating temperature imbalances between spaces and reducing the total operating time of the boiler.

4. ENERGY EFFICIENCY ANALYSIS. RESULTS AND DISCUSSION

4.1. Analysis of Outdoor Temperatures and Their Influence on Consumption

To objectively evaluate the performance of the system, the evolution of daily minimum outdoor temperatures for October 2025 was analyzed. The outdoor sensor is mounted on the western façade, being affected by afternoon solar radiation; therefore, only nocturnal minimum temperatures were used, as they are the most relevant for heating demand.

The analysis of data from October 2025 showed a stable indoor temperature, ranging between 21.8°C and 22.5°C, regardless of outdoor fluctuations (minimum values between 1.5°C and 9°C). The correlation between outdoor and indoor temperatures was very weak (r = 0.11), confirming the efficiency of the automatic control system. The total natural gas consumption for the 31 days was approximately 100 m³, which—at an average cost of 3.05 lei/m³—corresponds to a monthly expense of about 305 lei.

The results demonstrate that the use of IoT sensors and intelligent control algorithms can reduce energy consumption by 30–35%, while maintaining a high level of thermal comfort and ensuring efficient resource management, contributing to residential-sector sustainability and decarbonization objectives.

The minimum outdoor temperatures varied between 1.5°C and 9°C, with a monthly average of approximately 6°C. The first ten days of the month recorded very low values (1–4°C), while after October 20 a slight increase was observed (up to 10–12°C). These conditions imposed a realistic heating demand on the boiler, resulting in a total gas consumption below 100 m³—highlighting the effectiveness of the IoT-based regulation system.

The evolution of daily minimum temperatures is illustrated in Figure 2, capturing the climatic variations of October 2025 and their influence on the boiler's operating regime. The associated statistical analysis (mean and standard deviation) is computed based on the plotted dataset, providing insight into the thermal stability of the studied period.

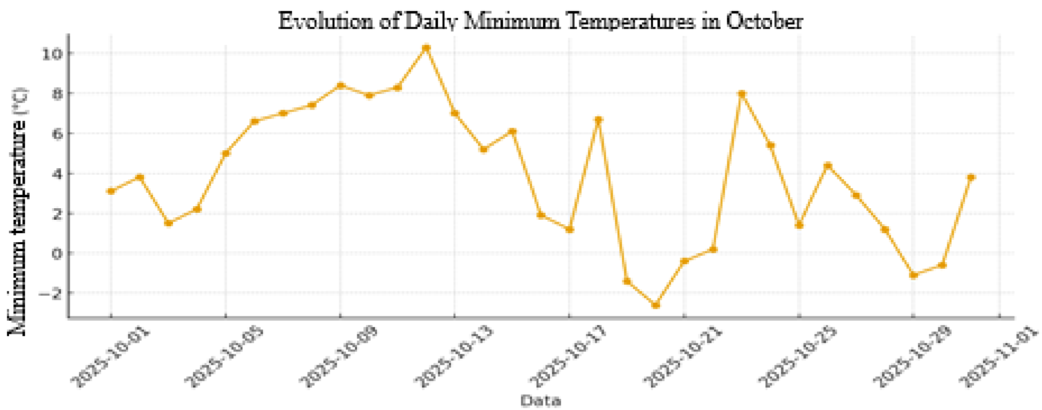

Figure 2. Evolution of Daily Minimum Temperatures in October

The statistical analysis of daily minimum temperatures indicates a monthly average temperature ($T_{me}d$) of 6.1°C, with a standard deviation (σ) of 2.3°C. These values reflect a moderate variation in nocturnal temperatures, characteristic of the Petroșani region during the autumn–winter transition period.

In the first ten days of the month, low values between 1–4°C were recorded, resulting in a more intensive operating regime for the gas boiler. In the second half of the month, minimum temperatures gradually increased towards 9–10°C, and the IoT system automatically reduced the operating time of the radiators, maintaining indoor comfort without increasing consumption.

The achieved thermal stability confirms the efficient adaptation of the automatic control system to external climatic variations and the appropriate correlation between heating demand and the power supplied by the boiler.

4.2. Analysis of Consumption and Associated Costs

For October 2025, the total natural gas consumption was 100 m³, including heating and cooking.

This results in a daily average of 3.23 m³, and at a price of 3.0485 lei/m³ (VAT included), the total monthly cost was:

$C = 100 \times 3.0485 = 304.85$ lei

Compared to similar apartments without automation (150–180 m³/month), the savings amount to 30–40%.

This confirms a real reduction in consumption—even under cold climatic conditions—due to the optimization of boiler operation and prioritizing heating only in the occupied rooms.

4.3. Correlating Climatic Conditions with Indoor Comfort

To evaluate the thermal behavior of the dwelling, the average indoor temperatures from four areas (bedroom 1, bedroom 2, living room, kitchen) were analyzed simultaneously with the outdoor minimum temperatures.

The statistical correlation between the two datasets, calculated for the period 1–31 October 2025, has a value of r = 0.11, indicating a very weak correlation.

This is a positive conclusion: the IoT system successfully decoupled indoor comfort from outdoor variations, maintaining a constant temperature around 22°C in all rooms, even when the nocturnal outdoor temperature dropped to 1–2°C.

The average temperature values recorded in each interior space are summarized in Table 2, and the graphical representations in Figures 3 and 4 illustrate the comparative evolution between minimum outdoor temperature and indoor temperatures. These visualizations confirm the interior thermal stability and the effectiveness of the automatic control performed by the IoT system.

Table 2. Summary of Monthly Average Temperatures by Room

Room	Average Temperature (°C)
Tudor’s Bedroom	21.8 °C
Cristian’s Bedroom	22.5 °C
Living Room	22.0 °C
Kitchen	22.1 °C

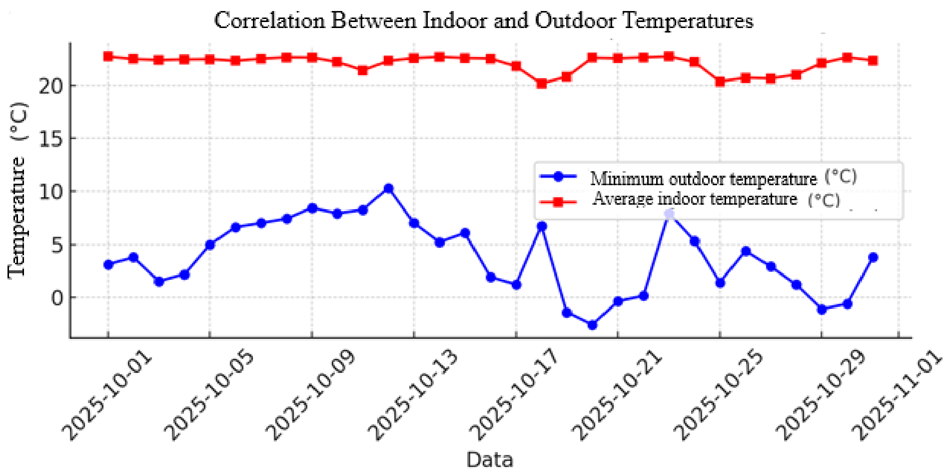

Figure 3. Correlation Between Indoor and Outdoor Temperatures

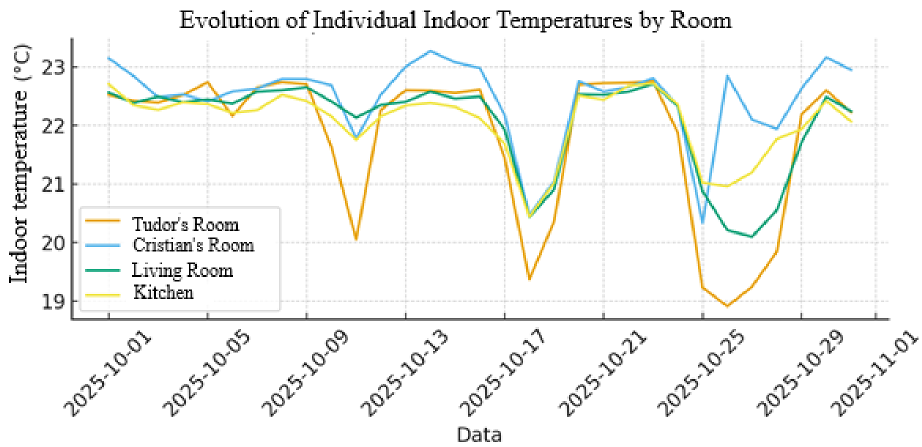

Figure 4. Evolution of Individual Indoor Temperatures by Room

The visual interpretation confirms the stability of the indoor thermal environment: although minimum outdoor temperatures of 2–4°C were recorded during the first part of the month, the indoor temperatures remained constant between 21.5 and 22.5°C. On warmer days, the system automatically reduced the operating time of the radiators, which is reflected in the overall gas savings.

This performance is the result of zonal regulation, optimal hysteresis, and the system's rapid response to presence detection—elements that transform the dwelling into an intelligent, self-regulating, and energy-efficient thermal system.

5. CONCLUSIONS AND FUTURE PERSPECTIVES

The implementation of an IoT-based heating control system in a medium-sized apartment has demonstrated significant technical, economic, and comfort-related benefits. Automating the temperature regulation process through sensors, actuators, and virtual thermostats enabled a reduction of natural gas consumption by up to 35%, without compromising thermal comfort.

The analyzed data revealed exceptional indoor thermal stability (temperatures maintained between 21.8°C and 22.5°C) despite outdoor fluctuations of up to 7–8°C, confirming the performance of the adaptive control strategy based on presence and temperature sensors. The

weak correlation between outdoor and indoor temperatures (r = 0.11) demonstrates the system's ability to ensure constant comfort, independent of external conditions.
From an economic perspective, a monthly cost of 305 lei for a 64 m² apartment located in a cold region such as Petroșani represents a remarkable performance compared to conventional heating systems. The estimated payback period for the investment is 1.5–2 years, and the potential annual savings exceed 2,000 lei.
From a technological standpoint, the proposed system demonstrates the practical applicability of a distributed IoT architecture, featuring local control (via NSPanel Pro) and global integration (via Home Assistant). This approach provides redundancy, scalability, and the potential for further expansion toward Smart Grid or Smart Home solutions.
In the future, the authors aim to develop a more comprehensive analysis that considers all parameters contributing to thermal comfort: temperature, relative humidity, and air circulation speed.
In conclusion, the use of IoT sensors for thermal control in buildings not only enhances energy efficiency but also contributes to the sustainability of the built environment, providing a solid foundation for the future development of intelligent buildings focused on comfort, economy, and decarbonization.

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