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Article

Assessment of HVAC Performance and Savings in Office Buildings Using Data-Driven Method

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Abstract: Enhancing energy efficiency within the building sector is imperative to curbing energy losses, given that this sector alone contributes to over 34% of global energy consumption. Employing a building management system, along with its regular updates, presents a strategic avenue to decrease energy usage, enhance building energy efficiency, and more. Tailored control strategies, aligned with the unique characteristics and usage patterns of each building, are essential for achieving energy savings. This article presents an evaluation of HVAC system efficiency in office buildings, utilizing a data-driven approach coupled with simulations conducted in building performance simulation software. The research explores the control strategy of an office building equipped with a constant air volume HVAC system, featuring a regularly controlled air handling unit. The objective is to boost energy efficiency while striking a balance between occupant comfort and energy consumption. The findings indicate that by analyzing measured data and adjusting the configurable parameters, the energy consumption of buildings can be significantly reduced. The close monitoring of indoor parameters by building operators and making corresponding adjustments to the HVAC system can yield energy savings of up to 16%. Leveraging these insights, this paper suggests integrating data-driven and dynamic simulation methods into building management system models to optimize HVAC systems, enhance energy efficiency, and advance ambitious carbon neutrality objectives.

Keywords: building management system; HVAC; energy efficiency; energy savings; optimization; data-driven

Citation: Borodinecs, A.; Palcikovskis, A.; Krumins, A.; Zajecs, D.; Lebedeva, K. Assessment of HVAC Performance and Savings in Office Buildings Using Data-Driven Method. *Clean Technol.* **2024**, *6*, 802–813. https://doi.org/10.3390/cleantechnol6020041

Academic Editors: Angel Mena-Nieto and Patricia Luis Alconero

Received: 15 March 2024
Revised: 9 May 2024
Accepted: 7 June 2024
Published: 14 June 2024

1. Introduction

In the last twenty years, significant factors such as advancements in technology, environmental concerns, and financial as well as energy crises have exerted a profound impact on global economic development and regional politics [1]. Energy matters have emerged as a crucial element influencing sustainable development on a global scale. Energy is indispensable for both production and the sustenance of human life. Global energy consumption has been steadily increasing at an average annual rate of 1.8% over the past decade [2].

In Europe, as well as globally, regulatory measures are being implemented to gradually eliminate the utilization of fossil fuels for energy generation. The RePowerEU plan [3] endorsed by the European Commission seeks to reduce the EU's reliance on Russian fuel and address the climate emergency. This strategy includes initiatives to improve energy efficiency, expand the spectrum of energy sources and accelerate the integration of renewable energy alternatives to achieve climate neutrality by 2050 [4].

As per The Global Status Report for Buildings and Construction (2022), the buildings and construction sector constitutes over 34% of the global final energy usage, with heating, ventilation, and air conditioning (HVAC) systems and associated energy-intensive appliances contributing to more than two-thirds of building energy consumption [5]. These figures make building energy efficiency one of the European Commission's top priorities for its transformation policy under the European Green Deal [6].

Ineffectively operating HVAC systems cause notable environmental problems because of their high energy consumption and inefficient operation [7]. Studies [8,9] have indicated that HVAC systems are responsible for around 40% of the total energy consumption in commercial buildings, making a substantial contribution to greenhouse gas emissions and the progression of climate change. Ineffective HVAC systems additionally play a role in indoor air quality concerns, potentially leading to issues regarding occupants' well-being and health [10,11]. HVAC-related loads are affected by many elements: the building type and location, local climate, occupancy level, equipment efficiency, thermostat settings, and building controls [12,13]. Indeed, a comprehensive examination of each of these influential factors can help in pinpointing distinct opportunities for energy savings. The aim of HVAC in commercial buildings is to uphold a comfortable and secure environment for occupants, equipment, and the building itself [14]. Thus, the minimum standards must ensure the functionality and safety of building construction and engineering and technical systems, such as preventing pipes from freezing and walls from growing mold, etc. [15]. However, many contemporary buildings prioritize air conditioning for maximum occupancy rather than tailoring it to the actual usage and needs. A prevalent control strategy for HVAC systems still relies on predetermined or fixed schedules that overlook occupancy patterns [16]. Specifically, significant energy savings without discomfort can be achieved by reducing the set point, especially during idle periods. Research indicates that even minor adjustments to the set point can lead to energy savings of up to 30% in buildings [17].

New building energy consumption standards [18] and regulatory measures [3] aimed at sustainable resource usage necessitate a shift in the management of energy systems. The efficient management of buildings is crucial, balancing the need for occupant comfort with the minimization of energy consumption. The integration of IoT sensors, remote control capabilities, the digitization of energy data, and real-time automated decision-making has spurred the creation of innovative energy management systems (EMSs) for buildings, microgrids, etc. [19]. A building management system (BMS) serves as a strategic approach to addressing these challenges, mitigating impacts, optimizing energy supply and demand, enhancing building energy efficiency, and achieving other objectives [20]. A BMS is a sophisticated control system implemented in a building to monitor and regulate its mechanical and electrical components, including ventilation, lighting, electrical infrastructure, and HVAC systems [21]. Ideally, the BMS would operate the building itself. But in real life, many buildings have outdated BMSs [20] that cannot analyze indoor parameters and manage some building systems, for example, ventilation and air conditioning.

Modern and efficient building management systems are underpinned by data-driven energy management frameworks, as discussed in several scholarly articles [22]. These frameworks have significantly enhanced the overall energy efficiency and indoor comfort for occupants by systematically collecting and analyzing historical indoor and outdoor data. Model Predictive Control (MPC) emerges as a prevalent technique within BMS frameworks due to its capacity to forecast building behavior in response to variations in external and internal conditions, as well as its ability to make subsequent adjustments to the HVAC system settings [23].

However, the development and implementation of new frameworks entail substantial labor and costs, rendering them unsuitable for traditional BMS installations. Additionally, while predictive control has proven highly effective, its practicality may diminish when confronted with persistent, "routine" internal parameters. Therefore, simpler and more cost-effective optimization methods may be warranted, particularly during the early stages or prior to the adoption of machine learning techniques, which can be executed utilizing existing BMS equipment and overseen by trained building operators.

This study investigates the performance of HVAC systems and potential energy savings by analyzing scheduling data from a constant air volume ventilation system. The study examines the base load, representing the energy consumption during inactive periods, and quantifies potential savings by effectively adjusting the set points during these times. Additionally, CO_2 level measurements are conducted to ensure that turning off the system does not compromise the indoor comfort for occupants. Results showcasing potential savings have been demonstrated specifically for office buildings. While previous research has touched upon studies of office buildings [24,25], there has been no comprehensive exploration of occupant comfort and CO_2 concentration measurements. Although this approach is complex, requiring the installation of sensors to measure indoor CO_2 levels, it offers a deeper understanding of variables such as the building type and occupancy, providing a unique perspective on the value of reducing the base load without sacrificing the indoor comfort quality. The European Union has already formulated recommendations for comprehensive ventilation and heating system requirements, which include the maximum CO_2 concentration levels in rooms, a measure already adopted in some countries and under development in others [26]. The COVID-19 pandemic worldwide has prompted the assessment of indoor air quality indicators in public buildings, impacting not only the health but also the comfort of occupants.

2. Research Motive

Ventilation and air conditioning systems cause the most problems in efficient building management and at the same time are the main element ensuring the comfort of occupants. Modern ventilation and air condition systems have a variable air volume (VAV) HVAC system that allows the air flow in each room of the building to be adjusted and that allows many comfort zones to be created. Each zone has unique parameters regarding the temperature requirements, occupancy, internal heat gains and pollution. And VAV systems, with the help of sensors and modern BMSs, are capable of creating comfortable working conditions by supplying the required amount of air for each room in automatic mode without human assistance. But in most cases, a constant air volume (CAV) HVAC system was chosen due to the initial cost of the VAV system. Unlike the VAV system, the CAV system provides a certain amount of air, which was calculated during system design. Some adjustments can be made, but they will affect rooms. In the CAV system, the amount of supplied air can be adjusted by reducing the power in the main air handling unit (AHU). The high comfort requirements of one room will negatively affect the energy consumption of the whole building. The settings of the new CAV ventilation system can be adjusted using air damper regulation, but this procedure needs to be performed for the whole building, which is not always possible because of the construction of the ventilation system and the equipment used.

Most CAV systems work according to schedules. The AHU turns on in the morning, and turns off late at night. Ideally, the air flow would be adjusted in accordance with the occupancy, but in most buildings, the AHU uses a constant air flow all day long. This drawback leads to increased HVAC energy consumption and unnecessary comfort conditions.

The challenge discussed here revolves around the energy efficiency of the office building complex illustrated in Figure 1. The referenced building is located in Riga, Latvia.

Figure 1. The office building complex examined in the case study (author photo).

Only one building was simulated for the case study (the one on the left in the photo). This building consists of four stories, with office spaces occupying floors 1 through 4, along with underground parking. The total area of the building is 1806 square meters, accommodating a total of 20 office workers.

The foundations and ceilings of the buildings consist of reinforced concrete, the walls are made of glass walls and reinforced concrete, and the roof consists of flexible sheet materials. The electricity consumption of the building is 327 kWh/m^2 per year, but the gas consumption for heating is 134 kWh/m^2 per year.

Ventilation in the building is provided by two modular air handling units. Air conditioning in the building is provided by five conditioning systems. The office building is equipped with a CAV HVAC system with scheduled AHU control. A diagram of the ventilation working schedule during the week is shown in Figure 2. On working days, the AHU turns on at 7:00 and works with 70% maximum air flow until 21:00. During the night, the AHU is turned off.

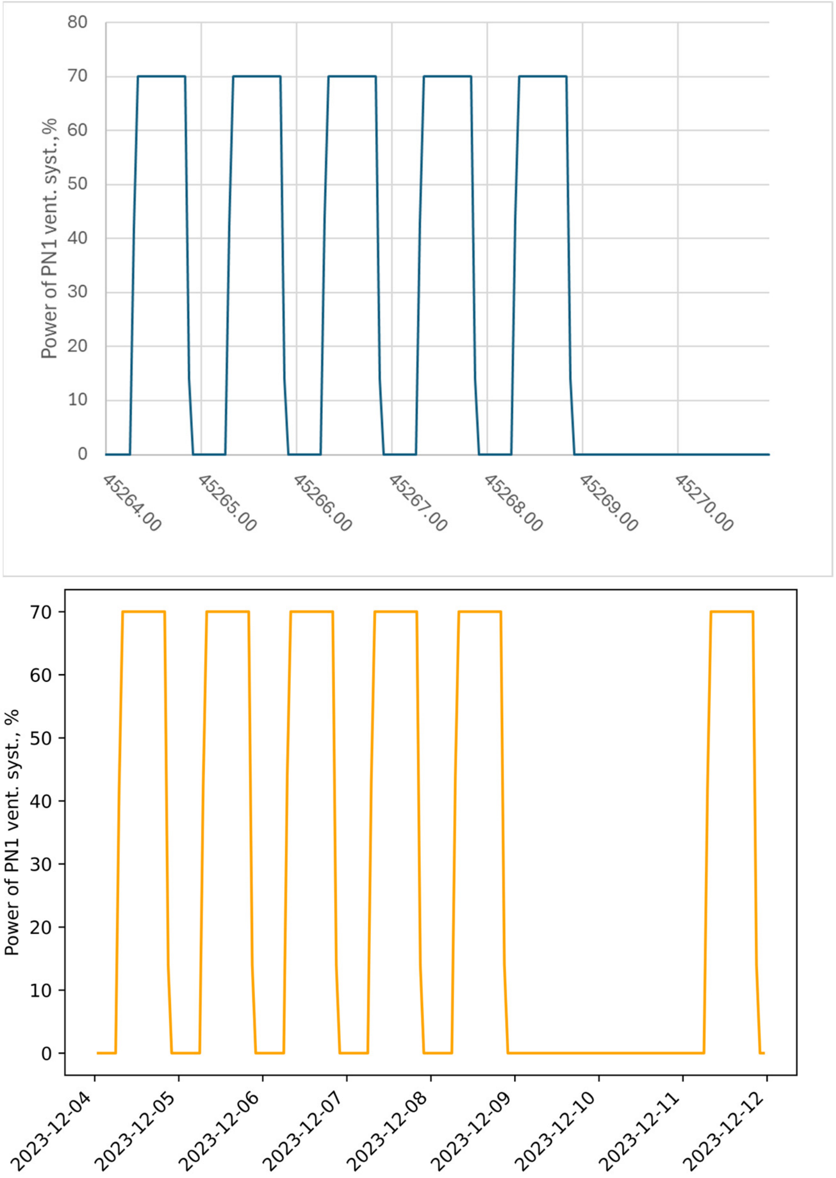

Figure 2. CAV ventilation system working schedule during the week.

As usually happens, the design occupancy and real occupancy vary greatly. As a result, the CO$_2$ produced by the occupants is significantly different from the design. Figure 3 shows the real CO_2 concentration of one of the office rooms during measurements. In Figure 4, the same office CO_2 concentration is considered during a typical workweek. From the measurements, it can be concluded that the mean peak CO_2 in the office is around 800 ppm on working days. The maximum value for CO_2 is 1126, and there is an unusually high concentration of CO_2 on only one day. The peak values are observed from 12:00 to 15:00. However, 800 ppm of CO_2 is a good air quality result for the office. ASHRAE and World Health Organization recommend that the CO_2 concentration is maintained under 1000 ppm [27,28]. But to decrease the energy consumption, the maximum CO_2 concentration can be increased.

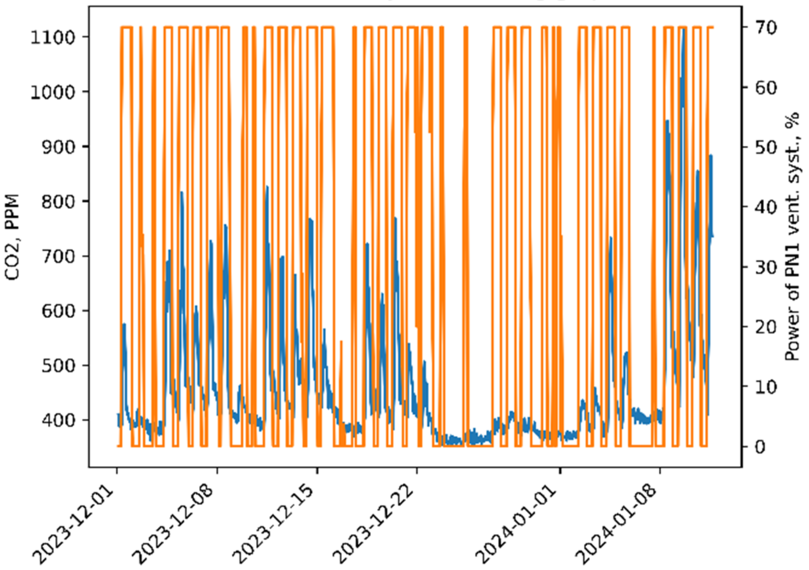

Figure 3. CO_2 concentration in one office and working schedule of ventilation system. (Blue line—CO_2; yellow—Power of PN1).

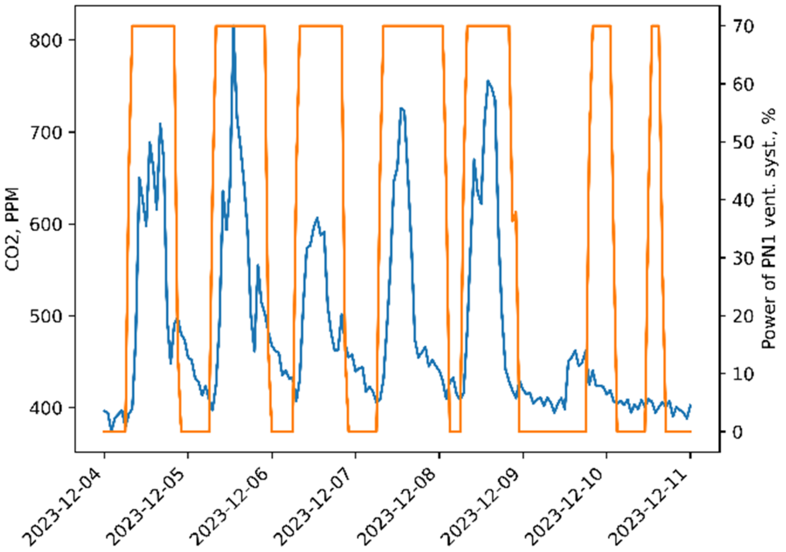

Figure 4. CO_2 concentration in one office and ventilation system working schedule the during week Blue line—CO_2; yellow—Power of PN1.

As shown in Figure 5, the ventilation system turns on at 7:00 when there is a CO_2 concentration of around 400 ppm, which is the typical outdoor CO_2 concentration. The same situation is observed at the end of the day; at 18:00, the CO_2 concentration is around 450 ppm. This indicates that there is an excess of supply air. To save energy, the AHU schedule can be adjusted and can be turned on, for example, at 9:00, when office workers start working, and can be turned off at 16:00 when the occupants are finishing work. During the night, the CO_2 concentration will naturally decrease.

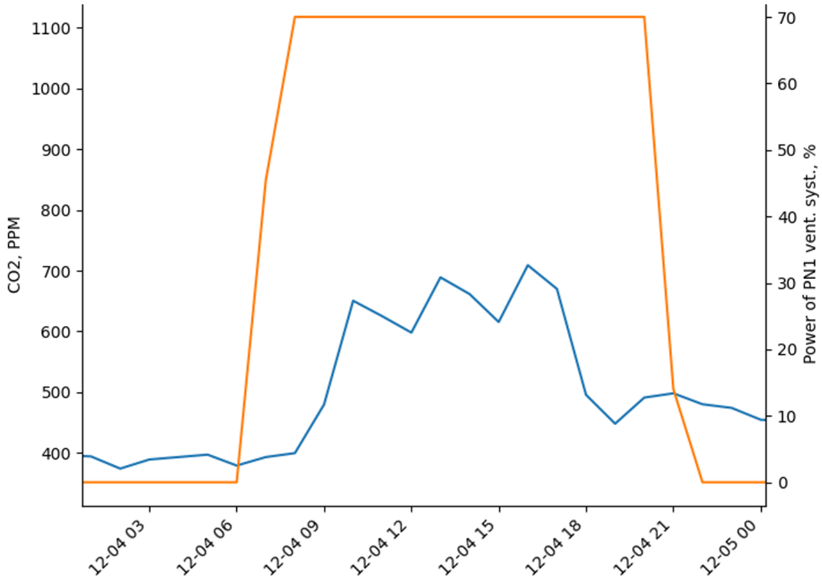

Figure 5. CO_2 concentration in one office and ventilation system working schedule during working day Blue line—CO_2; yellow—Power of PN1.

3. Materials and Methods

In the beginning, the system is configured with values derived from theoretical and designed data. However, the actual use and behavior of buildings in real-life scenarios often deviate from the originally established parameters. This deviation often provides an opportunity to reduce the energy consumption of a building. Optimization strategies can be implemented relatively simply and require minimal adjustments to the building management system (BMS) through the systematic collection and analysis of relevant information.

Adjusting BMS settings and optimizing heating, ventilation and air conditioning (HVAC) systems can be performed by trained building operators using existing BMS equipment. To optimize HVAC systems, important parameters such as indoor temperature planning, occupancy patterns, indoor air quality, ventilation rates, and schedules must be collected and analyzed. Decision-making processes should be based on historical data and the discrepancies observed between parameter activation times, internal reactions and their necessity. It is critical that the HVAC system maintains an optimal indoor environmental quality only during occupied periods, thereby ensuring maximum energy efficiency. Instances of premature system activation or delayed deactivation should be kept to a minimum, with determinations based on the indoor occupancy levels and indoor air quality, typically measured by monitoring CO_2 concentrations.

Figure 6 shows a schematic representation of a rough HVAC optimization algorithm grounded in a data-driven methodology. This algorithm holds applicability across various building systems, particularly within HVAC frameworks.

To test the theory, a model of the office room identical to the office room in the pilot buildings was created using the building performance simulation program IDA ICE [29]. A typical Latvian office was chosen (Figure 7). The office area was 147.4 m^2 and the room height was 3.14 m. The simulation model was made according to standard "Energy performance of buildings" [30]. The number of employees was 28 ($\approx$5 m^2/pers.), and it was assumed that the metabolic rate of the people in the office was 118 W/pers, or 1.127 MET. Occupancy was chosen according to standard EN 16798 [30], and this is shown in Figure 8. The airflow supply was calculated for a category II low-polluted building and was 2.03 $L/s \times m^2$ or 7.2 $m^3/h \times m^2$.

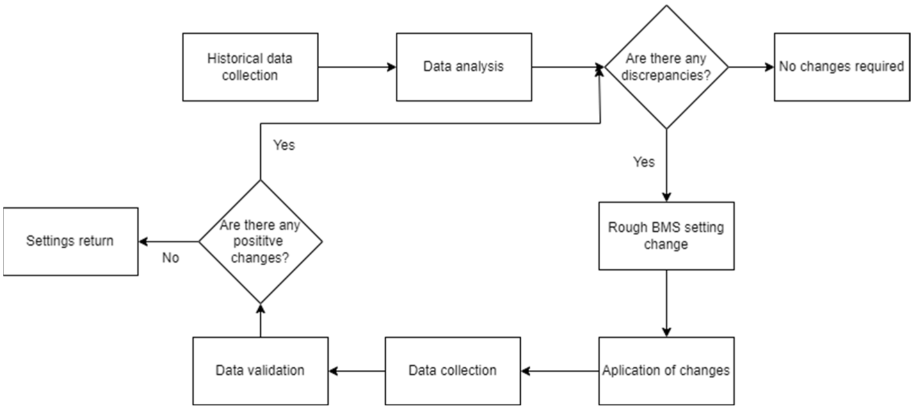

Figure 6. Rough HVAC optimization algorithm based on data-driven method.

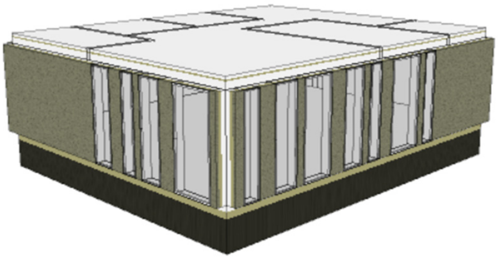

Figure 7. Simulated model of the office room.

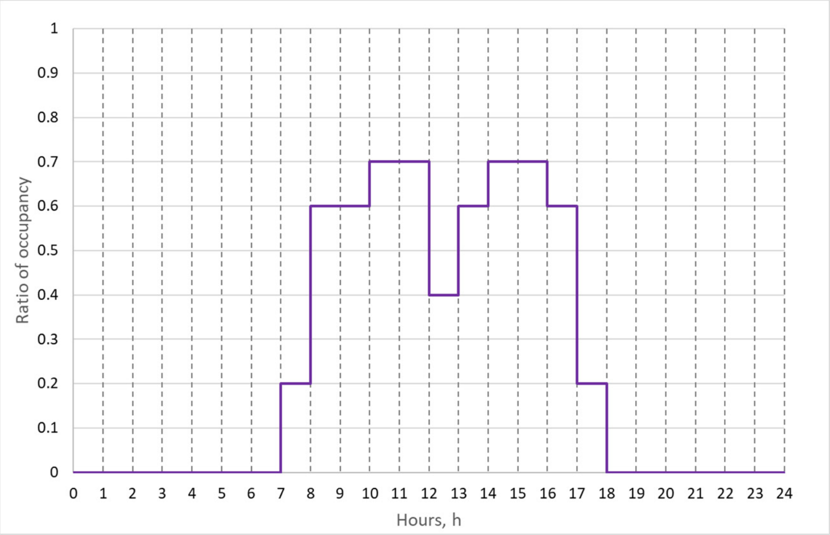

Figure 8. Office occupancy schedule according to standard EN 16798.

Several simulations were performed. The energy consumption and CO_2 level in the office room under EN 16798 and the researched office AHU working schedules were compared. Each schedule was edited by changing the start and end times of work. The results are shown in Table 1. In the results, for the EN 16798 AHU working schedule, reducing the operating time by one hour is an acceptable means of decreasing the energy consumption. For a period of 6 months, the potential energy savings are 451 kWh. At the same time, the maximum CO_2 value is under the ASHRAE-recommended limit. After reducing the operating time by two hours in the EN16798 schedule, the CO_2 level in the morning will influence workers, so this reduction in the operating time is not recommended for use. After reducing the operating time by one hour in the morning and three hours in the evening in the researched office, almost the same results were obtained for the

AHU working schedules: the reduction in the ventilation operating time does not affect the comfort of occupants and the energy savings are 451 kWh. After reducing the operating time by two hours in the morning and evening, the working conditions become unsatisfactory.

Table 1. Result of the simulations.

	Turn On	**Turn Off**	**CO_2 Avg, ppm**	**CO_2 Max, ppm**	**Energy Consumption, kWh (8 Months)**	**Energy Savings, kWh (8 Months)**
Real office	7:00	21:00	523	873	2300	
Real office −1 h, −3 h	8:00	18:00	631	985	1898	401.3
Real office −2 h, −5 h	9:00	16:00	1253	2704	1405	894.8
EN 16798	6:00	18:00	547	737	2904	
EN 16798 −1 h, −1 h	7:00	17:00	742	982	2453	451
EN 16798 −2 h, −2 h	8:00	16:00	1105	1940	1999	904.3

Figures 9–11 show the CO_2 concentration change in an office room with an EN 16798 AHU working schedule and occupancy for 8 months. During simulations after AHU, the working time reduced by two hours (one hour time of switching on and off) and the maximum CO_2 concentration does not exceed the acceptable limit of 1350 ppm, which corresponds to category III of office space types according to EN 16798. Despite this, the energy savings will be around 400 kWh for 8 months. After AHU, the working time is reduced by four hours (two hour time of switching on and off), maximum CO_2 concentration 33% of simulation time (1808 h) will be above 1350 ppm. However, upon deeper analysis, it was revealed that excess of CO_2 concentration above 1350 ppm (3 category) during working time was only 195 h or 3.57% of simulation time and above 800 ppm (2 category) 647 h or 11.77%. Energy savings with this approach will be up to 900 kWh or 16%.

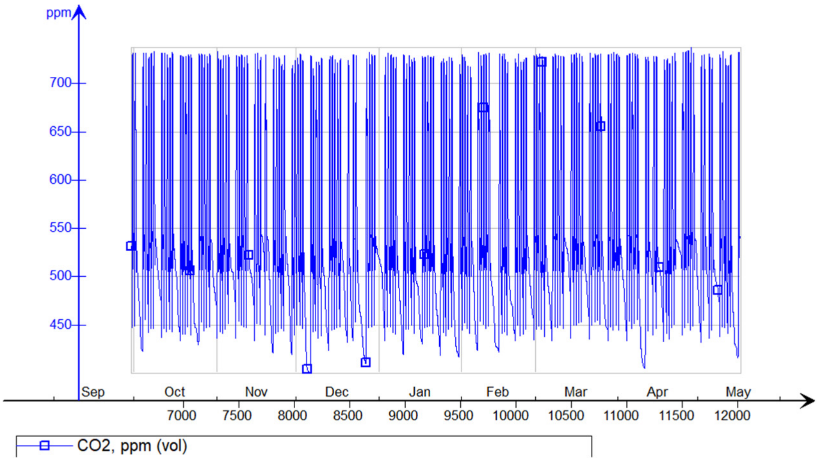

Figure 9. CO_2 concentration changes in office room according to EN 16798, with a working period of 6 a.m.–6 p.m.

It can be stated that the simple analysis of measured data and editing available changeable parameters can be used to reduce building energy consumption. If the building operator monitors the indoor parameters in detail and adjusts the HVAC system accordingly, 16% energy savings easily can be achieved. However, buildings must be equipped with sensors for historical data collection and the use of the building must be the same, without any significant changes in indoor parameters, occupancy and occupant behavior.

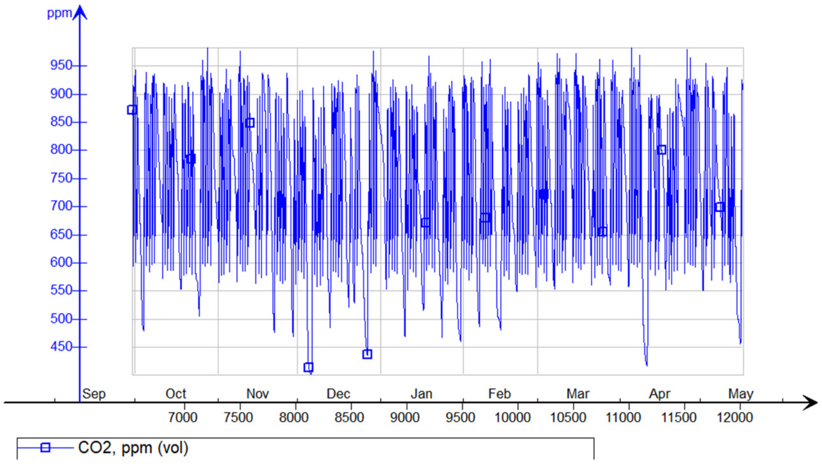

Figure 10. CO_2 concentration changes in office room according to EN 16798, with a working period of 7 a.m.–5 p.m.

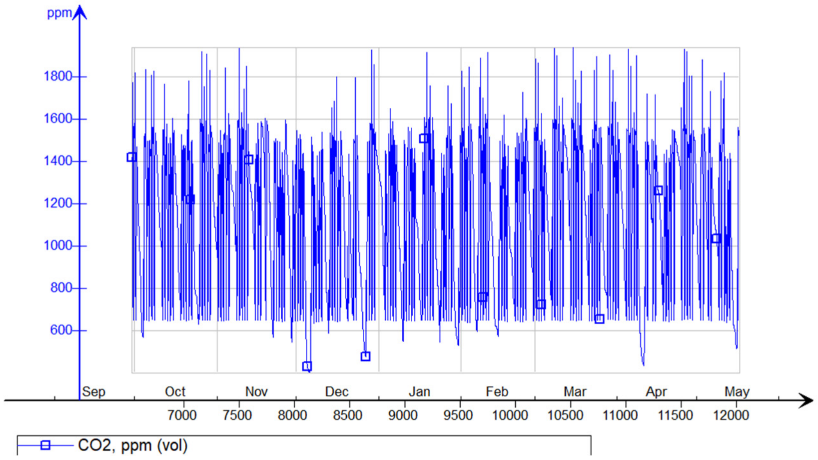

Figure 11. CO_2 concentration changes in office room according to EN 16798, with a working period of 8 a.m.–4 p.m.

4. Discussion

Figure 12 is a flowchart illustrating how a building can be controlled to maintain optimal levels of occupant comfort while optimizing energy use. The aim of this is the continuous monitoring of indoor building parameters, including temperature, humidity and CO_2 concentration levels, to ensure they remain in an acceptable range to promote occupant well-being and productivity. This entails the real-time monitoring and adjustment of environmental conditions to account for fluctuations in occupancy and varying levels of occupant activity in the building.

A main aspect of building management involves dynamically adapting the HVAC settings based on the actual needs of the occupants. This requires the integration of occupancy sensing technology to accurately determine the number of people present in certain parts of a building at any given time. Using occupancy data, building operators can implement the adaptive HVAC strategies best suited to current occupancy levels, thereby minimizing energy loss during unoccupied periods while maintaining comfort levels during working hours.

In addition, it is critical to recognize the impact of occupant behavior on indoor environmental parameters. Activities such as light exercise can increase the temperature, humidity and CO_2 levels in enclosed spaces. Consequently, building operators must use sophisticated algorithms to analyze historical data and identify the behavior patterns of occupants. By identifying these patterns, simple predictive models can be developed to anticipate indoor fluctuations and adjust the HVAC settings to mitigate any negative impacts on comfort and energy efficiency.

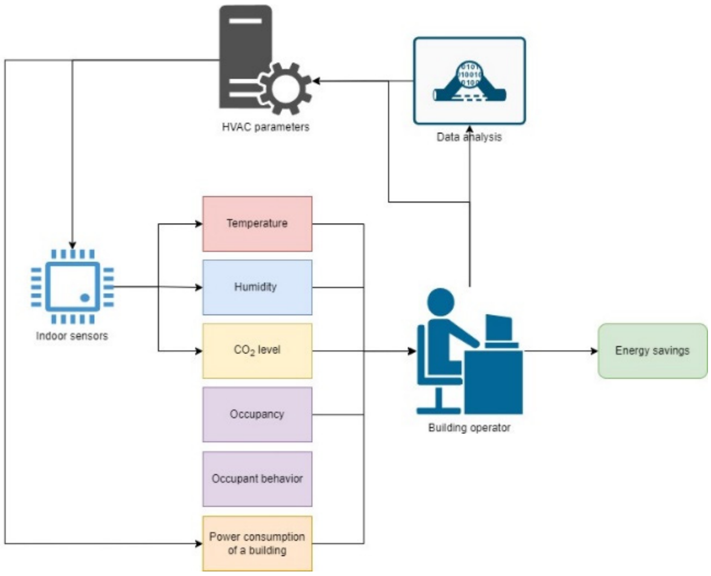

Figure 12. Block diagram of building management.

Looking to the future, future research on building management will likely focus on increasing the intelligence and adaptability of building management systems through the integration of advanced sensor technologies, new algorithms, and data analytics. This includes exploring new approaches in order to capture, process and make real-time decisions that optimize building performance in response to dynamic environmental conditions and changing occupant behavior. By advancing these areas of research, building management systems can evolve to provide unprecedented levels of comfort, energy efficiency and environmental sustainability in the built environment.

5. Conclusions

The findings of the study highlight the tangible benefits of implementing a data-driven approach to optimizing HVAC systems in office buildings. Through careful analysis and modeling, this study demonstrates the significant potential for improving energy efficiency while maintaining occupant comfort. The results show that by adjusting HVAC schedules based on actual occupancy patterns and room parameters, energy savings of up to 16% can easily be achieved. This represents a significant reduction in energy consumption without compromising the quality of the indoor environment.

In addition, this study highlights the practicality of implementing such rough optimization strategies within existing building management systems. By using historical data and systematically analyzing parameters, building operators can make informed decisions to optimize HVAC operations and minimize energy usage. The findings highlight the scalability of the proposed approach, noting its applicability to a variety of building types beyond office space. Whether in the commercial or residential building sector, data-driven optimization principles can be adapted to achieve similar energy efficiency improvements.

Looking to the future, this study suggests that future research and implementation efforts should focus on improving and expanding the capabilities of building management systems. This includes exploring advanced sensor technologies, new algorithms, and real-time analytics to improve the intelligence and adaptability of HVAC optimization strategies. The results confirm that the proposed data-driven approach offers a practical and effective way of improving the energy efficiency of HVAC systems in office buildings and beyond. By prioritizing evidence-based decision making and ongoing monitoring, building operators can achieve significant improvements in energy efficiency while maintaining an optimal indoor environment for occupants.

Author Contributions: Conceptualization, A.B. and A.K.; methodology, D.Z.; software, A.P.; validation, A.P. and K.L. formal analysis, A.P.; investigation, A.P.; resources, A.K.; data curation, K.L.; writing—original draft preparation, K.L.; writing—review and editing, A.P.; visualization, A.P.; supervision, A.K.; project administration, A.K.; funding acquisition, A.K. All authors have read and agreed to the published version of the manuscript.

Funding: Study being conducted based on agreement with SIA "ETKC" (Centre of Competence for Energy and Transportation) within the framework of project Nr.5.1.1.2.i.0/1/22/A/CFLA/001 co-funded by The Recovery and Resilience Facility.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Author Andris Krumins is employed by the company Lafivents Ltd. The remaining authors declare that the research is conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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