ACCEPTED MANUSCRIPT

Technical Sciences

Title: Adaptive microclimate control system to regulate conditions in a living-space

Authors: Łukasz Dziubiński, Seweryn Lipiński, Paweł Chwietczuk

To appear in: Technical Sciences

Received 13 April 2024;

Accepted 15 January 2025;

Available online 17 January 2025.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Accepted Manuscript

ADAPTIVE MICROCLIMATE CONTROL SYSTEM TO REGULATE CONDITIONS IN A LIVING-SPACE

Łukasz Dziubiński[1], Seweryn Lipiński[2*], Paweł Chwietczuk[3]

[1]*Faculty of Technical Sciences,*
University of Warmia and Mazury in Olsztyn

[2*]*ORCID: 0000-0001-9771-6897*
Faculty of Technical Sciences,
University of Warmia and Mazury in Olsztyn

[3]*ORCID: 0000-0002-2234-0554*
Faculty of Technical Sciences,
University of Warmia and Mazury in Olsztyn

*Correspondence: Seweryn Lipiński, Department of Electrical Engineering, Power Engineering, Electronics and Automation, Faculty of Technical Sciences, University of Warmia and Mazury in Olsztyn, 11 Oczapowskiego St., 10-719 Olsztyn, e-mail: seweryn.lipinski@uwm.edu.pl

Key words: microclimate regulation, adaptive control, smart home automation

Abstract

In recent years, smart home automation has become increasingly accessible, largely due to the availability of affordable and easy-to-implement electronic systems for control and measurement. While ready-made systems are widely available, self-designed solutions offer significant advantages, including tailored adaptation to user needs, low cost, ease of modification and expansion, and the ability for self-maintenance. This article presents a custom system designed for microclimate control in living spaces. The hardware components and control algorithms are thoroughly described, providing a foundation and inspiration for similar installations. Additionally, the article includes sample results demonstrating the system's effectiveness in adapting the microclimate to the user's comfort and preferences.

1. Introduction

Accepted Manuscript

Nowadays, an increasing number of people spend most of their time indoors, whether at work or at home. Prolonged stays in enclosed spaces can lead to a decline in air quality, which may negatively impact health, well-being, work efficiency, and sleep quality. Key factors influencing indoor air quality include air temperature and humidity, concentrations of particulate matter ($PM_{2.5}$, PM_{10}), carbon dioxide (CO_2) levels, as well as the intensity and colour of interior lighting (Bluyssen 2009).

Air temperature, lighting intensity and colour, as well as carbon dioxide (CO_2) concentration, have the most significant and direct impact on indoor well-being (Allen et al. 2016, Mujan et al. 2019). Elevated air temperatures can lead to excessive sweating, weakness, and fatigue, whereas low temperatures may impair concentration and weaken the immune system (Wolkoff et al. 2021). The average indoor CO_2 concentration is approximately 400 ppm, but in enclosed spaces with limited airflow, levels can rise significantly, particularly due to the so-called personal CO_2 cloud (Pantelic et al. 2020). Elevated CO_2 concentrations are associated with fatigue, reduced concentration, and potential headaches (Vehviläinen et al. 2016).

Lighting also plays a critical role in well-being. Insufficient light can accelerate fatigue and induce apathy, whereas excessive light may cause eye irritation, difficulty concentrating, and general discomfort. The colour of light further influences mood and performance: warm light is associated with relaxation and may reduce concentration and induce drowsiness, while cool light is stimulating and promotes productivity (Shahidi et al. 2021).

Humidity has a lesser effect on well-being, but low humidity levels can lead to the suspension of dust, pollen, and microbes in the air, potentially triggering allergic reactions and coughing. Prolonged exposure to dry air may also cause dryness of the mucous membranes in the eyes, nose, and throat (Derby et al. 2017). Conversely, high humidity can result in condensation on smooth surfaces, such as windows, and promote mould growth in these areas (Hurrass et al. 2017).

The optimal range of relative humidity depends on air temperature. For warm environments, humidity should be maintained between 45% and 55%, while in cooler conditions, the recommended range is 60% to 65% (Wolański 2016).

The concentration of particulate matter ($PM_{2.5}$) in the air does not directly affect our well-being. However, high levels are often accompanied by the unpleasant smell of exhaust fumes, which can cause discomfort and irritability. Long-term exposure to airborne particulate matter can lead to serious health issues. The most common health problems associated with high concentrations of particulate matter include respiratory diseases, such as lung cancer in severe cases, and allergies (Li et al. 2022, Pérez-Padilla et al. 2010).

As the above literature review indicates, the microclimatic conditions in living and working spaces are crucial. Therefore, this study aims to design and describe an adaptive microclimate control system for living spaces, which is intended to adjust the relevant parameters adaptively. The undeniable advantage of a self-made system is its optimal adaptation to the user's needs, low cost, ease of expansion, modification, and self-maintenance. Considering this, the article is intended to serve as a foundation, providing inspiration and a starting point for creating similar adaptive microclimate control systems for living spaces. The article outlines the system's assumptions, its structure (comprising both the devices and control algorithms), and the effects of its operation.

2. System description

2.1. Main assumptions

The microclimate control system has been designed to meet the following requirements:

- the user should be able to modify the system parameters according to their own needs;
- the system should be controllable by the user from a stationary touch screen or a smartphone;
- the system should be adaptive, taking appropriate actions based on readings from various sensors and adjusting to the user's preferences;
- the user should be able to continuously monitor the system's operation, with minimal human intervention required;
- the system should be reliable and capable of being calibrated as a whole.

Figure 1 shows the room in which the described system was installed, along with the location of its key elements. The room measures 4.5x3 m, has a door and three balcony windows, each measuring 204x73 cm.

Accepted Manuscript

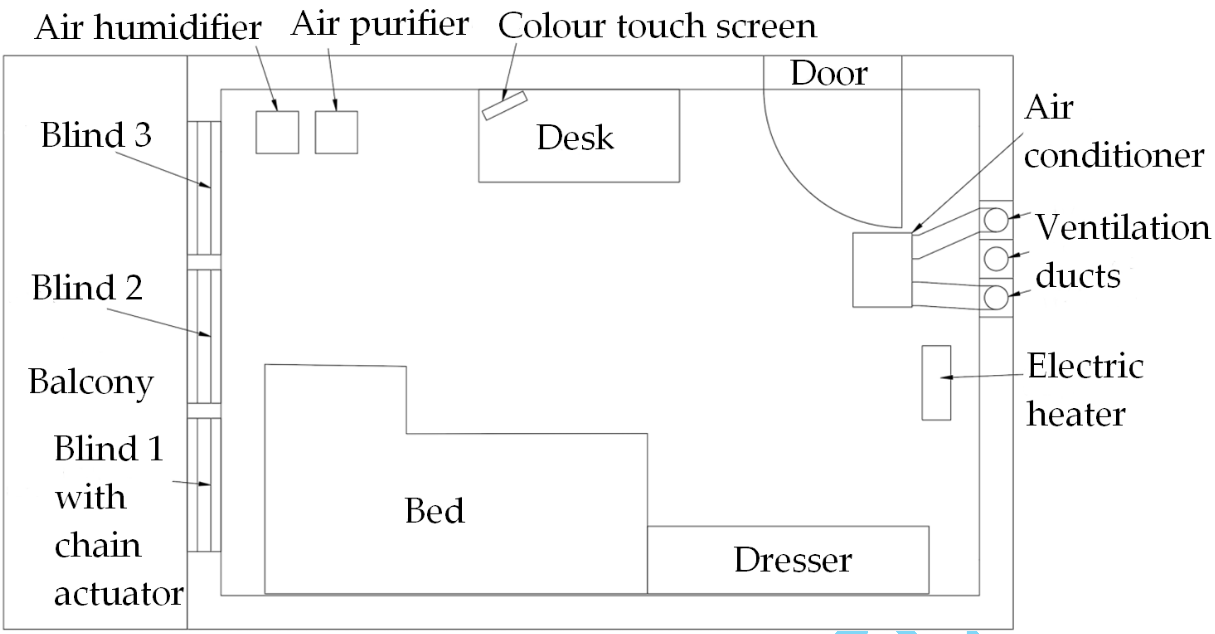

Fig. 1. Arrangement of system elements at the experiment site.

2.2. Block diagram of the control system

The layout of the adaptive microclimate control system is presented in the form of a block diagram in Fig 2. The role of each block is as follows:

(1) Microprocessor system based on ATmega2560 microcontroller - monitors the input ports and controls the output ports based on the parameters obtained and the developed algorithm;

(2) Evaporative air humidifier (Smartmi Evaporative Humidifier) - humidifies the air with varying levels of humidification;

(3) Air purifier (Xiaomi Air Purifier 3H) - purifies the air with different power levels of the built-in fan;

(4) Chain actuator (Micro Kit Mingardi 135 W)- responsible for tilting the windows;

(5) Window blinds (thermal-silver type) - can cover the windows to varying levels;

(6) Digital RGB LED lighting - each WS2815 diode can shine with different intensity and colour;

(7) Air conditioner (Rotenso Giru G35W);

(8) Electric heater (CH2500DW 2 kW);

(9) Colour touch screen (Nextion Intelligent, 10.1”, 1024x600) - allows the user to modify the system operating parameters and displays selected system parameters;

(10) Sensors – including:

- particulate matter sensor (PMS7003),

Accepted Manuscript

- CO_2 sensor (MH-Z19C),
- air temperature and humidity sensor (AHT20),
- photoresistors (used as lighting sensors).

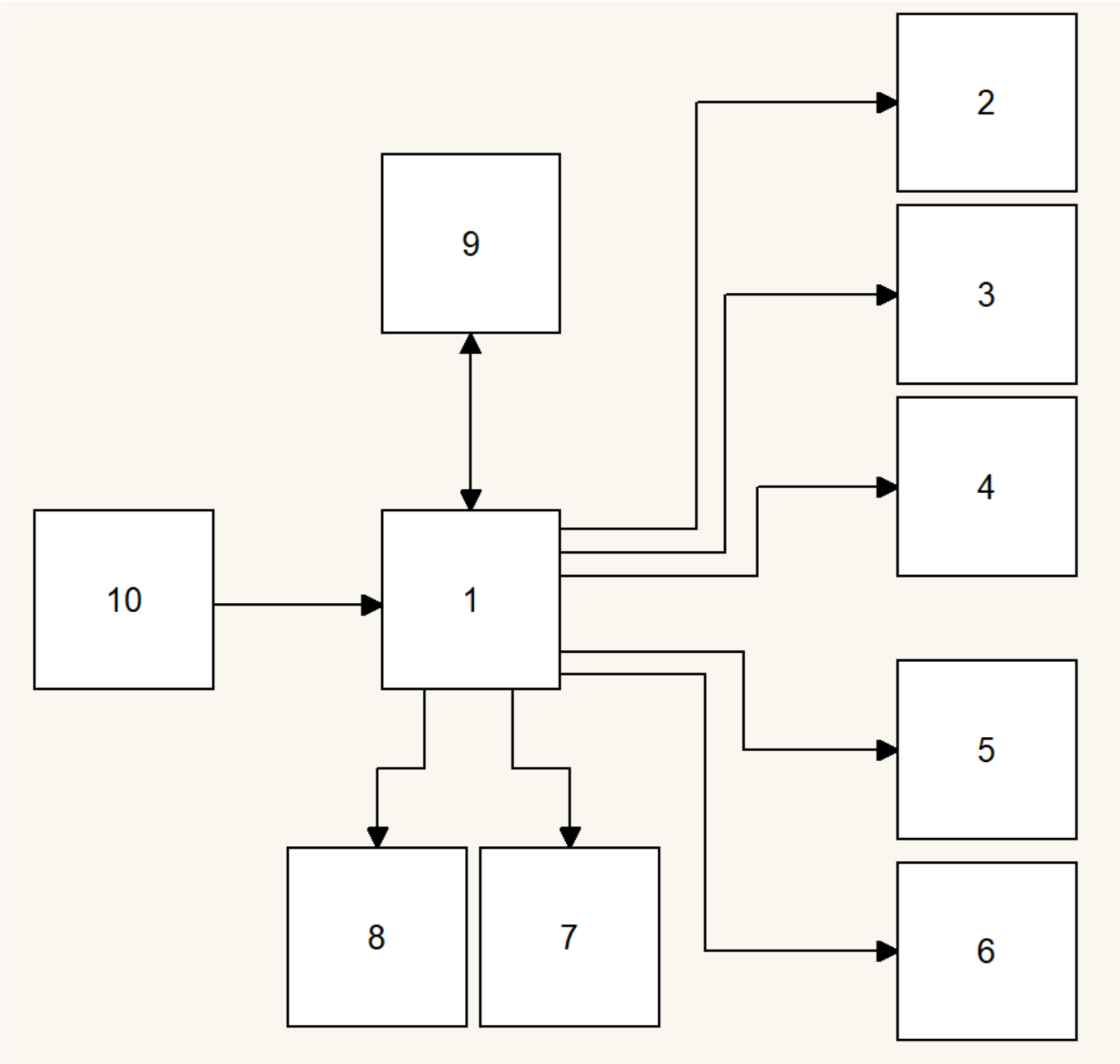

Fig. 2. Block diagram of the microclimate control system; 1 - data processing system; 2 – air humidifier; 3 - air purifier; 4 – window; 5 – blinds; 6 – LED lighting; 7 – air conditioning; 8 – heater; 9 – system to display system parameters and to modify parameters; 10 – data receiver.

In addition, the following remarks should be considered when installing the system and selecting devices:

- the humidifier (2) should not be ultrasonic, as it interferes with particulate matter sensors by creating microscopic water droplets that the sensor detects as contamination. Additionally, ultrasonic humidifiers break up impurities in the water, such as scale and microorganisms, into fine particles. These particles, including white dust from minerals, can be harmful to health (Daftary and Deterding 2011);

- blinds (5) should be of the thermal-silver type, which have a blackout and thermal coating. This prevents strong sunlight from penetrating and overheating the room, making it easier for the system to control lighting and temperature;
- LED lighting (6) should be installed on the ceiling to ensure that every part of the room can be illuminated.

2.3. Basics of the control algorithm

The basic version of the algorithm must consider the following aspects:

- target values - user-defined values for microclimate parameters, such as temperature, humidity, CO_2 concentration, $PM_{2.5}$ concentration, and light intensity;
- schedule - adherence to the time schedule set by the system user;
- dynamics of parameter changes - analysis of how quickly and in what direction the microclimate parameters change to adapt the system's operation to the prevailing conditions.

The primary aspect that should be considered in the algorithm is, of course, the target values of microclimate parameters.

There is no doubt that the key parameter directly affecting human comfort is temperature. The user defines the target temperature and the hysteresis, which determines the temperature range within which the system should operate. Hysteresis defines the tolerance range around the set target value, allowing the system to limit frequent switching of individual devices responsible for maintaining the temperature (electric heater, air conditioner, and window actuator). The higher the hysteresis value, the better it is for the system (lower frequency of device mode switching), but it may be less comfortable for the user due to noticeable temperature fluctuations (Cui et al. 2013).

The target value of air humidity should be selected based on the set room temperature. For example, for a temperature of 21°C, the recommended relative humidity is approximately 55% (Toftum & Fanger 1999), with a hysteresis of about 10 percentage points. Such fluctuations in humidity should not be strongly felt by humans. Taking these recommendations into account, these are the target temperature and humidity values that were set during system testing.

For CO_2 concentration, only the maximum permissible value needs to be determined, as only excess levels are undesirable. The lower the concentration, the better for the user. By default, the maximum allowable CO_2 concentration is 1000 ppm, the level at which people start

Accepted Manuscript

to perceive the air as stale (Azuma et al. 2018). This is also the maximum level recommended by the WHO (World Health Organization 2000), and for this reason, the maximum CO_2 concentration during system testing was set at 1000 ppm. However, the system allows for independent setting of the permissible CO_2 level, as literature shows that CO_2 levels have a very individual impact on work efficiency and overall human functioning (Azuma et al. 2018, Satish et al. 2012).

The situation is similar with the concentration of $PM_{2.5}$ in the air; here too only the maximum permissible value needs to be set. The maximum allowable value of $PM_{2.5}$ was set at 10 $\mu g \cdot m^{-3}$, as recommended by World Health Organization (2005). It should be noted that newer version of this recommendation (World Health Organization 2021), suggests that this value should be halved to 5 $\mu g \cdot m^{-3}$.

Based on personal experience, it was found that the best way to determine the value of light intensity in a room is to configure the system according to individual preferences. This value is given as a percentage, allowing the user to easily specify their requirements. A value of 0% means complete darkness, while 100% corresponds to the light intensity in the room during very sunny weather.

The scheduling aspect of a microclimate control system involves programming and coordinating individual activities at specific times. The schedule allows the user to adjust the microclimate in the room to meet changing needs throughout the day or week. The system should enable the user to adjust the schedule based on different times of the day (morning, noon, evening, etc.) and different days of the week (working days, days off, specific days, etc.). Typically, temperature and light intensity are the parameters most often subject to scheduling. For example, from morning to evening, the target room temperature might be set at 21°C with light intensity at 70%, while at night, the target temperature could be 18°C with lighting no higher than 5% to avoid disturbing sleep. The schedule is highly individualized, as everyone has different needs (e.g., varying work and sleep hours).

The dynamics of parameter changes refer to the system's ability to smoothly adapt to changing conditions both inside and outside the building. The system should respond to changes in outdoor air parameters, especially if they occur suddenly. Examples of such sudden changes include heavy rain, which may cause a drop in outside temperature, the sudden appearance of the sun from behind clouds, resulting in a sharp increase in indoor light intensity, or an increase in outdoor $PM_{2.5}$ concentration. Sudden changes can also occur indoors, such as a quick temperature change when the user opens a balcony door, or an immediate increase in air pollution due to smoking a cigarette in the room.

2.4 Operation of actuators

All actuators are controlled by a microprocessor central unit (MCU), in this case, the Arduino Mega 2560 (based on the ATmega2560 microcontroller). This MCU was chosen because it is inexpensive, easy to program, and has many input/output ports, allowing for potential system expansion.

The tasks of the window actuator include tilting the window to the appropriate angle (determined by the algorithm controlling the dynamics of parameter changes) in the following situations:

- the CO_2 concentration in the room is too high (i.e. higher than 1000 ppm);
- the room temperature is higher than the set temperature by at least the hysteresis value and is higher than the outside temperature (a sufficient temperature difference is required for effective cooling by letting in cooler outside air);
- the room temperature is lower than the set temperature by at least the hysteresis value and is lower than the outside temperature (a sufficient temperature difference is required for effective heating by letting in warmer outside air);
- the $PM_{2.5}$ concentration in the indoor air is significantly higher than in the outdoor air;
- the room humidity is higher than the set humidity by at least the hysteresis value and is lower than the outside humidity (a sufficient humidity difference is required for effective humidity reduction by letting in drier outside air).

It should be emphasized that if the outdoor particulate matter concentration is very high, the window will not be opened, even if one of the above conditions is met.

The tasks of the window actuator also include closing the window in the following situations:

- the CO_2 concentration in the room has dropped to the specified level, and no other condition for tilting the window is met;
- the room temperature is higher or lower (depending on whether the window was previously opened for heating or cooling) by at least the hysteresis value from the set temperature, and no other condition for opening the window is met;
- the significant concentration of $PM_{2.5}$ in the room has ceased, and no other condition for opening the window is met;
- the outdoor $PM_{2.5}$ concentration is significant.

The tasks of the air conditioner include:

Accepted Manuscript

- activating the cooling mode when the room temperature is higher than the set temperature by at least the hysteresis value and cooling by opening the window is not possible;
- starting the dehumidification mode when the room humidity is higher than the set humidity by the hysteresis value and reducing humidity by opening the window is not possible;
- turning off the cooling or dehumidification mode when the room temperature drops to the set temperature minus the hysteresis value, or the room humidity drops to the set humidity minus the hysteresis value.

The tasks of the electric heater include activating the heating mode when the room temperature is lower than the set temperature by at least the hysteresis value and heating by opening the window is not possible.

The tasks of the air purifier include regulating the fan power based on the $PM_{2.5}$ concentration in the room. If the concentration is equal to or lower than the set value, the fan power is set to the lowest level. If the concentration is higher than the set value, the fan power is adjusted according to the difference between these values. The greater the difference, the higher the fan power.

The tasks of the air humidifier include regulating the fan power based on the room humidity. The fan power is adjusted to keep the room humidity as close as possible to the set value. As the humidity increases above the set value, the fan power decreases until it reaches a value close to the set value plus the hysteresis value, at which point the fan is turned off. If the humidity drops below the set value, the fan power increases accordingly.

LED lighting control ensures that the room is illuminated with the appropriate light colour and intensity based on the time of day and individual needs.

The tasks of the roller blinds include:

- increasing the degree of window covering when it is bright outside and the room light intensity exceeds the set value, provided the increased intensity is not due to the system-controlled LED lighting;
- Reducing the degree of window covering when the room light intensity is below the set value and the outdoor light intensity is high enough.

Accepted Manuscript

3. Results and discussion

Figures 3-7 show the exemplary results obtained during system tests, illustrating how temperature, CO_2 concentration, relative humidity, light intensity, and $PM_{2.5}$ concentrations changed over time.

Figure 3 shows the control of CO_2 concentration. As can be seen, the system smoothly controlled the window opening, adjusting its degree of opening based on the current CO_2 concentration. At no point did the CO_2 concentration approach the limit value of 1000 ppm, remaining below 850 ppm.

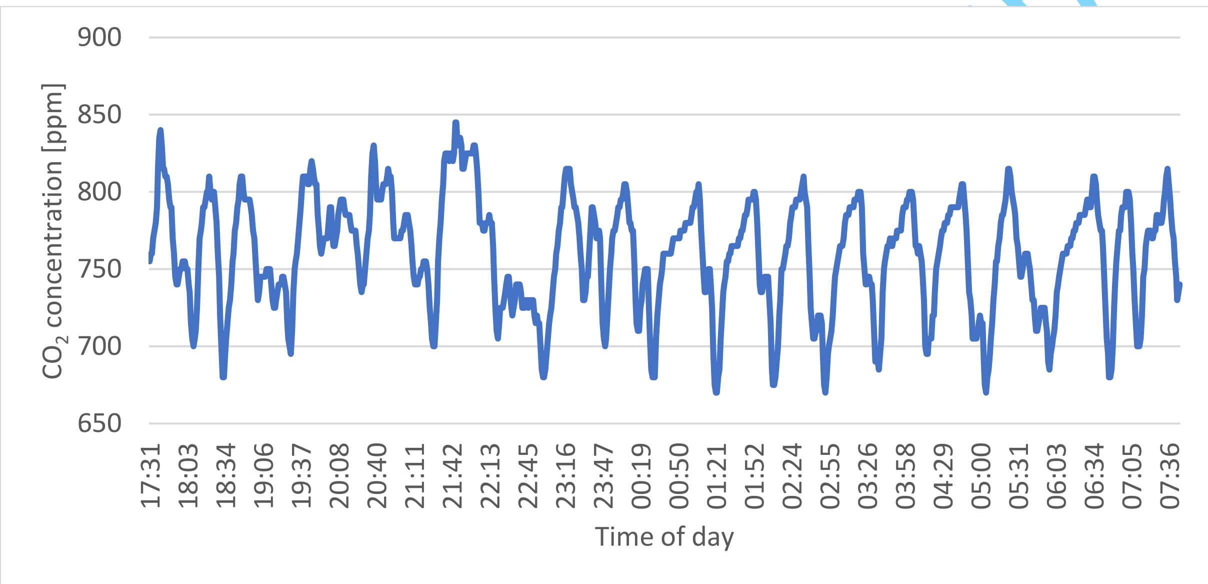

Fig. 3. CO_2 concentration control results.

Since the system smoothly controlled the window tilt, temperature fluctuations were very low, as shown in Figure 4. The temperature in the graph ranges from 20.5°C to 21.1°C (while the set temperature was equal to 21°C), resulting in a difference of 0.6°C. Considering that the default temperature hysteresis in home thermostats is 1°C, such fluctuations should be considered more than satisfactory.

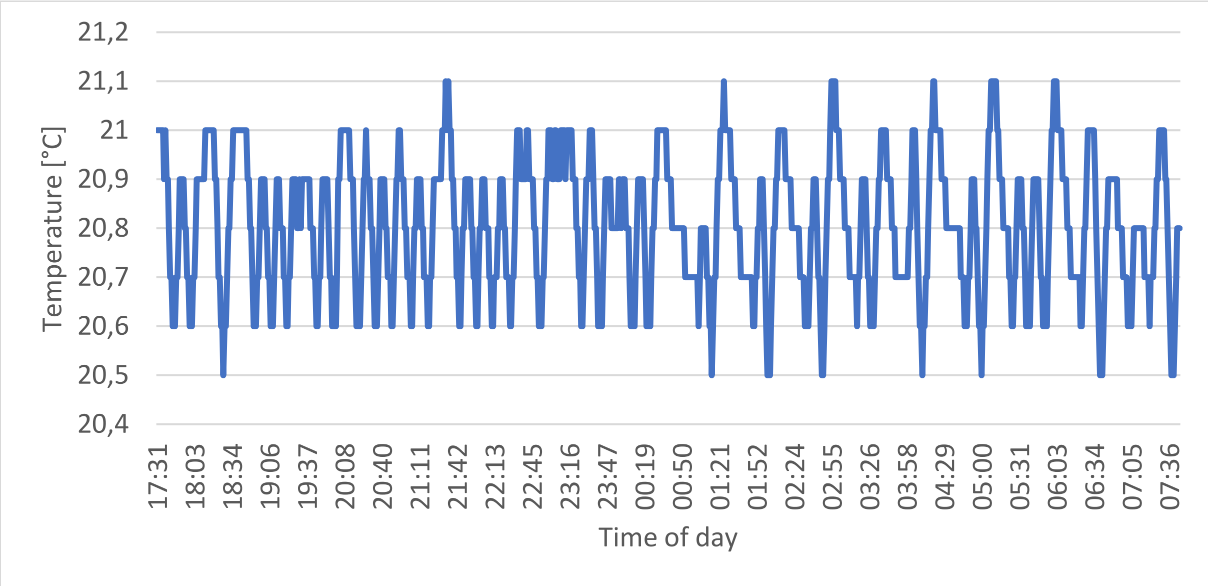

Fig. 4. Temperature control results.

Thanks to the low fluctuations in room temperature and the avoidance of excessive ventilation, stable relative humidity values were obtained, as shown in Figure 5. The average spread of relative humidity values is approximately 4%, and most measurements are between 56 and 59%, while the target humidity value is equal to 55%. As can be seen, the achieved humidity value is usually slightly higher than the target, but considering the recommended hysteresis, which is relatively large for humidity (i.e. 10%), this should not be considered a problem (Toftum & Fanger 1999).

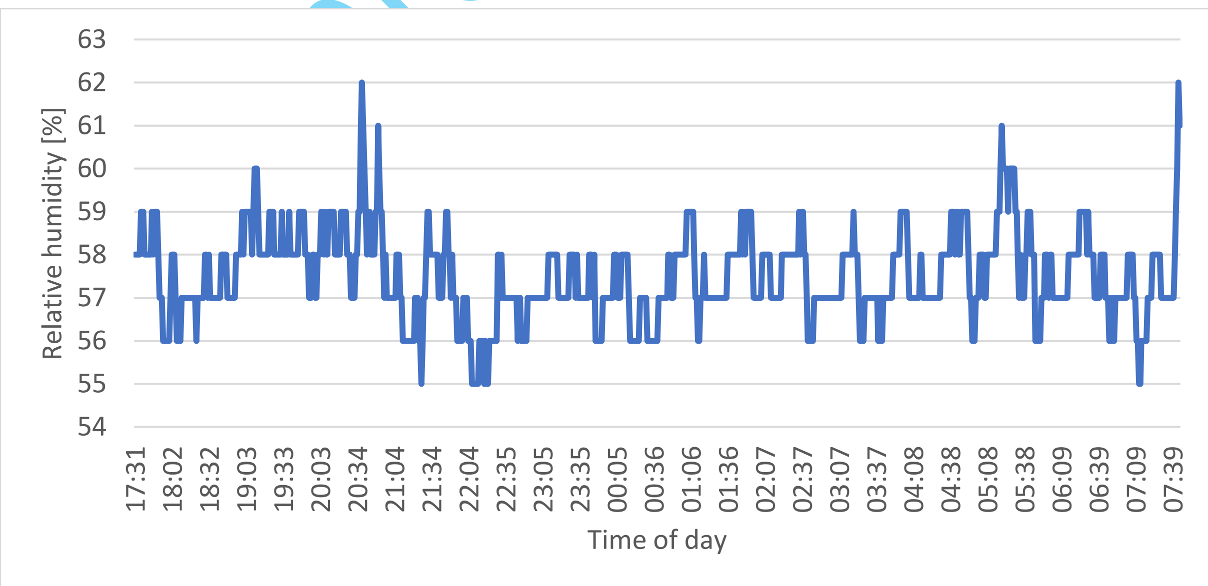

Fig. 5. Relative humidity control.

Figure 6 shows how the light intensity in the room changed. There are two key things to note about this drawing. The first are clearly noticeable start and end times of daily activities set by the user. The second, more important, is the fact that during the period of activity, the system effectively responds to changes in lighting, regardless of the conditions outside, the lighting conditions in the room are unchanged and stable.

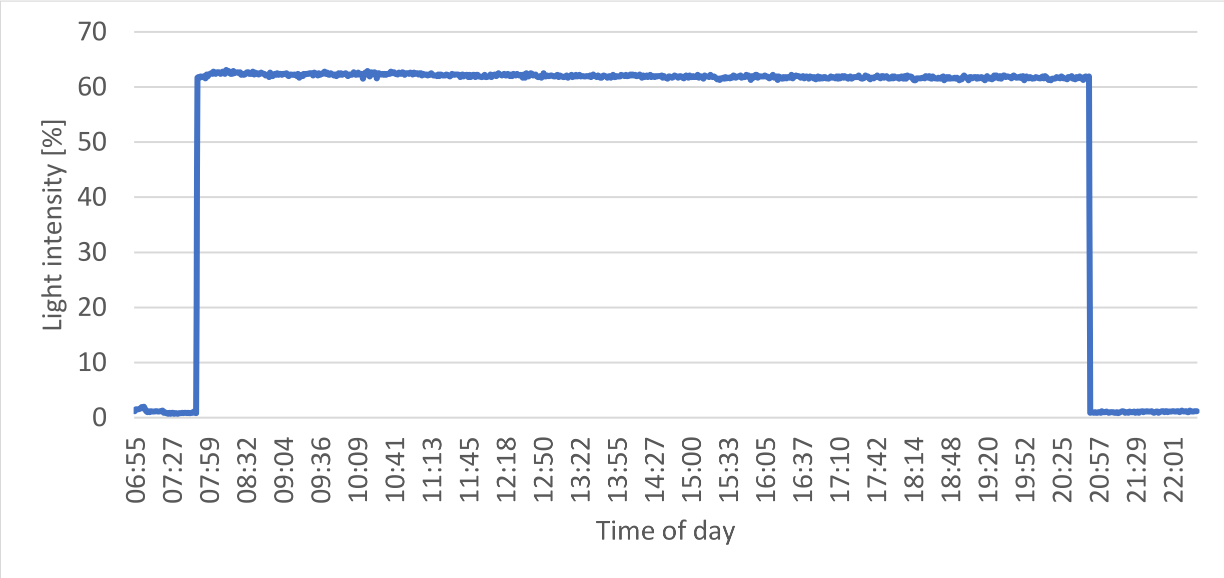

Fig. 6. Light intensity control.

Figure 7 shows the control of $PM_{2.5}$ concentration in the room. As can be seen, the air purifier effectively reduces the $PM_{2.5}$ concentration, keeping it significantly lower than limit value, which is equal to 10 $\mu g \cdot m^{-3}$. If we consider the WHO recommendations from 2021, i.e. a $PM_{2.5}$ concentration limit of 5, the vast majority of measurements are still below it.

Accepted M

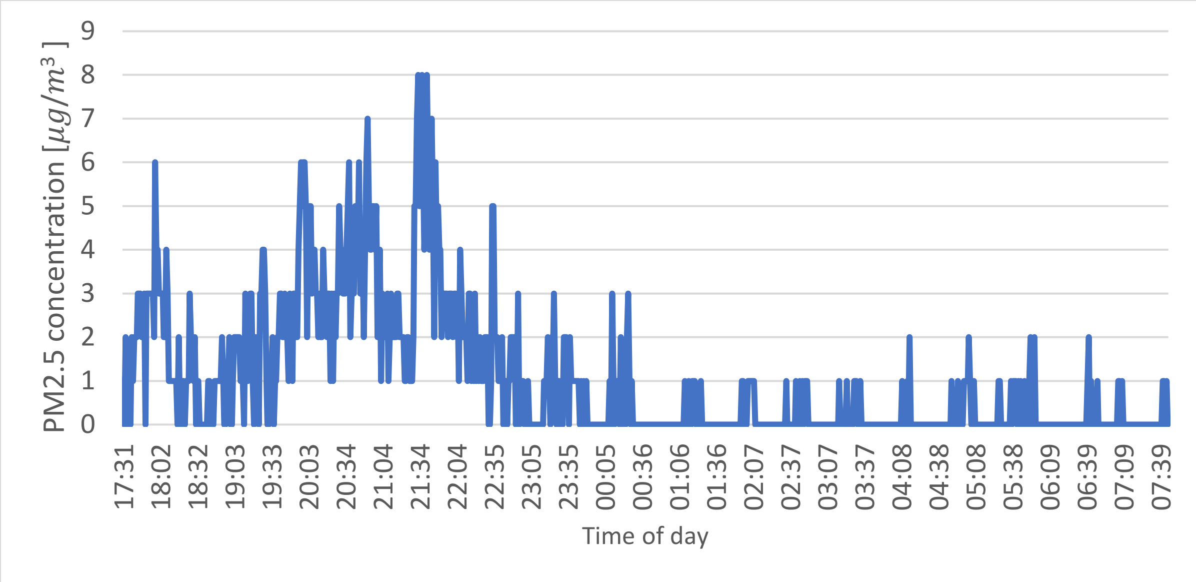

Fig. 7. Control of the concentration of $PM_{2.5}$.

To sum up the system tests, it should be stated that all parameters crucial for user comfort were automatically maintained at the appropriate level, which in turn leads to the conclusion that the described project was based on proper assumptions, the executive and measuring elements have been properly selected, and in consequence the proposed system was implemented correctly and so it can be a good starting point for other similar realizations.

4. Summary and conclusions

The aim of this article is to propose and test the capabilities of an adaptive microclimate control system in a single-family residential building, aimed at ensuring comfortable conditions for the user in the rooms they occupy. The system is designed to control key microclimate parameters such as temperature, humidity, light intensity, carbon dioxide concentration, and $PM_{2.5}$ concentration using actuator devices and a set of sensors.

Sample results demonstrating the system's operation proved its effectiveness in adapting the microclimate to the user's needs and comfort. It can be concluded that the presented system met the design expectations, providing comprehensive control over the microclimate in the living space. The inclusion of dynamic parameter adjustment in the system algorithm allowed for optimal management of device operations.

The dynamic parameter adjustment in the algorithm plays a crucial role. This approach enables the system to continuously adapt to current conditions, resulting in stable and effective operation, which is key to maintaining comfort. This helps avoid large fluctuations in microclimate parameters, which can disrupt the user's comfort.

Monitoring CO_2 concentration in a closed room can potentially be used to study the sleep patterns of individuals. Based on CO_2 concentration values throughout the sleep period, it is possible to determine information such as the start and end times of sleep and the sleep phases (Salvade et al. 2023). This opens the possibility of implementing additional sleep-related functions; however, it should be noted that for such monitoring to work, the CO_2 concentration control system would have to be turned off.

While analysing the functioning of the microclimate control system, the issue of noise generation by some system devices was identified. In a living space where acoustic comfort is important, noise can negatively affect the user's comfort and quality of life. One of the devices responsible for noise is the air conditioner, which can generate significant noise in cooling and dehumidification modes. Therefore, when selecting an air conditioner, one should consider not only its power but also its noise level.

Another relatively noisy device is the air purifier. At low fan speeds, it is inaudible, and this fan power may be sufficient for effective air purification most of the time. However, in the event of a sudden increase in pollutant concentration, the low-speed mode may be insufficient, requiring medium or high-speed operation, which generates more noise.

Similarly, the air humidifier is virtually inaudible at low speed, which is sufficient to maintain appropriate relative humidity values in the room. However, under certain conditions, it may be necessary to increase the speed, generating additional noise.

The window actuator generates a small amount of noise when opening or closing the window, but the sudden appearance of this sound at night when the surroundings are quiet may wake up people sleeping in the room.

Controlling CO_2 concentration contributes to increased electricity consumption because lowering the concentration requires opening the window, which introduces air at a different temperature than the room. As a result, the electric heater or air conditioner must operate more frequently to maintain the optimal room temperature. Therefore, the current system works well when the external temperature ranges from approximately 5°C to 25°C (Pisello et al. 2016). To increase system effectiveness and reduce electricity consumption, it is recommended to use an air recuperator. Using a recuperator instead of a window actuator would also partially solve the noise issue and excessive electricity consumption when controlling CO_2 concentration.

Finally, it should be noted that while ready-made smart home automation systems are available on the market, the key advantages of a self-made system are its optimal adaptation to the user's needs, low cost, ease of expansion, and self-maintenance. In terms of easy system expansion (especially regarding the number of inputs/outputs) and construction cost, the MCU-based system is better than systems based on programmable logic controllers (PLC). However, PLC-based systems have the advantage of simpler control algorithm creation without the need for programming knowledge (Kwaśniewski 2011, Lipiński et al. 2018).

References

Allen, J.G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., & Spengler, J.D. 2016. *Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments*. Environmental Health Perspectives, 124(6), 805-812.

Azuma, K., Kagi, N., Yanagi, U., & Osawa, H. 2018. *Effects of low-level inhalation exposure to carbon dioxide in indoor environments: A short review on human health and psychomotor performance*. Environment International, 121, 51-56.

Bluyssen, P. M. 2009. *The indoor environment handbook: how to make buildings healthy and comfortable*. Earthscan, London/New York.

Cui, W., Cao, G., Park, J. H., Ouyang, Q., & Zhu, Y. 2013. *Influence of indoor air temperature on human thermal comfort, motivation and performance*. Building and Environment, 68, 114-122.

Daftary, A.S., & Deterding, R.R. 2011. *Inhalational lung injury associated with humidifier "white dust"*. Pediatrics, 127(2), e509-e512.

Derby, M.M., Hamehkasi, M., Eckels, S., Hwang, G.M., Jones, B., Maghirang, R., & Shulan, D. 2017. *Update of the scientific evidence for specifying lower limit relative humidity levels for comfort, health, and indoor environmental quality in occupied spaces (RP-1630)*. Science and Technology for the Built Environment, 23(1), 30-45.

Hurrass, J., Heinzow, B., Aurbach, U., Bergmann, K.C., Bufe, A., Buzina, W., Cornely, O.A., Engelhart, S., Fischer, G., Gabrio, T., Heinz, W., Herr, C.E.W., Kleine-Tebbe, J., Klimek, L., Köberle, M., Lichtnecker, H., Lob-Corzilius, T., Merget, R., Mülleneisen, N., Nowak, D., Rabe, U., Raulf, M., Seidl, H.P., Steiß, J.-O., Szewszyk, R., Thomas, P., Valtanen, K. & Wiesmueller, G.A. 2017. *Medical diagnostics for indoor mold exposure*. International Journal of Hygiene and Environmental Health, 220(2), 305-328.

Kwaśniewski, J. 2011. *Smart home and other control systems in 100 examples*. BTC, Legionowo, Poland (in Polish).

Li, S., Wu, W., Wang, G., Zhang, X., Guo, Q., Wang, B., Cao, S., Yan, M., Pan, X., Xue, T., Gong, J., & Duan, X. 2022. *Association between exposure to air pollution and risk of allergic rhinitis: a systematic review and meta-analysis*. Environmental Research, 205, 112472.

Lipiński, S., Olkowski, T., & Pych, P. 2018. *Didactic development of a control system and control of steam boiler operating parameters using a programmable controller*. Education-Technology-Computer Science, 9(2), 304-310 (in Polish).

Accepted Manuscript

Mujan, I., Anđelković, A.S., Munćan, V., Kljajić, M., & Ružić, D. 2019. *Influence of indoor environmental quality on human health and productivity - A review*. Journal of Cleaner Production, 217, 646-657.

Pantelic, J., Liu, S., Pistore, L., Licina, D., Vannucci, M., Sadrizadeh, S., Ghahramani, A., Gilligan, B., Sternberg E., Kampschroer K., Wellbuilt for Wellbeing Project Team, & Schiavon, S. 2020. Personal *CO_2 cloud: laboratory measurements of metabolic CO_2 inhalation zone concentration and dispersion in a typical office desk setting*. Journal of Exposure Science & Environmental Epidemiology, 30(2), 328-337.

Pérez-Padilla, R., Schilmann, A., & Riojas-Rodriguez, H. 2010. *Respiratory health effects of indoor air pollution*. The International Journal of Tuberculosis and Lung Disease, 14(9), 1079-1086.

Pisello, A. L., Castaldo, V. L., Taylor, J. E., & Cotana, F. 2016. *The impact of natural ventilation on building energy requirement at inter-building scale*. Energy and Buildings, 127, 870-883.

Salvade, C., Tasso, V., Carloni, F., & Santambrogio, M. D. 2023. *Improving sleep quality through an arduino-based environment sleep monitoring system*. IEEE EUROCON 2023 - 20th International Conference on Smart Technologies, 6-11.

Satish, U., Mendell, M. J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., & Fisk, W. J. 2012. *Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance*. Environmental Health Perspectives, 120(12), 1671-1677.

Shahidi, R., Golmohammadi, R., Babamiri, M., Faradmal, J., & Aliabadi, M. 2021. *Effect of warm/cool white lights on visual perception and mood in warm/cool color environments*. EXCLI Journal, 20, 1379.

Toftum, J., & Fanger, P. O. 1999. *Air humidity requirements for human comfort*. ASHRAE Transactions, 40(8), 35-41.

Vehviläinen, T., Lindholm, H., Rintamäki, H., Pääkkönen, R., Hirvonen, A., Niemi, O., & Vinha, J. 2016. *High indoor CO_2 concentrations in an office environment increases the transcutaneous CO_2 level and sleepiness during cognitive work*. Journal of Occupational and Environmental Hygiene, 13(1), 19-29.

World Health Organization. *Air Quality Guidelines. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide*. 2005.

World Health Organization. *WHO global air quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. 2021.

World Health Organization. Regional Office for Europe. 2000. *Air quality guidelines for Europe* (2nd ed.) WHO Regional Publications, European Series, 91.

Wolański, P. 2016. *The influence of internal air pollution on the indoor microclimate and human health*. Archives of Waste Management and Environmental Protection, 18(3).

Accepted Manuscript

Wolkoff, P., Azuma, K., & Carrer, P. 2021. *Health, work performance, and risk of infection in office-like environments: The role of indoor temperature, air humidity, and ventilation*. International Journal of Hygiene and Environmental Health, 233, 113709.

Accepted Manuscript