NEW OPPORTUNITIES OF A MULTIPLE MEASUREMENT TECHNOLOGIES DEVELOPED TEST ROOM FOR THE INDOOR PARAMETERS AND USERS' INTERACTION IN DIFFERENT TYPES OF COMFORT AND DIGITAL TECHNOLOGIES (IOT)

Maximilian Günzel[1], Simon Stinglhammer[2], Werner Jensch[3]

1 *Munich University of Applied Sciences, Munich, Germany, Email: maximilian.guenzel@hm.edu*
2 *Munich University of Applied Sciences, Munich, Germany, Email: simon.stinglhammer0@hm.edu*
3 *Munich University of Applied Sciences, Munich, Germany Email: werner.jensch@hm.edu*

ABSTRACT

This research paper investigates the impact of user behavior on energy consumption, human comfort, and indoor parameters in buildings, with a specific focus on educational settings. Conducted at the Munich University of Applied Sciences, the research utilizes two test rooms with differing technological standards to accurately quantify user influence. The high-tech lecture room is equipped with advanced systems, including partial air conditioning, allowing users to actively control indoor air quality. In contrast, the low-tech reference room serves as a baseline for comparative purposes. Both rooms are outfitted with comprehensive sensors to measure parameters such as temperature, humidity, CO_2 concentrations, brightness, and user activities. The research underscores the critical role of user behavior in influencing energy consumption and comfort levels in educational environments. Actions such as adjusting room temperature, opening windows, utilizing sun protection, and operating electrical appliances significantly impact energy use. Furthermore, the study emphasizes the importance of implementing intelligent monitoring systems in school buildings, highlighting that user-friendly interfaces are crucial for effective energy consumption visualization by teachers and students. Innovations introduced in this study include the integration of a digital twin, real-time sensor data transmission via cloud connectivity, and a novel room control device. These technologies enhance user interaction, enable efficient data analysis, and optimize both energy efficiency and user comfort. The findings provide a robust foundation for further research and practical applications aimed at improving building energy management and occupant well-being.

1 INTRODUCTION

Energy consumption in buildings significantly impacts overall energy efficiency, particularly in educational institutions where occupancy patterns and user behaviors vary widely. Previous studies have highlighted the importance of occupant behavior on energy use (Delzendeh et al., 2017). However, there is limited research on the direct quantification of user influence in real-time, practical settings.

This paper presents an innovative approach using advanced test rooms equipped with multiple measurement technologies to monitor indoor parameters and user interactions. These test rooms (Table 1), developed at the Munich University of Applied Sciences, provide a unique environment for studying the interplay between user behavior, comfort, and energy consumption. The primary objective of this research is to quantify user impact on energy efficiency and comfort, contributing novel insights to the field of building energy management.

2 INFLUENCE AND IMPACT IN EDUCATIONAL INSTITUTIONS

The results from the analysis of integrative test spaces pave the way for a more in-depth investigation of the influence of user behavior and technological application in school environments. The discussion about the design of building interfaces, especially in the context of lighting controls, thermostats and

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digital interfaces, opens up a broader view of educational institutions. Research highlights the influence of environmental factors such as room temperature and ventilation on students' well-being and cognitive performance. In rooms with free ventilation, extreme temperatures or air velocities that are perceived as uncomfortable can occasionally occur due to the user's perceived ability to influence them (de Dear et al., 1997; ISSO 74; Nicol, McCartney 2000).

Another relevant finding, presented by Wyon (1996), shows that individual control of room temperature in the range of ± 3K increases mental performance in tasks by 2.7%.
However, applying these findings to classrooms frequented by a large number of students raises complex questions. In this environment, the implementation of an individual option to influence the room temperature is challenging. In particular, the difficulty of providing personalized control to each student could have a significant impact on perceived control and thus on well-being. Sedlbauer, Holm and Hellwig (2009) emphasize that perceived influence decreases with increasing number of people in the room.

3 SCIENTIFIC CONTRIBUTION AND NOVELTY

This research introduces a novel experimental setup comprising two test rooms with varying technological sophistication, designed to systematically study the effects of user behavior on energy consumption and comfort in educational settings. Table 1 shows the geometric data of the two test rooms. These are almost completely identical. In addition, the use as seminar rooms in educational institutions including occupancy is the same. Key innovations of the test rooms, specially the master room, include:
Digital Twin Integration: A real-time digital twin model that visualizes indoor environmental conditions and user interactions.
Multi-Domain Measurement Technologies: Comprehensive sensor arrays to capture temperature, humidity, CO2 levels, lighting conditions, and user activities.
User Interaction Analysis: Detailed analysis of how different user groups (students, faculty) interact with building technologies and impact energy consumption.
These features distinguish our study from existing literature, offering a practical framework for improving energy efficiency through user behavior modification.

Table 1: Geometric Data Measuring Spaces

Parameters	Unit	Master Room	Reference Room	Difference
Base	m²	77,9	77,8	0,1
Ceiling height	m	3,00	3,20	0,20
Volume	m³	234,1	247,8	13,7
Face lenght	m	9,0	9,0	0
Room depth	m	9,0	9,0	0
Transparent surface	%	55,3	55,3	0
Occupancy with	pers cm	38	41	3

4 PRESENTATION OF THE TEST ROOM AND REFERENCE ROOM

The rooms are divided into a high-tech lecture room and an associated reference room. The technology installed in it was built as part of the EnEff research project (FKZ 03ET1075A), among others.
The orientation and location of the two rooms is similar. In addition, the use of the two test rooms is identical. Seminars and courses take place there at the same time and on the same days. The main use of both rooms are courses for master's students in building technology and industrial engineering.

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The master room has a decentralized partial air conditioning system with several thermodynamic air treatment stages. The target values of indoor air quality (air temperature and CO_2 concentration) can be influenced by the users. The users of the room have the option of influencing the operating modes of the partial air conditioning system depending on the comfort requirements via a control display. A new type of visualization in the form of a digital twin is also installed.
The digital twin also offers various visualization options, including in the form of heatmaps and charts of individual sensor values. The lecture room and the reference room were equipped with comprehensive sensors for the evaluation of the data (Table 2).

Table 2: Selection of sensors used (Winkler M. *et. al*., 2016)

Parameters	Measured data
Temperature	indoor air temperature, outdoor air temperature, surface temperature
Humidity	relative humidity
Concentrations	mixed gas voc, CO_2 concentration
Brightness	outside brightness, room brightness
Activities	presence, window opening, sun protection
Energy	heat meters, electricity meters

The schematic diagrams (Figure1) illustrate the master room, a sophisticated test environment designed to investigate indoor environmental parameters and user interactions. Configured as a classroom, the room features several rows of seating and a teacher's podium at the front.
The room is equipped with various sensors to measure energy and indoor climate parameters:

- **Teacher's Area/Front of the Room**: This area is equipped with sensors that measure relative humidity, CO_2 concentration, and VOC (volatile organic compounds). These sensors provide data on the air quality in the front portion of the room.
- **Middle of the Room (rear wall)**: Sensors at this location measure air temperature, relative humidity, and CO_2 concentration, thereby monitoring the indoor climate in the central area of the classroom.
- **Ceiling Area (above the seating)**: Sensors installed in this area measure relative humidity and CO_2 concentration, offering insights into the air quality above the seating areas.
- **Window Area**: Heat meters are installed at the window front to measure heating energy consumption, contributing to the monitoring of energy usage for heating purposes.

In addition to these primary sensors, the room is also equipped with window contact sensors, electricity meters, and an external weather station with various sensors. These additional sensors provide comprehensive data on indoor air quality, energy consumption, and external weather conditions. It is important to note that some installed technologies, such as the control display, digital twin, and ventilation system, are not depicted in these schematic diagrams.
The same set of sensors located in the teacher's area, middle of the room, ceiling area, and window area are also installed in the reference room. This allows for the collection and analysis of comparable data, facilitating the investigation of performance differences and environmental conditions between the two rooms.

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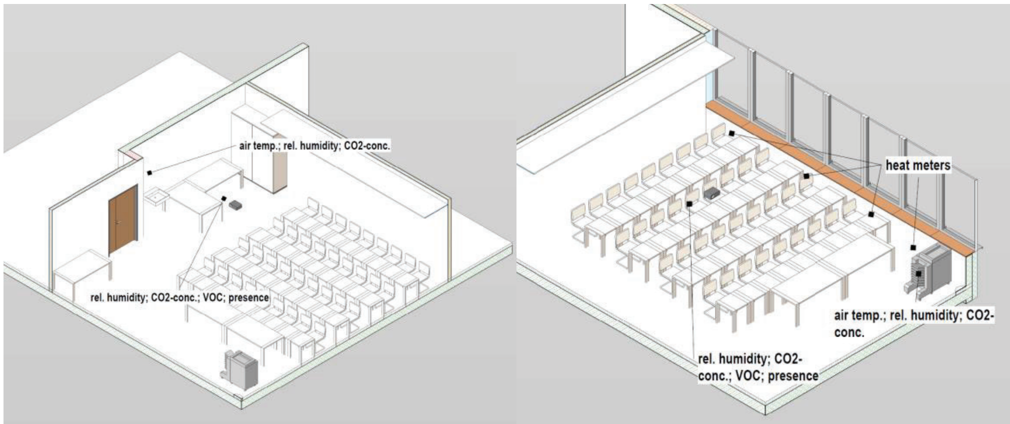

Figure 1: Schematic Diagrams of the master room

5 CLASSIFICATION OF THE TEST ROOM

By dividing it into two rooms with different technology standards, the user influences on the energy consumption of classrooms can be better quantified.

An analysis of 396 scientific publications on test rooms (cf. A.L. Pisello *et. al*., 2021) shows that the two measurement rooms can be assigned to the 4% of spaces with three or more physical domains that can be measured/studied. The analysis also shows that of the publications published by June 2020, the majority (82%) were published in Europe and Asia.

A special feature of the room is the use in a real environment by students in teaching. It can therefore be assigned to the 3% of the rooms examined that have the type of use "classroom". This allows the students, as users of the room, to have a direct influence on the comfort parameters, which is listed in 21 of the 396 publications examined.

Likewise, the use of external sun protection as well as the exterior façade is a special feature compared to the rooms examined. Only three of the rooms have external sun protection and four have internal sun protection. A window is available in most test rooms (68%) that are integrated into a building. Most of the test rooms examined (Figure) are detached from existing buildings (43%). Test rooms housed in buildings are included in 32% of the publications examined. Of the rooms, about half (49%) have a floor area of more than 20 m².

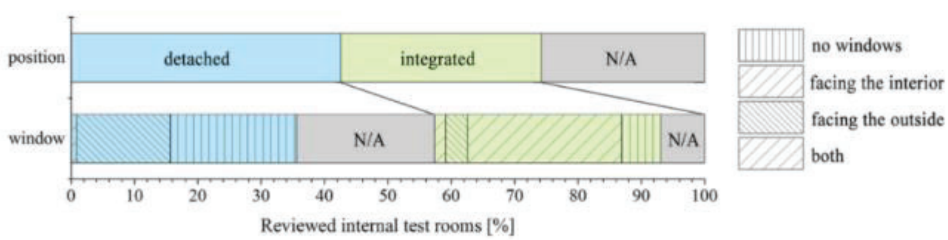

Figure 2: Overview of the layout of test rooms in terms of integration and windows (A.L. Pisello *et. al*., 2021)

In the majority of the test rooms, central air treatment is carried out and room-by-room control by the users is not possible. "The most commonly centrally controlled parameter is air temperature, followed by humidity and air quality control." (A.L. Pisello *et. al.,* 2021)

Particular attention is paid to the low-tech reference room. This serves as a real reference environment compared to the highly tenologized lecture room. This makes it possible to quantify the user's influence on comfort and interaction with the end user.

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After analyzing the classifications listed above, the highly technological test room at the Munich University of Applied Sciences stands out as one of the most specific and detailed test rooms in terms of measurement technologies for indoor room parameters, energy consumption, and user comfort. The unique extension through a digital twin and associated digital technologies further enhances its capabilities.

6 USER BEHAVIOR IN THE CONTEXT OF TEST ROOMS

Figure 3 shows the different levels that are to be understood under the term user. It deals with the concept of the "user" and its different manifestations in the context of buildings and spaces.
The term "end-user" describes people who are in and interact with a building or space. This can include, for example, customers, visitors or employees. In the context of educational buildings and test rooms, the term "end user" refers to pupils, teachers or lecturers or professors.

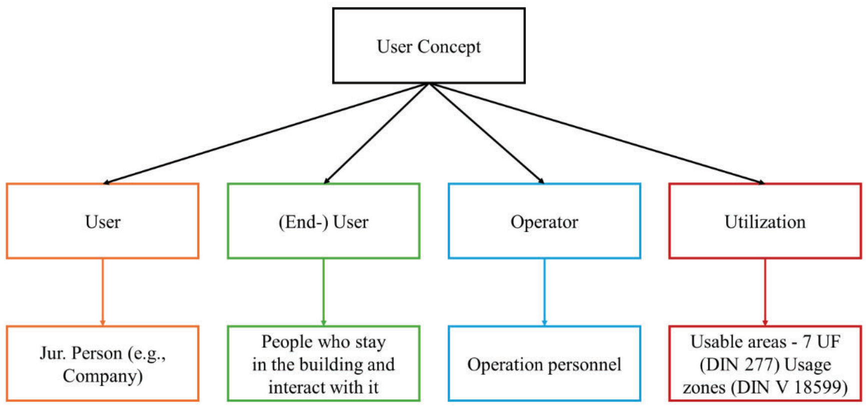

Figure 3: The different levels of the user concept (NuData Campus)

6.1 Energy-relevant user behavior

User behaviour in buildings, especially with regard to energy aspects, is often characterised in the literature by the term "occupants' presence and actions" (OPA). Any behaviour and activities of the end users affect the building, its technical installations, the comfort and, ultimately, the resulting energy consumption. Under Annex 53, the concept of energy-related occupant behavior has been defined by defining "observable actions or reactions of a person in response to external or internal stimuli, as well as actions or reactions of a person to adapt to environmental conditions such as temperature, indoor air quality and sunlight". (Annex 53 Final Report)
Users already interact (passively) with the built environment through their presence. This is complemented by movement in the building. Even without active interaction, thermal loads, carbon dioxide, as well as vapours, odours, etc. and humidity already occur by the users. These must be either mechanically, e.g. through appropriate ventilation, or through subsequent active action, e.g. window ventilation. In addition, there are the so-called (active) actions. These can either be of non-adaptive origin, such as the use of electrical devices, or can be triggered adaptively by triggers.
For example, the user may open the window due to increased temperature or poor air. If it closes it again, either the desired comfort is achieved, or another factor is the trigger here: closing due to cold despite bad air, closing due to excessive street noise, etc.
In university buildings, the following actions and interaction of users are most often expected:

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Adjustment of the room air temperature: Depending on the type of room use and the type of technical interaction to increase the room air temperature Opening the windows/window ventilation: To improve indoor air quality, but also to lower the room temperature.

Use of sun protection/shading: shading by means of sun protection against excessive heat input (overheating, increase in room temperature), but also to prevent glare and mirror effects.

Use of electric lighting: ensuring working brightness due to lack of natural lighting (windows). Connection with e.g. shading, the image effect when using PCs, etc. Despite sufficient natural daylight, energy may be required for lighting.

Use of electrical appliances: The technical equipment at universities and the associated electrical power consumption varies greatly depending on the user. Students mainly use their own computer equipment. Occasionally, devices are also used for personal comfort, such as fans and heaters. (NuData Campus)

6.2 How does the user interact?

In buildings, a variety of interactions between end-users and building interfaces are discussed, which are crucial for understanding human behavior, energy consumption, and occupant comfort in built environments. These interactions vary significantly in their complexity and ease of use, and they play a crucial role in designing efficient and comfortable buildings.

Lighting controls, allow users to adjust the lighting in a room according to their needs and preferences. Interactions can be through conventional light switches, buttons, digital control panels, or even through computer and smartphone apps. The motivation for these interactions is often driven by visual discomfort, safety concerns, or a desire for a certain atmosphere. The ease of use of the light switches plays a crucial role in user satisfaction (Day *et al*., 2020, p. 10).

Thermostats, are a commonly used interface that users may struggle to understand, especially due to the delayed effects in the room. Improved design and usability of the interface could help reduce negative impacts and allow users to have better control and understanding (Day *et al*., 2020, p. 4).

Windows and window shades allow users to control the natural lighting and ventilation in a room. Interaction with these interfaces may be motivated by the desire for thermal or visual comfort.

Digital and gestural interfaces represent a significant advance in the interaction between end-users and buildings. These interfaces encompass a wide range of technologies, from tactile and surface-based interfaces to ambient, gestural, effort-based, and context-aware user interfaces. These innovative interaction techniques create numerous new possibilities for the design of digital building interfaces, but require further research to understand how users will interact with these new technologies. (Day *et al.*, 2020, p. 12).

6.3 User influence in energy-efficient schools

A central aspect of the research project "Energy-efficient schools – EnEFF:Schule" of the Federal Ministry for Economic Affairs and Energy (BMWi) was user satisfaction and the possibility of user influence on the indoor climate. The finding that the well-being of the building is an important factor in well-being is confirmed by the evaluation of indoor climate parameters, including room temperatures, air freshness and lighting conditions. When looking at the possibilities of influencing light, sun protection, temperature and mechanical ventilation, it became apparent that the type of control is accepted, but direct influence is often not possible.

Especially in the school environment, teachers are often limited in their ability to act directly on room parameters, although over 70% want to influence the temperature and about 90% the lighting control. Particularly noteworthy is the issue of mechanical ventilation, where only 22% of the student body confirm that the automatic ventilation system improves the air. Here, 89% of teachers would like to be

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able to regulate the air independently via window openings and 60% would like to have an influence on the ventilation system (Reiß *et al*., 2021).

6.4 Energy efficiency through building automation and user influence

The analysis shows that the implementation of single-room controls in school buildings offers an opportunity to save energy by allowing each room to be operated separately and independently. This enables a targeted reduction in energy consumption, especially during extracurricular events.
Despite modern technologies and an energetic orientation, there is often a lack of a comprehensible user interface. In some of the schools surveyed, difficulties in usability led to a general dissatisfaction with the new technical building equipment.
In order to enable users, especially teachers, to effectively illustrate energy consumption in the classroom, a user-friendly interface or an interface in the room is advisable. This could be realized by intelligent monitoring systems in order to sustainably promote the understanding of the relationships between user behavior and energy consumption (Winkler, M., Jensch, W., 2015).

7 VISUALIZATION OF ENERGY DATA AS A MONITORING SYSTEM

The possibilities and effects of intelligent monitoring systems are also shown in the study "Do in-home displays affect end-user consumptions? A mixed method analysis of electricity, heating and water use in Danish apartments". Canale et al. investigates how the visualization of energy data and consumption influences the behavior of residents.
The results show that the introduction of in-home displays (IHDs) in homes has led to a decrease in energy consumption. "When the IHDs started working in this building, the average consumption of cold water, hot water, electricity and heating decreased by 17%, 23%, 12% and 17% respectively. End-user surveys supported this and found a positive effect of IHDs." This decrease was partly caused by the changes in residents' daily behavior in response to the information provided by the IHDs.
It has been observed that the mere presence of the screen in the home can lead to a reduction in consumption, even without frequent active interaction with the screen.
The study suggests that the presence of IHDs and awareness of monitoring itself may have an impact on residents' consumption patterns. This suggests that the provision of real-time energy consumption data and the associated increased attention and awareness of energy consumption are key components to influence residents' behaviour towards energy consumption. (Canale *et al*. 2021)

8 TRANSFER AND CLASSIFICATION IN THE CONTEXT OF TEST ROOMS AND THE MASTER ROOM

As the research results of Canale et al., Day et al., the Annex Report and NuData Campus, among others, have shown, the importance of energy impact and well-being in buildings lies in user interaction and visualization of energy data. An investigation of these two decisive influencing factors in combination and in a real test environment is therefore indispensable. Thanks to its multi-domain equipment and reference environment, the real test room created at the Munich University of Applied Sciences creates the basis for these investigations. This is complemented by a newly installed state-of-the-art operating device and the recently created visualization of the energy data in the form of a digital twin.

8.1 Interaction by room control unit

In order to explore the interaction of users with the space, a new type of surface control device was introduced. This device allows users to select one of the predetermined modes depending on the situation and individual needs. The modes, including Comfort, Normal, Sport and Eco, are equipped with individually adjusted parameters for light, temperature and ventilation. For example, Comfort mode offers an increased room temperature, while Eco mode aims to save energy and provide a lower

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room temperature. The user's interaction with the operator can be recorded and analyzed, among other things, by the frequency of the selected modes.

8.2 Cloud connection for real-time sensor data

The comprehensive sensors in the room transmit the collected data in real time to a cloud. This cloud connection not only enables central data storage, but also continuous analysis and evaluation of the measured parameters. With real-time data available, quick adjustments can be made to optimize energy consumption and maximize user comfort.

8.3 Digital twin and BIM space model

The introduction of a digital twin, integrated with a Building Information Modeling (BIM) spatial model, offers a new form of visualization.

Figure 1: Digital Twin Visualization

A screen in the room not only presents static information, but also displays dynamic heat maps and live charts of the measured parameters (Figure 4). This visual representation allows users to understand the current state of the space and make targeted decisions to optimize energy efficiency and comfort.

9 Preliminary Results and Expected Outcomes

Initial observations indicate a significant difference in CO_2 concentration levels between the high-tech (Master) and reference rooms, which correlates with user complaints regarding indoor environmental quality.

9.1 CO_2 Concentration Analysis

The CO_2 concentration data, illustrated in Figure 5, shows that the reference room consistently exhibits higher CO_2 levels compared to the master room throughout the winter period. This is particularly evident during periods of high occupancy, where the CO_2 levels in the reference room frequently exceed 1500 ppm, reaching peaks above 2000 ppm. In contrast, the master room maintains CO_2 levels below 1000 ppm for the majority of the observation period, demonstrating the effectiveness of its advanced ventilation and air quality control systems.

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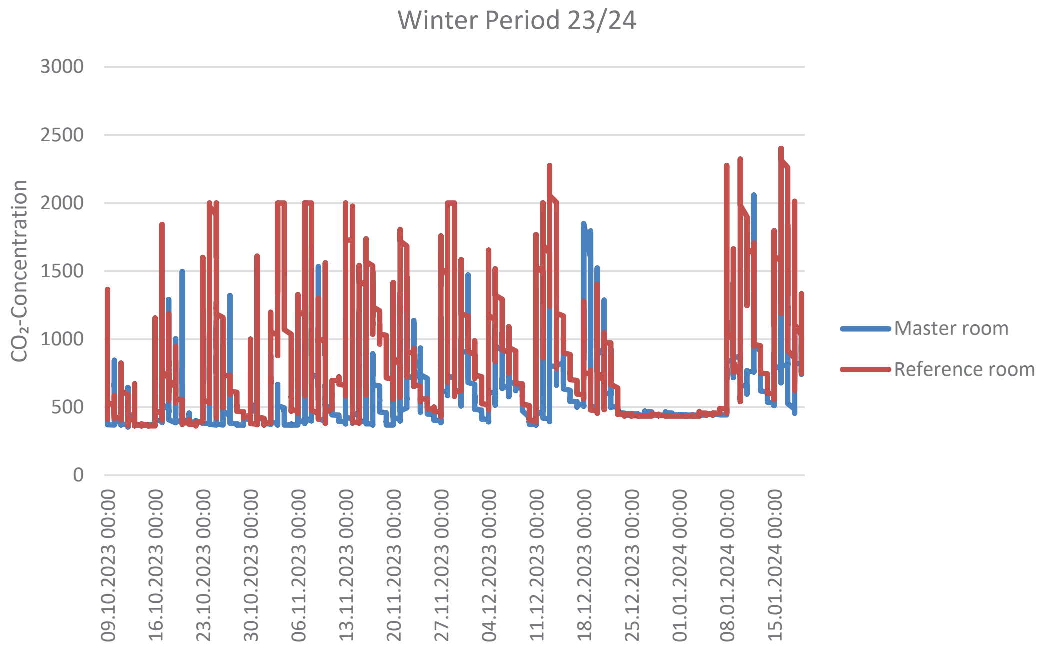

Figure 5: CO_2 Concentration in Master Room and Reference Room during winter period

9.2 User Complaints Analysis

The impact of elevated CO_2 levels on user experience is further substantiated by detailed data on user complaints, as illustrated in Figure 6. The reference room, which consistently exhibits higher CO_2 concentrations compared to the master room, shows a marked increase in user complaints. These complaints encompass issues such as rapid fatigue, lack of concentration, and poor indoor environmental quality, highlighting the significant influence of indoor air quality on user well-being and performance.

Rapid Fatigue: The data reveals that users in the reference room report experiencing rapid fatigue 40% more frequently than those in the master room. This suggests that higher CO_2 concentrations contribute to quicker onset of tiredness, potentially due to reduced oxygen levels and the associated difficulty in maintaining alertness and energy levels.

Lack of Concentration: Complaints regarding lack of concentration are 50% higher in the reference room compared to the master room. This substantial difference underscores the impact of poor air quality on cognitive function. Elevated CO_2 levels are known to impair cognitive performance, making it challenging for individuals to focus and process information efficiently.

Poor Indoor Environmental Quality: Complaints about the overall indoor environmental quality are 25% more frequent in the reference room. Users perceive the air quality as being significantly worse, which can affect their comfort and satisfaction with the environment. Poor air quality, characterized by high CO_2 levels, can cause discomfort, respiratory issues, and a general sense of dissatisfaction.

These findings clearly indicate a direct correlation between higher CO_2 levels and a decrease in user satisfaction and performance. The higher frequency of complaints in the reference room underscores the importance of maintaining optimal indoor air quality to enhance user experience, healthiness, and productivity. Ensuring adequate ventilation and air quality control is crucial in mitigating these negative effects and improving the overall environmental conditions within educational settings.

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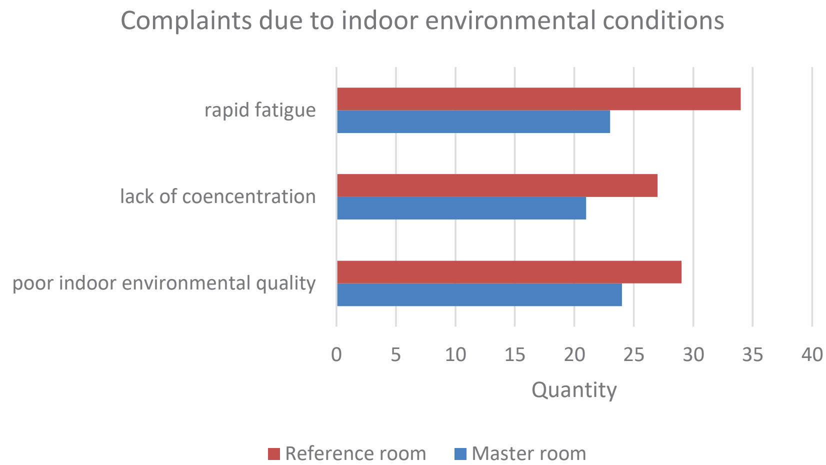

Figure 6: Complaints due to Indoor Environmental Conditions in Master Room and Reference Room

9.3 Expected Outcomes

Based on the preliminary results, several expected outcomes can be outlined, emphasizing the potential benefits of the advanced environmental control systems installed in the master room:

Enhanced Ventilation: The advanced ventilation systems in the master room are designed to significantly improve indoor air quality by effectively reducing CO_2 levels. This enhancement is anticipated to lead to a noticeable decrease in user complaints related to air quality issues, such as rapid fatigue, lack of concentration, and poor indoor environmental conditions. Improved ventilation ensures a constant supply of fresh air, which dilutes indoor pollutants and maintains CO_2 concentrations at a lower level. This not only enhances the comfort of the occupants but also supports their overall health and well-being. As a result, users are likely to experience a more pleasant and conducive environment for learning and working.

Improved User Performance: Lower CO_2 concentrations in the master room are expected to have a positive impact on user performance. Elevated CO_2 levels have been shown to impair cognitive function, leading to difficulties in concentration and increased fatigue. By maintaining CO_2 levels within optimal ranges, the master room's advanced ventilation system can help users stay alert and focused for longer periods. This improvement in air quality is likely to translate into better academic performance, as students and staff can engage more effectively in their tasks without the hindrance of poor indoor air conditions. Enhanced cognitive performance and reduced fatigue contribute to a more productive and efficient learning environment.

Energy Efficiency: Not directly measured in the preliminary results, the efficient operation of the HVAC (Heating, Ventilation, and Air Conditioning) systems in the master room is expected to lead to improved energy use profiles. The advanced systems are designed to balance comfort and energy consumption by optimizing the operation based on real-time data from various sensors. This optimization ensures that energy is used efficiently, reducing waste while maintaining a high level of indoor comfort. The expected outcome is a more sustainable and cost-effective operation of the HVAC systems, which aligns with the goals of energy efficiency and environmental responsibility. By reducing the overall energy consumption, the master room can serve as a model for energy-efficient practices in educational institutions.

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10 SUMMARY

This research paper explores the significance of user behavior on the energy consumption, human comfort, and indoor parameters of buildings, specifically in classroom settings. Conducted at the Munich University of Applied Sciences, the study utilizes two test rooms with varying technological standards to quantify the impact of user interactions. The high-tech lecture room features advanced systems allowing users to influence indoor air quality through partial air conditioning, while the low-tech reference room serves as a baseline for comparison. Both rooms are equipped with comprehensive sensors to measure parameters such as temperature, humidity, CO_2 concentrations, brightness, and user activities. The study highlights the critical role of user behavior in affecting energy consumption and comfort in educational environments. Actions such as adjusting air temperature, opening windows, using sun protection, and operating electrical appliances are examined for their impact on energy use. The paper also discusses the implementation of intelligent monitoring systems in school buildings, emphasizing the importance of user-friendly interfaces to enable effective visualization of energy consumption. Key innovations presented in this research include the integration of a digital twin, real-time sensor data cloud connection, and a novel room control device. These technologies enhance user interaction, facilitate efficient data analysis, and optimize both energy efficiency and user comfort. The findings provide a foundation for further research and practical applications aimed at improving building energy management and occupant well-being.

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