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The use of digital twins and AR for indoor environmental quality: classroom as a dynamic laboratory for hands-on and applied STEM-based teaching modules

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Abstract

Through a collaboration between the Virtual Technology and Design program and the Integrated Design Lab at the University of Idaho, this research aims to establish a holistic framework to address the current challenges of indoor environmental quality and energy efficiency in rural schools in Idaho State. After a national report showed that Idaho had the worst-funded schools in the country, the governor launched a new initiative to retrofit poorly performing facilities. Schools across the state can use this proposed framework to benchmark current IEQ and energy performance by collecting data and outline methods to improve their classroom through education, visualization, operations, and capital improvements. Schools have significant potential to promote knowledge and skills for sustainable development through building science-related learning opportunities for students, teachers, and administrators especially when given real-time interaction with IEQ data that will improve social, economic, cultural, and environmental outcomes. With occupant high densities, an educational mission, and outposts in areas impacted by wildfire smoke, Idaho's rural schools are ideal laboratories for understanding IEQ impacts on health, well-being, productivity, and energy use. The first research objective will establish educational modules to teach schoolteachers and administrators the fundamentals of building science, especially topics related to indoor environmental quality and energy performance. These modules will use real-time data collected from a sample of rural schools in Idaho and identify region-specific challenges and opportunities. The next step is to build a framework that streamlines the processes for both teachers and their students to collect IEQ data, evaluate it, visualize it, and then use it to identify opportunities for intervention. The framework will use real-time data collection as inputs to a digital twin for a dynamic virtual representation of the typical classroom. Using the digital twin, the framework will provide real-time visualization of indoor air quality data using augmented reality to facilitate learning and assessment and correlate real-time data to the physical environment and the occupants' behaviors. Incorporating the digital twin and AR will support the STEM hands-on and applied education objectives for students and teachers, making the research directly applicable to their daily activities. Finally, the framework will identify opportunities to visualize and analyze the collected data for assessment and intervention. The goal is to streamline the data collection and visualization, allowing teachers and students to navigate the collected data, assess the current trends in data, and identify opportunities for intervention.

Introduction

Indoor environmental quality (IEQ) refers to the conditions inside buildings that directly impact the health and well-being of their occupants. Key factors influencing IEQ include indoor air quality (IAQ) [1], thermal comfort [2], lighting quality [3], [4], [5] and acoustics [6]. However, a building with poor IEQ can lead to health problems, increasing the risk of Asthma, allergies, fatigue, and loss of concentration [7].

The IEQ is affected by the outdoor environment, such as climate zone, traffic, soil type, shadow, and shade context, the occupants and their activities and behavior, such as the number of occupants, physical activity, pests and pets if any, and the construction material used and furniture, the HVAC system and mechanical ventilation, the age of the building and many other factors [8].Children are especially vulnerable to the negative health effects associated with poor IEQ because of their higher metabolic demands and increased ventilation rates, which elevate their exposure to air pollution [9]. Research shows that children spend about 65–90% of their time indoors, with a significant portion of that time in schools [10]. Schools often have a high density of people per square meter, which increases the impact of occupants on IEQ in return. Schools, in particular, are very critical buildings as they serve as place of education for children for many years. Ensuring good IEQ is essential for enhancing the quality of education and the productivity of both students and staff, highlighting the influence of environmental conditions on students' learning processes [11]. Research shows that thermal discomfort can reduce overall performance by 15% to 30%. In contrast, improving class temperature by 2°F can lead to a 2% increase in math scores [12], [13]. Good ventilation can improve decision-making by 5% to 20%, increase the speed of completing assignments by 8%, and decrease illness-related absences by 3% [12], [14], [15]. Additionally, access to good daylight can reduce the symptoms of seasonal affective disorder (SAD) and improve student test scores by 10% while also increasing math and reading speeds by 20% to 26% [16], [17]. Therefore, it is essential to assess the IEQ of schools, as it can lead to long-term negative effects on the respiratory health, productivity and cognitive performance of both children and adults [18], [19].

School buildings offer a unique opportunity for students to learn about building science through contextual learning. One such opportunity is using the classroom as a living laboratory to explore and learn about IEQ [20], [21]. All relevant elements are readily available and directly impact students, allowing them to learn about their environment while actively trying to improve it.

Students can use monitoring and scanning devices to gather essential data about their classroom's IEQ. The collected data can help researchers, and the school evaluate the current conditions while engaging students in hands-on experiential learning, thus increasing their understanding of the subject [22]. Additionally, integrating technology such as digital twins, virtual reality (VR), and augmented reality (AR) in the physical classroom, helps connect the collected data directly to the students' real-world perceptions of their environment [23]. A digital twin is identified by the National Academies of Science, Engineering and Medicine (NASEM) as a set of virtual information constructs that mimics the structure, context and behavior of a natural, engineered, or social system. It is dynamically updated with the data from its physical twin, has a predictive capability and informs decisions that realizes value [24], [25].

Digital technologies are transforming how people learn and are increasingly introduced at all educational levels [26], [27]. The essential role of technology in face-to-face education is reflected in initiatives such as the U.S. National Educational Technology Plan [28], [29]. Which emphasizes the importance of reconfiguring physical learning environments (e.g., classrooms) to facilitate technology-mediated learning (TML).

When integrated into physical classrooms, digital technologies can offer immediate feedback, promote interaction, and support diverse learning needs by providing adaptive learning experiences [30], [31], thereby enhancing student engagement and learning outcomes [32], [33].

Understanding the real-time conditions of the IEQ in the classroom can help identify intervention opportunities at low, mid, and high costs. This allows students, teachers, and researchers to actively participate in improving their school's IEQ. Additionally, schools can present evidence-based needs for interventions to policymakers, which can help secure funding to address current issues and provide guidelines for future design and planning of schools in the area.

Schools in Idaho:

Current issues related to IEQ, and problems related to budget for Idaho schools.

Idaho schools are facing significant challenges. According to Fields and Savransky [34], Idaho has the lowest per capita investment in school infrastructure in the nation. According to a 2022 state legislative report, over half of the school buildings surveyed were older than 50 years [35]. Furthermore, Idaho is one of only two states that require a supermajority (two-thirds of voters) to pass a school bond. As a result, many districts have struggled to pass school infrastructure bonds even when they carried a majority of the vote [36], Consequently, many schools in Idaho are in poor condition, with major maintenance often delayed. This situation leads to avoidable problems, such as heating failures that leave classrooms of kindergarteners bundled in coats and blankets, a lack of cooling systems causing dehydration and heat-related illnesses, and hazardous air quality due to coal boilers or forest fires and the absence of adequate air filtration. These issues are so severe that, at times, students miss class or the schools are forced to close [37], [38].

In this research, the focus will be on rural schools that serve students with great needs. Ninety-one percent of the schools considered for this research are Title I school-wide programs, with an average of 38% of students eligible for free or reduced lunch [39]. Eighty-five percent of our districts are classified as rural, and the remaining ones are considered "towns." Additionally, 85% of these districts contain federally identified disadvantaged communities. This research targets Idaho schools that are in disadvantaged areas in a state that currently lacks green energy and efficiency opportunities for schools.

Methodology:

This study aims to create a framework that can be replicated and executed to support STEM education for many schools, specifically focusing on Building Science, IEQ, and the use of technology such as digital twins, augmented reality, and virtual reality experiences. The goal also includes identifying IEQ problems, proposing intervention measures, and providing recommendations for decision-makers and school designers. The methodology is performed in three major steps as shown in Figure 5.

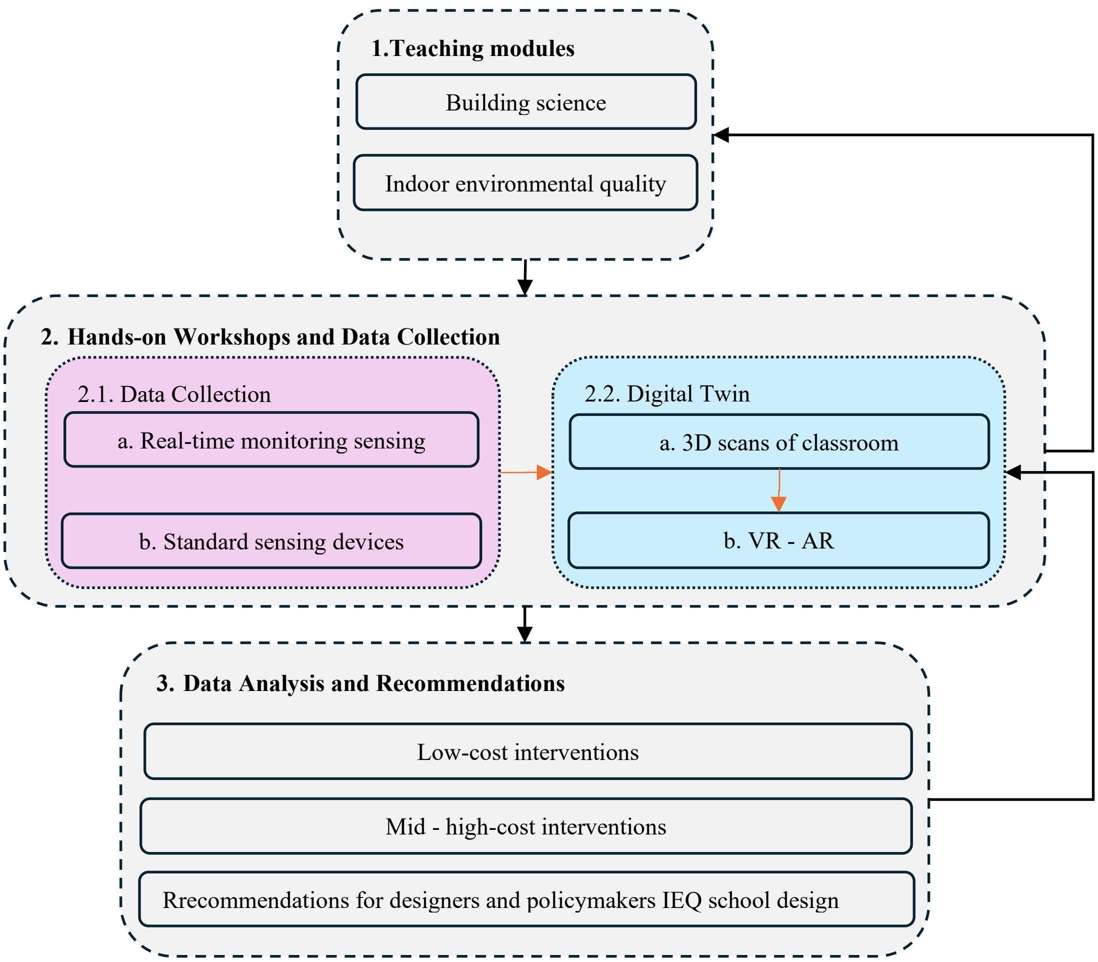

Figure 5. Methodology workflow

The project is developed in three steps.

Step 1: Teaching Modules

The first step is to design teaching modules for teachers and students that cover topics related to building Science and IEQ. These modules can cover introductory, essential, and general knowledge and can be taught online or in person through presentations and hands-on activities. The content of the teaching modules will evolve over time as hands-on activities and data collection provide more context and real-world examples.

Step 2: Hands-on Workshops and Data Collection

The second step involves organizing hands-on workshops where students collect IEQ-related data in their classrooms and create a digital twin. This step is divided into two sub-steps. 2.1. focuses on collecting IEQ data, in which 2.1.a. focuses on real-time data collection, and 2.1.b. focuses on data collection with standard sensing devices. While 2.2. focuses on creating the classroom's digital twin with 2.2.a. scan the 3D classroom, and 2.2.b. connect it with the IEQ data and build the AR and VR experience. The data collected from this step will help evolve the teaching module by providing real-life examples.

2.1.a. This sub-step includes the installation of monitoring devices that collect real-time data on IEQ. Students will learn how to install the device in their classroom, access the dashboard and understand the data. These sensors continuously collect data at 5 or 15-minute intervals. The monitoring devices will collect data for the following:

1- temperature, 2- relative humidity, 3- chemicals (TVOCs) Volatile Organic Compounds originating from everyday products, such as paints, pressed wood, and more, 4- fine dust (PM2.5), these tiny particles pose a critical threat to health as they can infiltrate the respiratory system and bloodstream, leading to various health issues. 5- carbon dioxide (CO_2), indoor exposure to carbon dioxide can impair performance and decision-making.

2.1.b. Students will also collect data for the environment using other sensing devices, such as a thermal imaging camera to check for thermal bridges and understand that surfaces can have different temperatures based on their insulation level, light sensors and noise sensors. Students will also be taught how to read the results and understand the data.

2.2.a In this step, students will learn how to create a digital twin of their physical classroom. They will use the LiDAR technology available on newer iOS devices to scan the classroom, export the models to 3D software, and navigate the virtual environment of their classroom using an avatar.

Newer iOS devices are equipped with a built-in LiDAR scanner within their camera system, which emits infrared light pulses and measures the time it takes for them to bounce back after hitting nearby objects. The time difference between the emitted light pulse and the reflected pulse allows the LiDAR sensor to calculate the distance to each object based on the speed of light.

Additionally, Apple has developed the RoomPlan API [40], a new Swift API that utilizes the camera and LiDAR scanner on iPhones and iPads to create a 3D floor plan of a room, capturing key characteristics such as dimensions, walls, windows, doors and some furniture. Several applications, such as iRhino 3D [41], make use of this system. With a built-in LiDAR scanner, iRhino 3D allows users to scan a room or object directly using the device's RoomPlan technology. Once the scan is complete, iRhino 3D automatically generates a Rhino 3D model based on the captured data. The 3D model generated inside Rhino 3D will then be connected to Unreal Engine using Blueprint. Unreal Engine is a 3D computer graphics game engine, and Blueprint is a node-based visual scripting system in Unreal Engine that is used to create interactive mechanics and elements. Inside Unreal Engine, students can view the 3D model of their classroom and virtually navigate it using avatars.

2.2.b. Students from the University of Idaho will connect the gathered data to the virtual environment and connect science to reality by overlaying and visualizing the data inside the virtual environment. This integration allows for data visualization in augmented and virtual reality, enhancing the direct connection between students and their environment. It fosters a more immersive learning experience, ultimately increasing engagement and understanding.

Step 3: Data Analysis and Recommendations

This step involves analyzing the data collected from steps 2.1.a. and b. This analysis will help identify low-cost interventions that students and teachers can easily identify and implement. For instance, if CO2 levels rise above 1,000 ppm, they can open windows, or if the temperature inside increases on hot days, they can lower the thermostat. Additionally, data will be logged over an extended period to analyze the results and identify appropriate measures for mid and high-cost interventions.

A system will also be developed that utilizes real-time data and statistical analysis models to detect IEQ-related issues. This system will notify occupants of any problems and automatically suggest solutions.

Finally a set of recommendations will be provided for decision makers and school designers to improve IEQ and provide adequate support.

This methodology aims to foster an understanding of IEQ, engage students in hands-on experiential learning, and provide suggestions for improving indoor environmental quality in schools.

Preliminary data:

Preliminary data for indoor temperature and CO_2 in classrooms are collected for several schools in Idaho; Table 1. shows the schools, room numbers, and data collection type for each room.

Real-time data with minute intervals collected from the classrooms for indoor temperature and the results are shown in Figures 1 to 3, and for CO_2 the results are shown in Figures 4. Data was collected from Friday, 5/10/2024, at 12:00 AM and ended on Wednesday, 6/12/2024, at 23:55, except for the W-school; data collection ended on 6/7/2024 at 23:55.

Table 1. The schools, rooms numbers and type of data collected for each room.

School	H-School		L-School		M-School					W-School	
Room #	200	309	12	28	101	106	121	203	205	01	09
Temperature	x	x	x	x	x	x	x	x	x	x	x
CO_2	x			x							x

1.1. Schools' current conditions:

Each of the schools had brick exterior walls with double-paned and tinted windows. None of the buildings surveyed in this research had an energy management system. Instead, they each rely on pneumatic controls that require manual adjustment. Also, none of these buildings have central air conditioning. They use either steam or hot water distributed through fan coil wall registers for heating. Cooling is provided only through opening the windows. A handful of classrooms in each building have window-mounted residential AC units. The number of hours of cooling has increased for this area over the last 15 years. While cooling may not have been necessary before, it may be necessary in the future to maintain a productive learning environment. This data set captures the end of the school year. School ended on June 5th, but one can still see high and low temperatures during the final weeks of May 2024.

H-School:

This building was constructed in 1937 with an annex added in 1991. Many of the windows are operable but most had blinds drawn for at least the top half of the window. Some of the classrooms recorded temperatures near 16ºC (61ºF) during the school morning. There is no cooling in the fan coil units – only a hot loop. When it is hot outside, the classrooms can overheat. Figure H-R-309 shows the indoor temperatures at the end of the school year, with some classrooms going above 26ºC (80ºF) while class was in session.

L-School:

This building was constructed in 1952 with a major addition in 1991. This building received the most temperature complaints in the district. With an exposed sunlit side, there can be a 5ºC-8ºC

(9ºF – 14ºF) temperature differential between the east and west classrooms according to the facility manager. As with the other schools, the dry bulb air temperatures in the classrooms could dip to 16ºC (61ºF) during the school morning and rise above 25ºC (77ºF) during warmer weeks.

M-School:

This building was constructed in 1956. As with the other buildings in this study, the existing thermostat controls require manual adjustment, which makes it challenging to implement building-wide strategies like setbacks over weekends and breaks.

W-School:

This building was constructed in 1955. The classrooms in this building showed some of the most consistently cold air temperatures. Yet, even at this site, some of the classrooms reached above 24ºC (75ºF) on a warm day, which is a swing of over 8ºC (14ºF) during the same school day. Classrooms monitored for CO_2 showed fair but not excellent levels of outdoor air ventilation.

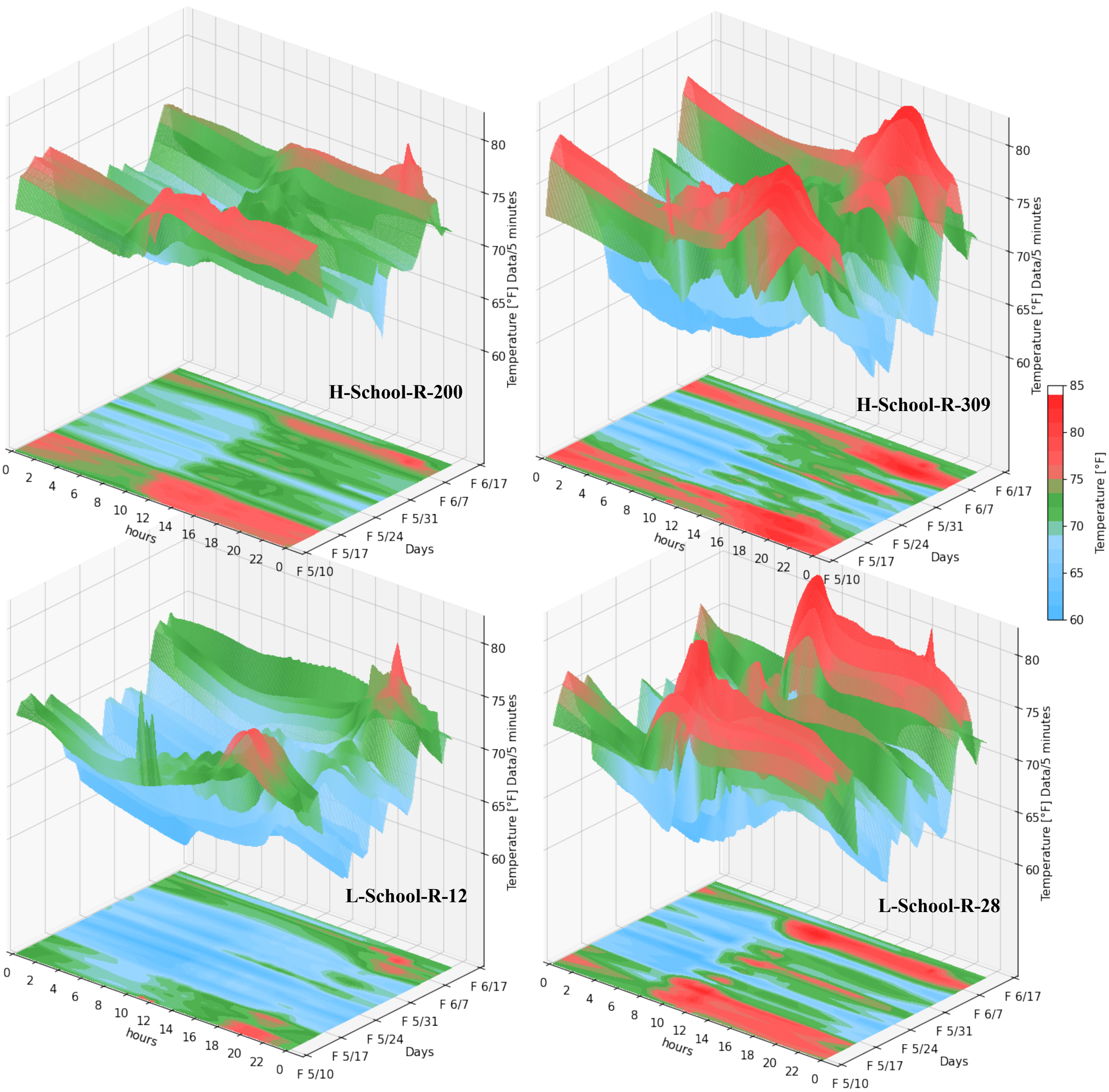

Figure 1. Indoor temperature collected in 5-minute intervals for several classrooms in schools in Idaho.

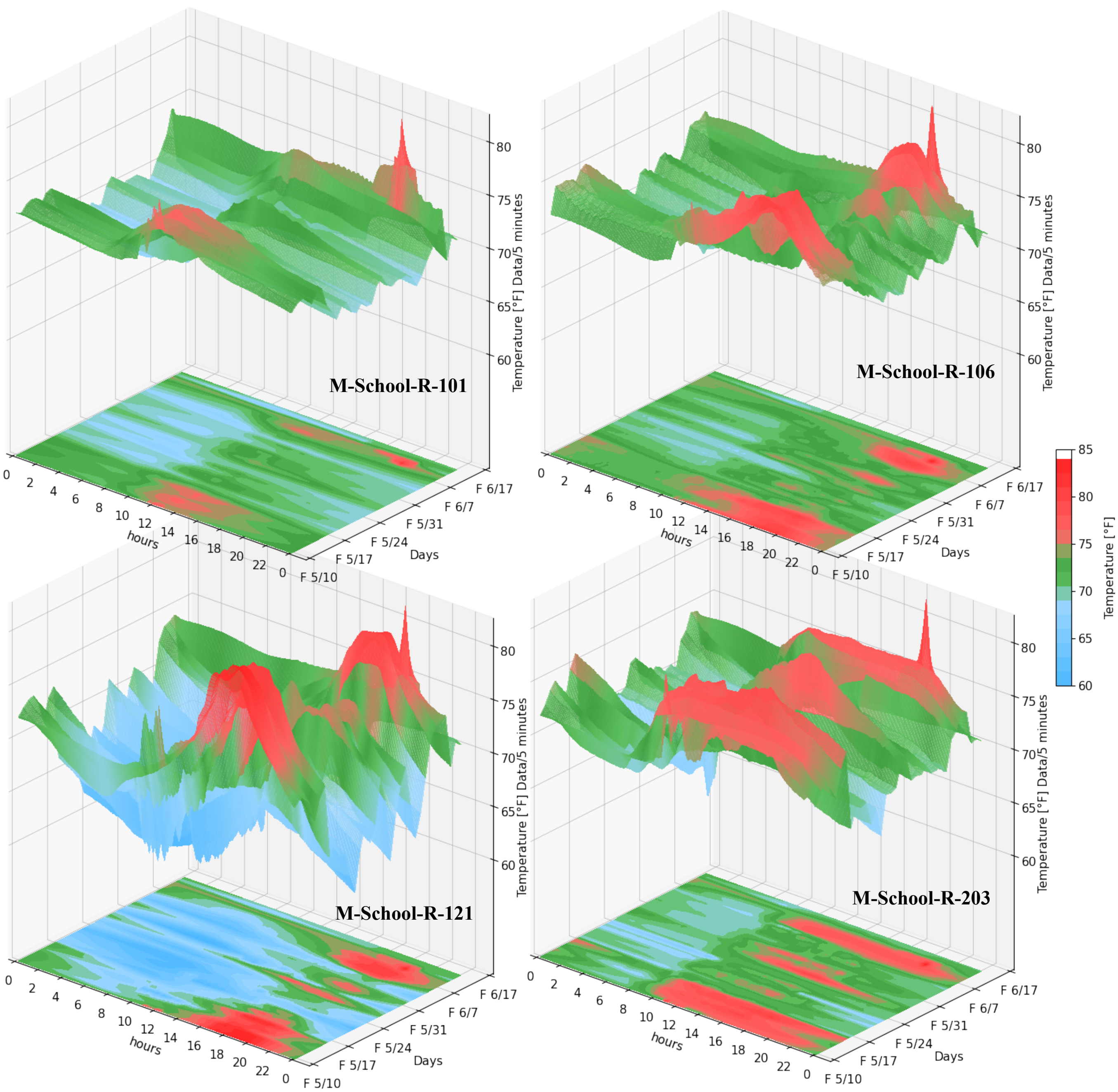

Figure 2. Indoor temperature collected in 5-minute intervals for several classrooms in schools in Idaho.

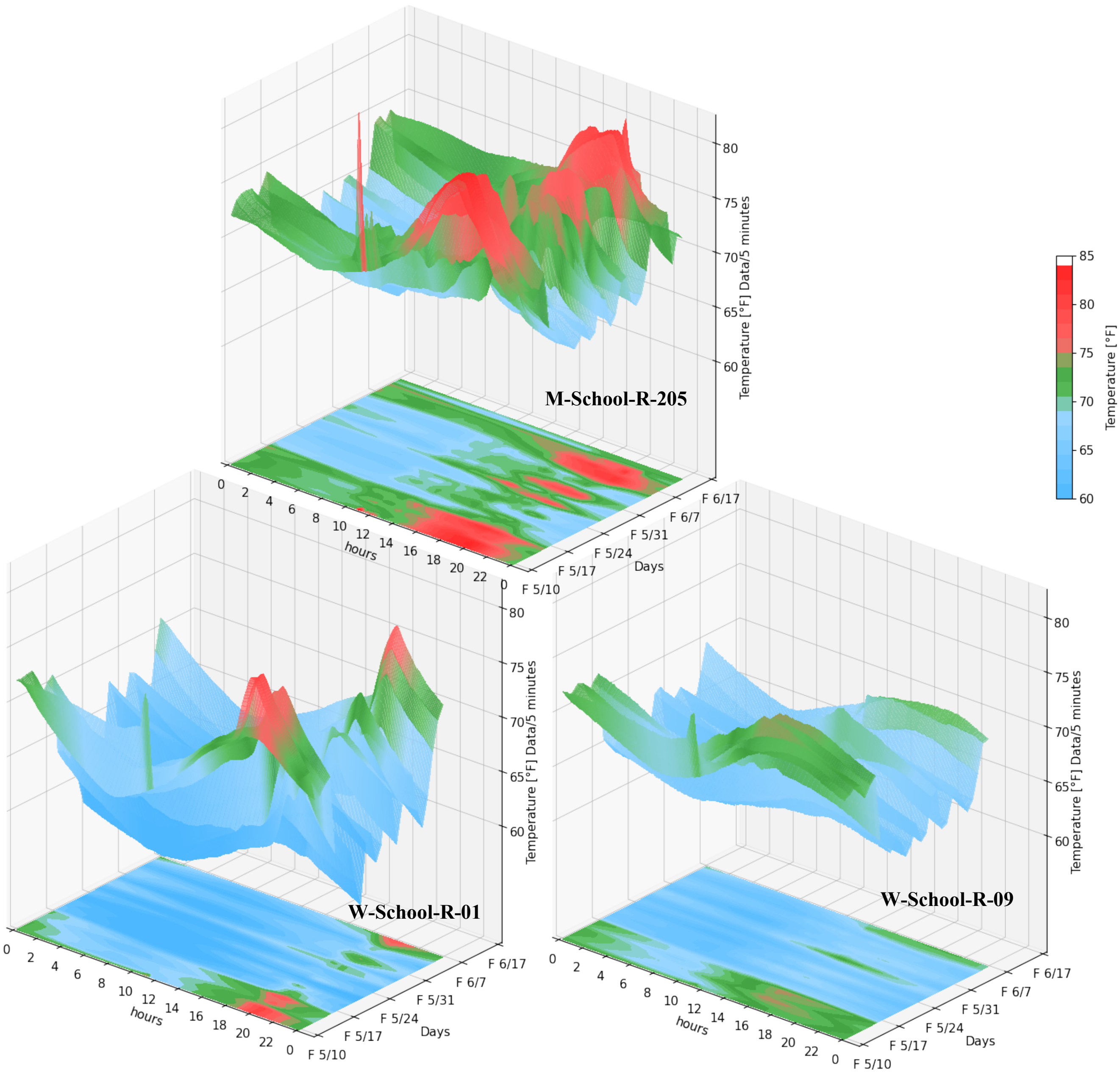

Figure 3. Indoor temperature collected in 5-minute intervals across several classrooms in schools in Idaho.

Figures 1 to 3 shows large fluctuation in indoor temperatures, which can dip as low as 16ºC (61ºF) during the school day in school W and as high as 26ºC (80ºF) during the school day in school H.

The majority of the measurements indicated adequate levels of outdoor air circulation as estimated by CO_2 levels as shown in green in Figure 4. However, there were some instances (e.g. in H-R-200), where CO_2 levels were over 2,500 ppm. These readings were taken in the spring, the time that operable windows are most prevalently used. These CO_2 levels may appear significantly different during mid-winter when few windows are opened by the teachers.

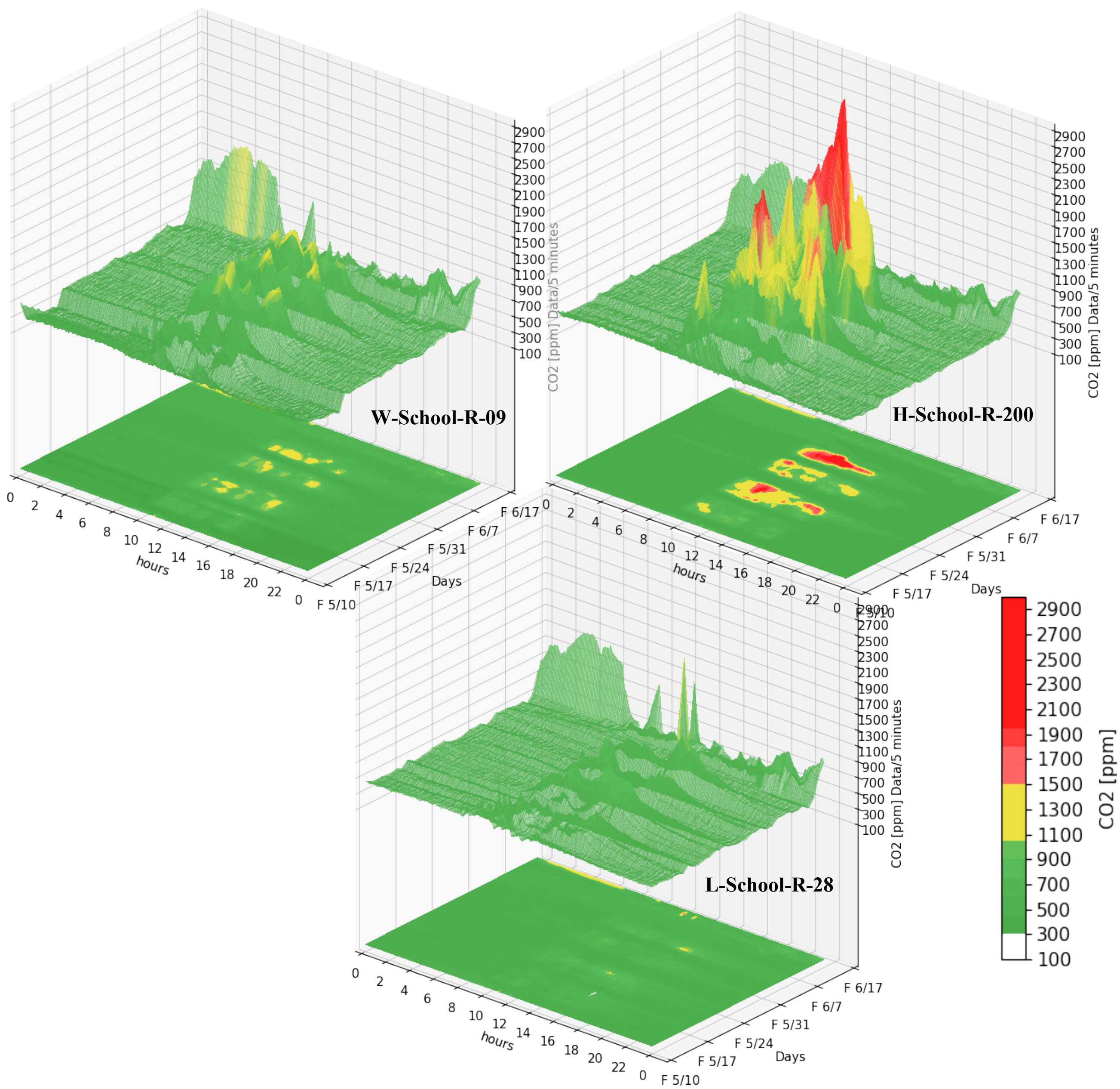

Figure 4. Indoor CO2 levels collected in 5-minute intervals across several classrooms in schools in Idaho.

Conclusion:

This ongoing research explores the integration of science, engineering, and technology to support STEM education, specifically focusing on Building Science and IEQ in schools. The essential role of technology in face-to-face education is reflected in initiatives such as the U.S. National Educational Technology Plan, which underlines the importance of reconfiguring physical learning environments (e.g., classrooms) to facilitate TML particularly in under resourced communities. For this research we will focus on schools in underprivileged communities in Idaho.

Preliminary data have been collected from multiple schools in Idaho, providing early insights into indoor temperature and CO_2 levels across classrooms. The results show considerable temperature fluctuations, with some classrooms experiencing conditions as low as 16°C (61°F) and others exceeding 26°C (80°F) during school hours. Additionally, while CO_2 levels were generally within acceptable ranges, certain rooms exceeded 2,500 ppm. These findings suggest potential challenges in thermal comfort and air quality that may impact student learning and well-being.

The full study has the following objectives:

> -Educating teachers and students about building science and indoor environmental quality through hands-on activities.
>
> - Supporting the educational process using digital twin technology to improve comprehension through interactive visualizations of IEQ real-time data.
>
> - Helping students and teachers in identifying low-cost interventions to improve IEQ in their classrooms
>
> - Recommending a range of mid- and high-cost interventions tailored to each school's needs.
>
> - Developing a framework that can be replicated in other schools.
>
> - Providing guidelines for the development of future schools.
>
> - Providing evidence to inform decision-makers on financial strategies to support school renovations aimed at improving IEQ.

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