Improving Digital Twin Usage to Reduce Energy Inefficiencies

The front entrance of the Sheila Scott Building

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Improving Digital Twin Usage to Reduce Energy Inefficiencies

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Abstract

In Spring 2022, the University of Worcester in the United Kingdom installed a Digital Twin in the Sheila Scott building as part of their carbon neutrality initiative. Our team's goal was to improve upon its usage to further energy reduction initiatives. We consulted the data collected by the sensors from the Digital Twin to identify potential energy inefficiencies. We then compared our findings against building user experiences to find causation and proposed inexpensive short-term and long-term recommendations for energy reduction within the building.

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Executive Summary

As part of the University of Worcester's decarbonization initiative, a Digital Twin was installed in the Sheila Scott building. A Digital Twin is a nearly 1:1 digital replica of a building that monitors various aspects of the building, such as temperature, occupancy, and energy usage. The Digital Twin has been installed and running since Spring 2022 and the university now wants to utilize the Digital Twin to identify energy inefficiencies within the building and make the Sheila Scott building become more energy efficient and reduce carbon emissions. The goal of this project was to utilize the Digital Twin model to identify energy inefficiencies and key human interaction factors in the University of Worcester. To achieve this goal, our team outlined the following list of objectives to achieve our goal:

1. Understand the design and the future use of the Digital Twin.
2. Understand the behavior of the Sheila Scott building's users.
3. Identify energy inefficiencies in the Sheila Scott building.
4. Make recommendations on how to advance Digital Twin pilot.

Findings

The following findings emerged from interviews, building observations and analysis of the sensor data from the Digital Twin.

The Digital Twin has documented significant heat loss in the building during the winter season. Figure 0.1 shows a graph detailing the recorded temperatures across the final days of January. This graph was created from the Digital Twin's sensor data of seven different rooms in the Sheila Scott building. The solid red line indicates the maximum temperature (20℃) and the blue line indicates the minimum temperature (18℃) according to the University's heat and comfort policies. Looking at the graph, it can be noticed that the temperature in these rooms seem to oscillate and does not plateau long throughout these three days. Room SS02 is reported to be over the maximum and is located on the northern side of the building, where the boilers are located. The room that is predominantly below the minimum for comfort is located on the southern side of the building. This data has shown the severity of heat retention within the building as rooms have reportedly shown to be unable to maintain stable temperature.

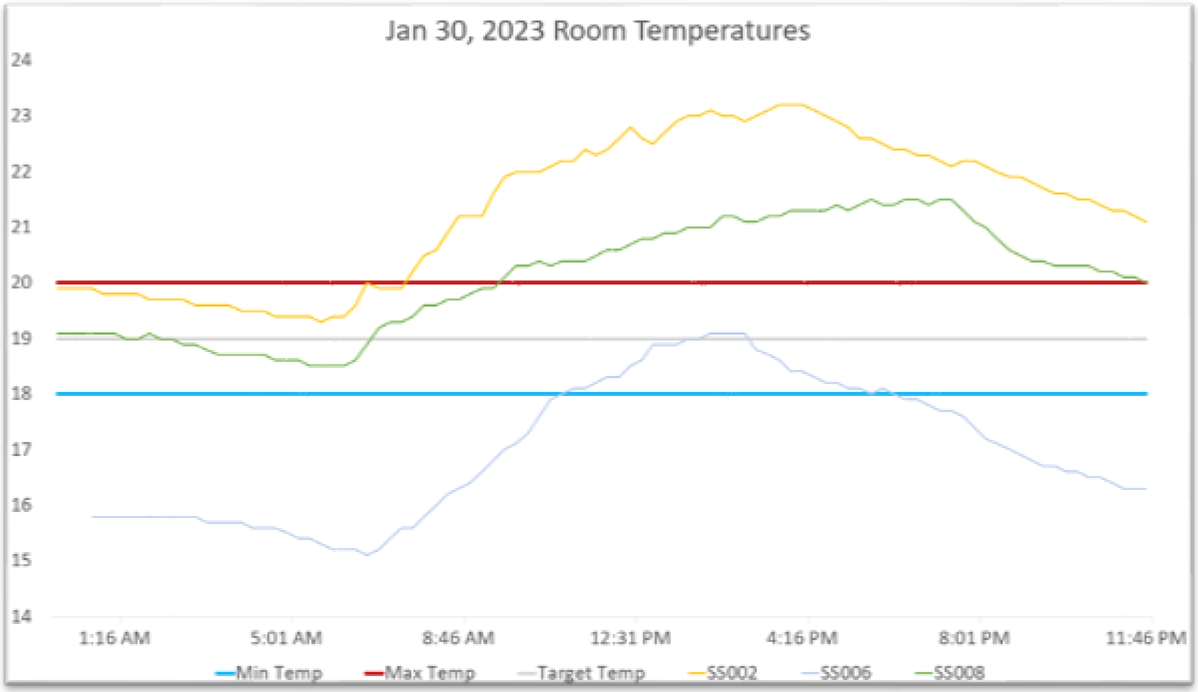

Figure 0.1: Graph of temperatures in the Sheila Scott Building for January 30, 2023

The windows are a significant cause of heat loss. The single glazed windows installed in the Sheila Scott go from ceiling to floor along the backside of the building, where nine of the building's lecture and skill rooms are located. Thermal imaging and verbal testimonies from our interviews have made it clear that these windows are not helping rooms retain heat. According to sensor data from colder seasons, some rooms in the building are below the suggested temperature of 19°C. The recommended thermal resistance, also known as the U-value, for windows in buildings is commonly in a range from 1.2 to 1.6, but single glazed windows have a U-value of 5.58. This means that heat passes through them quite easily. This leads to heat escaping the building during the winter and substantial amounts of heat entering during the summer.

The roof is not sufficiently insulated. The roof of the Sheila Scott building is made of a standing seam metal roof. These types of roofs are meant to be very energy efficient because they reflect the sun effectively while being lightweight and durable. However, due to the lack of maintenance and the poor insulation of the roof this is not the case. The roof is very thin and often leaks, with staff claiming they must place buckets in certain areas to collect water from said leaks. Analysis of the Digital Twin sensor data has shown the lobby being colder than regulations would have it be, which the roof has been identified to be a contributor of.

HVAC underperforms due to heat loss throughout the building. There are 2 midrange boilers in the plant room with enough room for a third. According to Dave Mourby, the infrastructure coordinator of the university, the building would be properly heated if it weren't for the factors that cause heat loss. Some of these factors relate to the infrastructure of the building, and some relate to the HVAC system in the building.

The heating pipes lack insulation causing the heating system to be less effective. We identified an average of 4℃ difference between the northern and southern sides of the building, although the difference was noticed to be large as 11℃. The pipes lack proper insulation, causing the water to cool as it travels through the building, making rooms become less heated and falling below classroom standards during colder seasons.

There is poor ventilation in the building. The building currently does not have a dedicated ventilation system, with almost all ventilation coming from windows and doors. When rooms start to get uncomfortably hot for occupants, staff would open windows. However, the windows do not open very much and do not have a significant impact on reducing the interior temperature. Staff often open doors as a better way to vent the building as seen in Figure 4.3, but they still state that it is sometimes not enough.

Space heaters can create inaccurate sensor data. Rooms can sometimes go below 18℃ in the winter due to the various factors of poor heat retention. To provide a comfortable environment for the students, space heaters are brought into colder classrooms during this time. Technicians and some instructors confirmed that staff would supply their own heaters. The use of these heaters will consume more energy than normal and will give the sensor for the Digital Twin inaccurate data.

Recommendations

Based on our findings, we have derived the following recommendations that incorporate short-term energy solutions for the Sheila Scott building and long-term recommendations for the Digital Twin pilot program:

Short-Term

Installation of thermal curtains. This is a low-cost easy solution to prevent heat loss from windows as the curtains would increase the thermal resistance of the area around the windows.

Use material to block the lower section of windows. This would entail using inexpensive material to effectively block lower portions of the windows to reduce heat loss from it.

Insulation on the heating pipes. The heating pipes are not insulated and cause heat to be lost when heating the parts of the building further from the boiler.

Finish installation of LED lighting in Sheila Scott Building. The Sheila Scott building is still using fluorescent bulbs that are less energy efficient than LED bulbs, causing energy to be ineffectively used.

Long-Term

Organize data collection. The data obtained by the Digital Twin and its sensors are put into a spreadsheet and is currently organized in a manner that makes it hard to work with from a user standpoint. The data sheet can be overwhelming to users and takes a long time for them to utilize it. One approach to make the datasheet more user friendly is through using Python or some other programming language to process and filter the datasheet into a format that would allow users to better comprehend the data in the sheet.

Create accessible Digital Twin visualization. At this time, the Digital Twin model and data visualization can only be viewed through the HoloLens headset. The headset can only be viewed by one person at a time and tends to give the user motion sickness. Exporting the visualization into a form so it can be seen on a screen would allow more individuals to access it at a given moment.

Slow implementation of the Digital Twin. In the opinion of the estate staff, the most practical method of proceeding with this program would be by slowly implementing the technology in the other buildings, allowing this program to efficiently be implemented and utilized.

1.0 Introduction

Global CO_2 emissions have been steadily increasing over the past 50 plus years (Papadis et al., 2020). Many established institutions are on a mission to play their part in the worldwide effort of decarbonization. If these trends continue, the US Department of Energy state that the Arctic could lose all its ice by the summer of 2040. The UK government aims to reduce energy usage by 15% by 2030 and have net zero carbon emissions by 2050. They identified that energy usage in buildings is a large energy sink and have aimed to mitigate this.

With the improvements of lightbulbs in the form of LED lights, new frameworks for HVAC systems and additional advancements made in internet of things management equipment, technology has been improving to reduce energy usage in buildings. Smart sensors, such as motion-based lights and automatic dimmers, have been shown to improve energy efficiency in buildings (Sambandam et al., 2019). Smart sensors help reduce inefficiencies derived from human behavior in buildings, such as individuals leaving the lights on or opening windows in rooms (Zhao, Zhang, C., Xu, et al., 2021). Understanding this, the University of Worcester has planned to improve energy utilization on their campus through the implementation of a Digital Twin model in one of their buildings to monitor and identify key factors contributing to energy inefficiencies within it.

Digital Twin technology can help reduce energy in buildings. A Digital Twin is a virtual representation of a physical entity. These can include things like buildings, airplanes, wind turbines, etc. The twin displays data collected from smart sensors inside the physical entity and then uploads it to the database of the twin. It can then use past data with real-time data to determine and predict various aspects of the entity's performance. These aspects can include areas such as energy usage, temperatures, and others. The Digital Twin will display this information with the virtual model so users can visualize the report. Some of the benefits of using a Digital Twin include the ability to monitor existing products, reduce risk of accidents and unplanned downtime, reduce maintenance burdens, and prototype ahead of manufacture (TWI, 2023). People who have access to the twin can make changes to the model to predict how different areas of the physical entity will be affected by the changes made. For example, someone could test, in the digital model, the effects of energy consumption in the event a new HVAC system is installed in a building. Human factors play a significant role in this system as the ways people interact with entities, such as buildings, can lead to poor energy usage. These interactions can involve space utilization and heat retention. Poor practices in these areas from users of buildings can impair the impact of the Digital Twin.

In 2022, a study took place that examined how well the Digital Twin in the Sheila Scott building at the University of Worcester in England was operating and how human factors could affect the information displayed by the pilot. The study had looked at issues such as room occupancy and types of ways people could be potentially wasting energy within the building. Through observations and interviews with various stakeholders of the building, the study revealed that the building had poor space utilization (Kievra, R., Han, Y., et al., 2022). Rooms were often empty or under capacity when reserved. For example, there were cases of staff members reserving two rooms at once and leaving one empty while equipment was left on and idling. The study also looked at factors that may result in poor heat retention such as open windows and doors in classrooms. The authors provided recommendations on how to improve the Digital Twin at the end of their report (Kievra, R., Han, Y., et al., 2022). The Digital Twin pilot program was incorporated into the Sheila Scott building in the spring of 2022, and it has been running since then.

The goal of this project is to utilize the Digital Twin model to identify energy inefficiencies and key human interaction factors in the University of Worcester. We have identified the following objectives we need to complete in order to accomplish this mission: understand the design and the future use of the Digital Twin, understand users' behavior in the Sheila Scott building, identify how the sensor's data trends could provide information for energy reduction, review previous reports about the Sheila Scott building, and create recommendations to improve the Digital Twin model. We hope that through the accomplishment of these goals that the University of Worcester's Digital Twin pilot program can be advanced and implemented into other buildings across the campus.

2.0 Background

To better understand the purpose of this project, it is important to explain the context behind it. In this chapter, we have explained the importance of energy efficiency, some more recent methods to aid it its pursuit and how the University of Worcester has aimed to maintain energy efficiency.

2.1 Energy Usage in Buildings.

Energy usage in buildings is not sustainable. Over the past 50 plus years, global CO_2 emissions have increased along with global energy usage. About 30-40% of global energy usage and 30% of global CO_2 emissions are due to building usage. In addition to this, it's been shown that 53% of energy usage in buildings is attributed to HVAC, 11% from lighting, and 30% from other appliances (Sabapathy, Ragavan, et al., 2010). According to the US Department of Energy, scientists predict that if we continue our current energy usage trajectory, the Arctic could be ice free by the summer of 2040.

The United Kingdom has been making attempts to reduce energy consumption by putting policies in place and setting goals for energy reduction, with their main objective being net zero carbon emissions by 2050 (Net, 2021) and, in the short term, reduce energy demand by 15% by the year 2030 (UK, 2022). The UK has deemed global energy consumption a serious issue and has proven the efficacy of their policies thus far. The UK's change in primary energy consumption graph to other developed countries, such as the United States and Canada, the United Kingdom is doing comparatively well in terms of year-to-year usage. While the UK still has not reached their goal of net zero carbon emissions, they have objective goals set in place to ensure long term change.

2.2 Strategies to Reduce Energy in Buildings.

The high levels of energy usage in buildings leads to building operators looking for ways to reduce usage costs by using more energy efficient methods. With HVAC and lighting consuming large amounts of energy in buildings (Figure 2.1), there has been a great amount of research done on approaches on how to reduce energy usage in these areas.

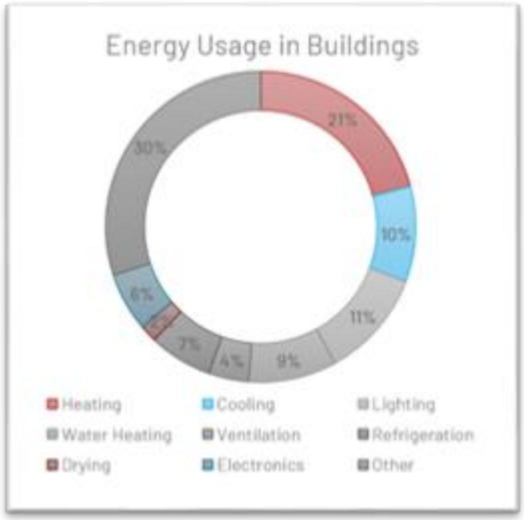

Figure 2.1: Pie chart of energy usage in building

Buildings with older HVAC systems in place have a particular set of difficulties to face when trying to reduce energy usage. There have been different approaches to reduce temperature loss to lessen the need for HVAC systems to run as according to Friege and Chappin (2014) research on this subject such as such as retrofitting walls, windows, and roofs, since it was seen as a more efficient option as opposed to destroying and rebuilding the buildings to bring it up to standard. The intended retrofitting that they spoke of would include insulation being installed in exterior walls, doors, and weatherizing the windows to prevent temperature loss. Beyond implementing new physical components to improve heating in buildings, there are other ways to make old HVAC systems more energy efficient. Recently, a new framework for older HVAC systems has been in development, that is simulation free and not model specific and that has been shown to reduce energy usage by 16.7% (Liu, Balaji, B. et al., 2022). This would allow for the potential of older systems to still be used and reduce costs when trying to implement energy efficiency.

When it comes to lighting, fluorescent light bulbs are more energy efficient than filament bulbs, however LED light bulbs are more efficient than incandescent light bulbs (Sambandam et al., 2019). Sambandam and their team (2019) noted that more modern buildings are installing LED bulbs while older buildings are swapping their bulbs for more efficient ones. Other strategies noted involved smart scenarios, such as motion detectors in rooms that would automatically turn off the lights if a room is vacant or unattended for a significant period. In addition to this, automatic dimmers were installed so that when natural light was detected coming from inside the room, the lights would dim (Sambandam et al., 2019). These findings demonstrated methods to reduce energy usage and ways to negate issues that come from inhabitants leaving the lights on for extended periods of time in unattended rooms.

The inhabitants of a building influence its energy efficiency. Zhang Zhao (2021) states the initial difficulties with trying to predict human behavior on energy utilization. His team's findings (Zhao, Zhang, C., Xu, et al., 2021) show a way to counteract human behavior-based inefficiency through proper, extensive modeling or detailed energy efficiency education given to building inhabitants, specifically for school centered buildings. This, in comparison to other methods building managers are looking at, is a less expensive alternative to promote energy efficiency.

A newer and still evolving component to aiding in energy reduction is internet of things (IoT) technology. As it has grown it has proven to be quite useful in managing and maintaining buildings. This involves more than motion sensor lights, as it would involve different sensors and meters being installed to help compile the building information to identify issues. There was a study done to validate the efficacy of IoT in sustainability (Metwally, Farid, et al., 2022). From their study, it was determined that IoT technology that buildings that utilized IoT technology to aid in sustainability was proven to be successful as the system in place allowed for issues to be identified and resolved when combined with user involvement. Their (Metwally, Farid, et al., 2022) research also made note of how IoT technology by itself cannot resolve all issues with a building but is most effective when user involvement is promoted within the building. IoT solutions for sustainability, however, are expensive and have a wide variety of how it can be implemented.

2.3 Digital Twin Technology Application

The term "Digital Twin" (DT) refers to the virtual copy or model of any physical entity (physical twin), both of which are interconnected via exchange of data in real time (Singh, M., Fuenmayor et al., 2021). This helps us understand how the physical state of a DT works in real time. A 2014 study by Grieves described the process of developing a Digital Twin for a building as the identification of three main parts: a) physical products in real space, b) virtual products in virtual space, and c) the connections of data and information that ties the virtual and real products together. The Digital Twin technology allows us to use new strategies to obtain information about energy usage in specific areas.

Digital Twins are being implemented in universities worldwide to understand the energy behavior of a building, and to optimize or reduce its energy consumption. According to Stavros Koltsios (1970), the developed building DT model aims to document the building's dynamic information and provide insights to increase its energy performance and enhance indoor environmental conditions. Among all these universities that are using Digital Twin technology, the University of Birmingham in UK has implemented a Digital Twin to reduce as much as possible the energy consumption of the buildings and achieve its net zero goal. A net zero goal is to reduce the amount of greenhouse gas produced by buildings in use, making sure that what is produced is no more than the amount taken away.

To properly execute this technology, one must follow the 5 levels of development of the Digital Twin. The consultants from CPW stated in their Building Heat Decarbonization Plan report that a "Digital Twin can fall under 5 levels of maturity beginning with 2 foundation levels and 3 operational levels.

Foundational Levels:

1. 3D digital model of the physical asset (static data) – geometry and relevant asset information that supports the use case. Visualize the products that comprise building systems and the spaces they serve to enable FM teams to virtually investigate problems quickly and understand the impact on operations resulting from a shutdown.
2. Collect and track historical data and integrate within the Digital Twin environment. Using this data, carry out analytics to deploy scenarios that deliver improvements to the system and mitigate risk, enabling teams to develop insight about poorly performing equipment.

Operational Levels:

3. Collect real time data via IoT devices that relate back to assets and spaces relevant to the proposed use cases. To compare baseline data and make changes to optimize building systems.
4. Integrate data from third parties and external sources. Access data from external sources, for example, local weather and building use for incorporation within the system to further enhance performance.
5. Autonomous Digital Twin. The ability for the system to self-optimize building performance through autonomous reasoning." (June 2021)

These levels are necessary to identify and describe the current stage of the Digital Twin, so we can have a better understanding of the benefits and results by using this technology at a specific stage of progress.

The interaction of humans with the Digital Twin has developed over time. Some of the main technologies supporting the human-DT interface include virtual reality, augmented reality, haptic interactions, gesture recognition, and voice recognition (Ashwin Agrawal, et al. 2023). The connection of humans and Digital Twin technology is key to determining future human life scenarios that involve the development of smart technology in different fields of work. Human-machine interaction (HMI) is key technology for implementing smart manufacturing, which primarily focuses on the issues of communication, interaction, and cooperation between humans and machines (MA, Xin, 2019), which is a vital component when trying to incorporate human behavior in digital models. The connection that exists between humans and machines prepares humans to design structures that can be monitored to increase the reduction of ineffective forms of communication and cooperation between them.

2.4 The Sheila Scott Building

The Sheila Scott building is located at the University of Worcester's St. John's campus and is the site of a Digital Twin pilot. Also known as the Clinical Skills and Simulation Centre, the Sheila Scott building is used to educate students in various medical programs that the University has through realistic simulations. Some of the programs that the University holds in this building include Paramedic Science, Nursing, Midwifery, Physiotherapy, and Occupational therapy (University of Worcester).

As noted in a 2022 study, the Sheila Scott building presents some notable physical features with its design and layout as the exterior of the building consists of brick walls and metal roofing and the layout of the building displays an unusual shape, as it is relatively long and has straight bends near the end of the strip of the building (Kievra, R., Han, Y., et al., 2022). The layout of the building can be seen in Figure 2.2. Most of the rooms within the building can be classified as two distinct types: seminar rooms and skill rooms. Seminar rooms are like traditional college lecture classrooms, where lectures take place with rows of students listening. Skill rooms are where students get to learn medical practices through a hands-on simulation. The location of each type of room can vary, as the roles of rooms are not permanent fixtures and can be changed with prior preparation. Due to these rooms having different uses, each room's needs will vary depending on many factors. These factors include human elements, such as the amount of people that will be using the room and energy considerations, such as amount of equipment in use, cooling and heating systems, and ventilation (Han, Y., et al., 2022).

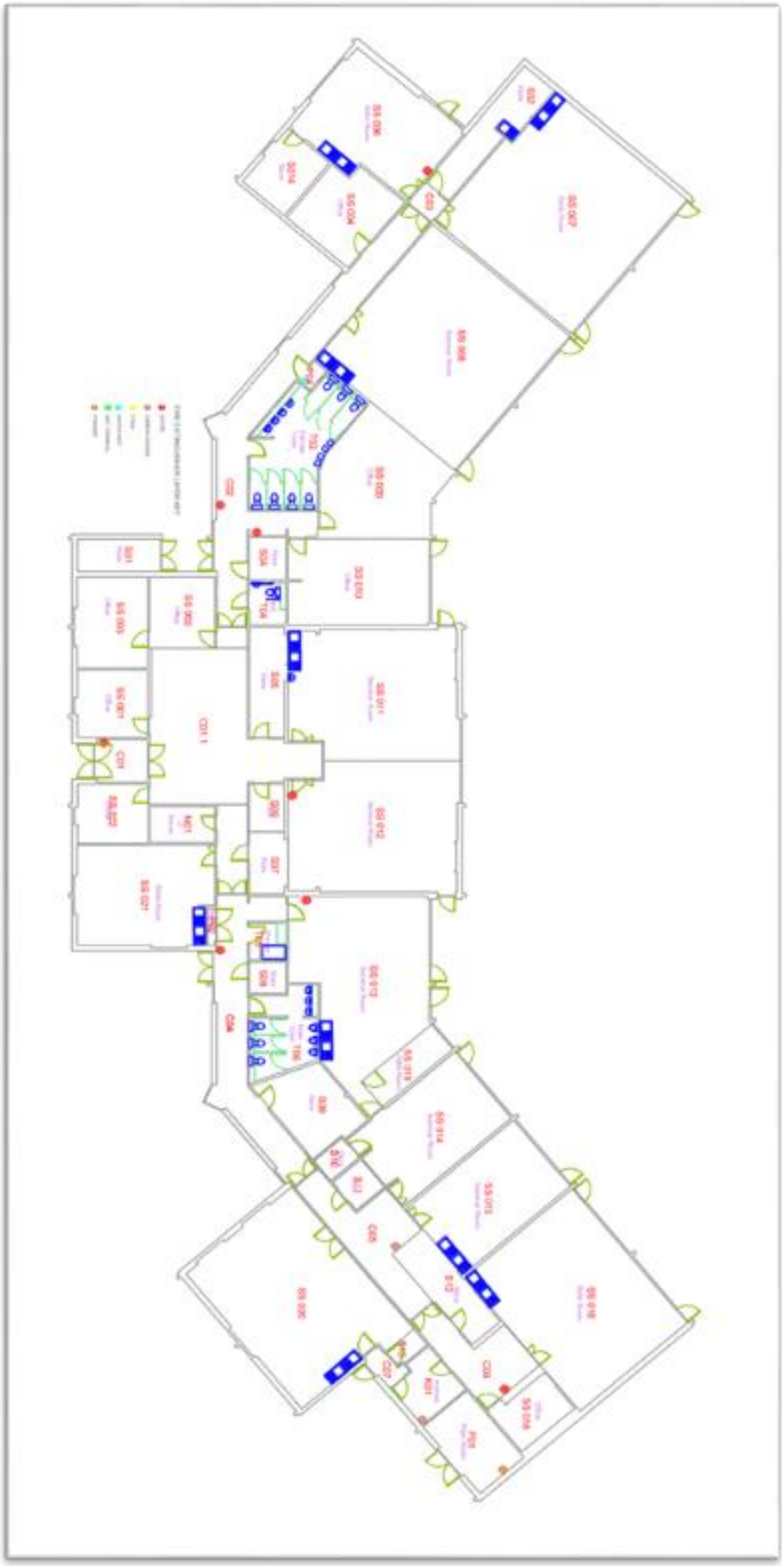

Figure 2.2: A layout of the Sheila Scott building from a 2-dimensional overhead view. (University of Worcester)

In July of 2019, the University of Worcester declared a climate emergency and later established a goal to reach a net-zero carbon campus by 2030 (University of Worcester). An important step in order to achieve that goal was to develop a Heat Decarbonization Plan (HDP). The HDP examines what the Sheila Scott building is comprised of, how the building functions, and how energy is being used throughout the building. The document ends by providing recommendations of actions that can be taken to reduce energy and costs in Sheila Scott. The university plans for the HDP for the Sheila Scott building to be the first phase in an effort to lower carbon emissions across buildings across all campuses.

Estates and Registry services staff at the university wanted to determine if the Sheila Scott building was being used effectively. After running surveys across the St. John's campus, the staff members concluded that the building displayed poor space utilization (Han, Y., et al., 2022). One of the methods they thought of to carry out their decarbonization plan was to implement a Digital Twin in the Sheila Scott building which was used to simulate and analyze its real-world counterpart. It was introduced in the spring of 2022 and has been running for almost a year. If success in energy reduction is found with the Digital Twin used for the Sheila Scott building, the University of Worcester plans to expand the model to other buildings across the campus.

The university wanted to ensure the implementation of a Digital Twin pilot for the Sheila Scott building was successful, and a study was carried out that looked at the potential problems surrounding the pilot (Han, Y., et al., 2022). This study considered a variety of factors that could help the twin pilot perform more effectively and how human factors played a role in the energy displayed. One of the key elements the study focused on was how well the building was performing in terms of space utilization. One of their findings was that there were some challenges with how people were using the reservation system, which was leading to energy being wasted. The authors observed that 62% of rooms that they observed were empty, even though the reservation system states the room was being used (Han, Y., et al., 2022) revealing that energy is being misused in these rooms while they are empty. This is because the reserved rooms are set up and operated by the technicians as if the rooms are being used, so energy is being used on lighting and heating inside the rooms. The study also revealed that there was a lack of understanding and communication of proper sustainable use. Their report provided many recommendations through interviews and observations about how they believe the Digital Twin could be operating more efficiently. Some of these recommendations include the addition of a Digital Twin management team, a standard room capacity limit, improvement of the timetabling system, and creation of a better feedback system for building's users (Han, Y., et al., 2022). The university hopes these recommendations will help make the twin pilot able to achieve their goals and plans to use this technology in other buildings on the campus if the twin is successful.

3.0 Methodology

The goal of this project is to utilize the Digital Twin model to identify energy inefficiencies and key human interaction factors in the University of Worcester. In this chapter we describe our objectives and explain what methods we will be executing to achieve this goal.

3.1 Understand the Design and the Future use of the Digital Twin.

For us to understand the current Digital Twin design and how it is expected to be used, we sought to answer the following research questions.

1. What information does the Digital Twin collect about the building?
2. How is that information expected to be used?
3. What aspects of the Digital Twin have already been executed? Which ones are planned for future project analysis?
4. Are rooms consistently within university temperature guidelines?
5. What rooms are problematic in the Sheila Scott Building?
6. What is working well? What difficulties have been encountered?
7. What documentation exists that can help us learn more about the pilot?

We had multiple discussions with Simon Dutton and Katy Boom to answer these questions. At the University of Worcester, Katy Boom is the Director of Sustainability and Simon Dutton is the Head of Building and Information Services. These individuals have been involved in the planning and implementation of the Digital Twin pilot. Semi-structured interviews gave us the opportunity to explore a range of issues while providing flexibility for the interviewees to lead the conversation in directions we did not know to ask about.

3.2 Understand the Behavior of the Sheila Scott Building's Users.

A crucial element in improving the efficiency of the Digital Twin is understanding how human factors were affecting the results given by the twin. To understand the human factors involved in the Digital Twin, the team researched the following questions:

1. Are rooms demonstrating poor space utilization? Is there a problem with the reservation system the university has?
2. What are factors that people may have noticed about the rooms that could result in poor energy utilization?
3. What factors can the students and staff control? Can and do they control the thermostat, open windows, etc.?
4. How can different perspectives from the various roles of the building's stakeholders provide useful information on these issues?

To answer these questions, we interacted with students and staff as explained below.

3.2.1 Students

To understand how students use the building, we conducted informal focus groups from students who use the Sheila Scott building. Focus groups are an effective method of collecting information from multiple students and were chosen over surveys because there aren't enough students that use the Sheila Scott building to gather significant data. Focus groups allow for the group to interact with students more and collect more accurate qualitative data than a survey would allow.

The questions asked to the students are mainly focused around whether they have observed any of the human factors that would interfere with the twin model data collection. We planned to ask the students around five questions with possible follow up questions. The talks were set to take around five or fewer minutes so we would use less of the students' time and the students would be more encouraged to participate. Our team reached out to the students by being present in the building and politely asking students to take part when they appear to have spare time, such as after classes. Before conducting multiple interviews, we tested our questions with a couple of students in the building to determine which ones answered our research questions. The focus group questions can be found in Appendix A.

3.2.2 Teachers

Staff members such as teachers who use the building can provide similar information as students but can give some additional information on the energy usage and reservation system. Staff members have experience with how the rooms are used and are familiar with the reservation system the university has in place. We conducted semi-structured interviews with some of the staff so they can elaborate on answers to our research questions and provide their thoughts on how energy can be used more effectively in the building. Interviews can also determine how the recommendations provided by the study conducted last year were incorporated. The study done in the building in 2022 revealed that staff had a significant role in leaving empty or under capacity reserved rooms (Kievra, R., Han, Y., et al., 2022). An example of this was that teachers were reserving two rooms at once and leaving one room empty. The staff are likely not experts on energy usage in the building, hence us conducting a guided interview will help gather more information. The plan to reach the staff is to contact staff of the university, like the sponsors, to obtain contact information about the Sheila Scott Building's staff. The language of the questions we will be asking will be reviewed by local staff to verify cohesion. The interview questions can be found in Appendix C.

3.2.3 Estate Staff and Technicians

Estate staff are an important group to gain information from as they will likely be the most informed on space utilization and energy usage within the Sheila Scott building. The estate staff are likely experts in how energy is used in the building, so we conducted unstructured interviews with them. We spoke with Dave Mourby, the Infrastructure Coordinator at the university, about this information. The team asked questions about energy usage in buildings, how the Digital Twin model may assist his work, and possible recommendations he may have in reference to improving the Sheila Scott building. Our team wanted to find out if any of the recommendations made by the study group last year have taken effect and where they believe the energy usage in the building could be more efficient. The research questions for understanding the behavior of the building's users were brought to the interview as a general guide. We reached out to them through email or with the help of Katy Boom, Director of Sustainability of University of Worcester, as well as Mr. Simon Dutton, Head of Building Information and Digital Systems. The research questions that were covered in this interview can be found in Appendix B.

Technicians were another valuable resource of information. Technicians are staff members in the Sheila Scott building that have a lot of experience of how the building functions on an average workday. The Sheila Scott building is used for nursing students to physically practice different scenarios they may encounter as a nurse through simulations. The technicians are the staff responsible for setting up the rooms they use for simulations. The technicians know more about energy usage and factors that occur inside of the building, such as open windows, lights left on, use of space heaters, etc., compared to the other users of the building. The technicians also have firsthand experience with the reservation and could provide some insight into the challenges with the system and potentially some recommendations as well. Our team reached out to the technicians through email and interviewing for about ten to fifteen minutes. The research questions that were covered in this interview can also be found in Appendix B.

3.3 Identify Energy Inefficiencies in the Sheila Scott Building.

Drawing from information obtained from Section 3.2, we started to get a better understanding of how other buildings work with respect to energy efficiency. While the sensor information in the Sheila Scott building is an invaluable resource, being able to learn how to effectively apply this information is another key step to reducing energy usage and improving the Digital Twin model. After consulting with the University estate staff and reviewing the Digital Twin sensor information, we determined the temperature sensor was the most useful sensor for the purpose of our project.

Combining staff interviews and student interviews, we can get an idea of how the building is being used. By analyzing temperature data gathered by the pilot model, we can begin to identify energy usage compared to inhabitant activity, allowing us to answer these questions:

1. Is the technology implemented in the building operating as intended?
2. Does the Digital Twin data validate the claims made by the building's users?
3. Are rooms consistently within university temperature guidelines?

4. What rooms are problematic in the Sheila Scott building?
5. What are the biggest sources of energy inefficiencies from the building's infrastructure?
6. To what extent is human interaction affecting the potential efficiency of the Sheila Scott building?

After conducting interviews and observations, our team wanted to compare the claims made with the data Digital Twin collected. The Digital Twin's data is stored in an excel spreadsheet. The team went through a three-month data set to create graphs of the temperatures in different rooms in the building over certain periods of time. We started out by sorting the given data set by individual sensor typing and time instead of the originally formatted by sensor time entries. A new tab was then created for each time period we wanted to analyze. The only pieces of information we pulled for the temperature graphs were the time/date and temperature. We then selected the array for the desired time period from the main data set and entered that into a column. We repeated the process for every Sheila Scott building room we were given full data sets for. We then created graphs of temperature with respect to time from this data. After this step, key points of interests and trends could be determined that would help answer questions two through four above.

Observations of the building from the project team members were used to track information such as notable features that would result in energy loss, how users of the building interact with it, and other areas of interest that may not necessarily be picked up through the twin's sensors. Our team worked with the technicians and instructors in the building to see when rooms are being reserved because when the rooms are reserved, they are set up and use energy as if someone is using them regardless of whether anyone is using the room. We verified if rooms were the correct temperature with a manual temperature reading device. We also determined for ourselves how users interact with the building.

3.4 Make Recommendations on how to Advance Digital Twin Pilot.

We developed two different types of recommendations. First, we create short-term recommendations for low-cost ways to conserve energy in the building. We also create long-term recommendations which will specify the benefits of improving the Digital Twin process, and what is the next step to advancing the Digital Twin pilot program. To make these recommendations, we aimed to answer these questions starting with the short-term recommendations to long-term recommendations:

1. What low-cost steps could address causes of energy efficiency revealed by the Digital Twin pilot?
2. What other low-cost steps could address other energy problems evident in the building?
3. What methods can practically be implemented to improve the Digital Twin model?
4. How can user accessibility to the model become better in assisting stakeholders carry out better energy use practices?
5. What are the next intended steps of the Digital Twin Pilot?

Our team utilized various methods to pinpoint issues with building performance using Digital Twin data. We visited the Sheila Scott Building to assess the accuracy of the sensors transmitting information to the Digital Twin by comparing sensor data against manual measurements we took. Additionally, we conducted interviews and observations with staff and students who frequently use the building to gauge their familiarity with the Digital Twin technology. This provided us with valuable insights to create cost-effective and concise recommendations for energy savings in the future.

4.0 Findings

Within this chapter we will review our findings discovered from the investigations carried out into the current state of the Sheila Scott building through the previous methodology. This reflects trends discovered from interviews with building users and those in charge of managing the building. Regarding the Digital Twin, trends were discovered and reviewed from data analysis and compared to the information gathered from interviews.

4.1 Sheila Scott Building and Twin Implementation

This section is dedicated to findings regarding the Sheila Scott building's history discovered during research.

4.1.1 Diagram of Sheila Scott building

The diagram in Figure 4.1 shows the layout of the Sheila Scott building from an overhead perspective.

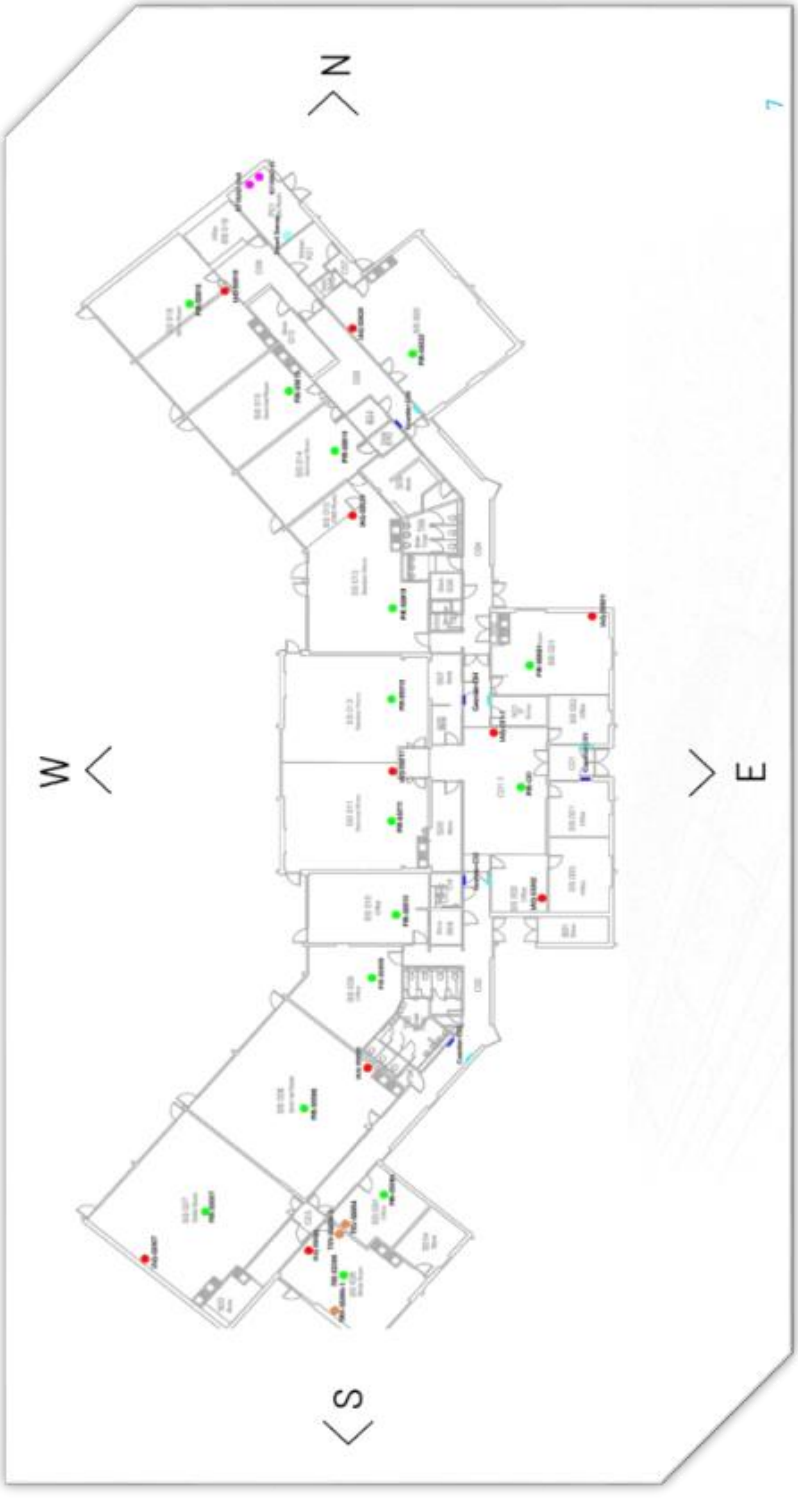
N
W
E
S

Figure 4.1: Diagram of Sheila Scott building layout

The rooms that start with the label “SS” (SS 008 for example) represent classrooms and offices. The areas that begin with the label “C” are meant to be the corridors of the building. The rooms being with “T” and “K” shown restrooms and the kitchen respectively. Finally, the rooms labeled with “P” show the locations of plant rooms in the building, where the mechanical and electrical equipment for the building’s operations are located. P01, shown on the most northern side of the building, is where the two boilers that heat the building are located.

4.1.2 Construction and Condition of the Building

The building is a single story and was constructed in the 1980s. The windows are single glazed windows with metal frames. Some of these windows reach from the ceiling to the floor in two separate panels and make up a large section of the exterior wall. The other sections of the external walls are constructed from brick and blockwork. The internal walls are made from blockwork as well, with plasterboard and skimmed finish. The roof of the building is a standing seam roof, which is typically known to be energy efficient and high-quality roofs. The internal ceilings were made from plaster board and ceiling tiles. The building is in mediocre condition that will be discussed further in later sections. Actions have been taken to repair certain issues with the condition of the building, such as leaks in the roof, but some of these problems persist.

4.1.3 Digital Twin Implementation

There are 37 different sensors located throughout the Sheila Scott building. The location of various sensors can be seen throughout the building in Figure 4.1. There are different types of sensors that collect different information. The various types of sensors used, and their functions can be found in Figure 4.2. The main sensors that were examined during this project were the Indoor air quality sensors and people counters sensors. These sensors can be found in Figure 4.1 represented by green dots and dark blue areas respectively. The data from the sensors is collected every 15 minutes and uploaded to the Digital Twin’s database.

Ref.	Device Description	Location	Quantity	Type	Function
1	Indoor Air Quality Sensor	Rooms and Lobby	10	Wireless	Combined temperature, humidity, and CO2 sensor
2	Occupancy Detector	Rooms	15	Wireless	IR detector to detect movement

3	People Counter	Circulation	5	Wireless	Break beam people counter for bi-directional travel
4	Thermostatic Radiator Value	Office and Skills Rooms	3	Wireless	Radiator control
5	Pipework Temperature Probes	Plantroom	2	Wireless	Domestic hot water flow and return temperature
6	Smart Server	Plantroom	1	Wired	Local processing and connectivity to university network
7	Wireless Gateway	Plantroom	1	Wireless and Wired	Data connectivity with field devices

Figure 4.2: Function of different sensors in the Sheila Scott building

The sensors appear to be reading accurate data, but instances such as human factors may create variances in what the expected data. The graph in Figure 4.3 displays the temperature collected from the indoor air quality sensors in various rooms throughout the month of January. The thick horizontal lines represent the university temperature guidelines. The maximum temperature is 20 degrees Celsius, minimum is 18 degrees Celsius, and target temperature is 19 degrees Celsius. The graph shows that some rooms are overheated while another room is consistently below the minimum temperature according to university heating and comfort policy. The line representing room 6 shows very large spikes in temperature for certain days. This data tells the user that something is happening that is likely outside of the normal heating system, and this is why human factors are important. The peaks are a possible representation of space heaters being used within rooms during these days. This is believed to be due to the cold nature of room 6 and confirmation from staff and technicians of the building that space heaters are occasionally used.

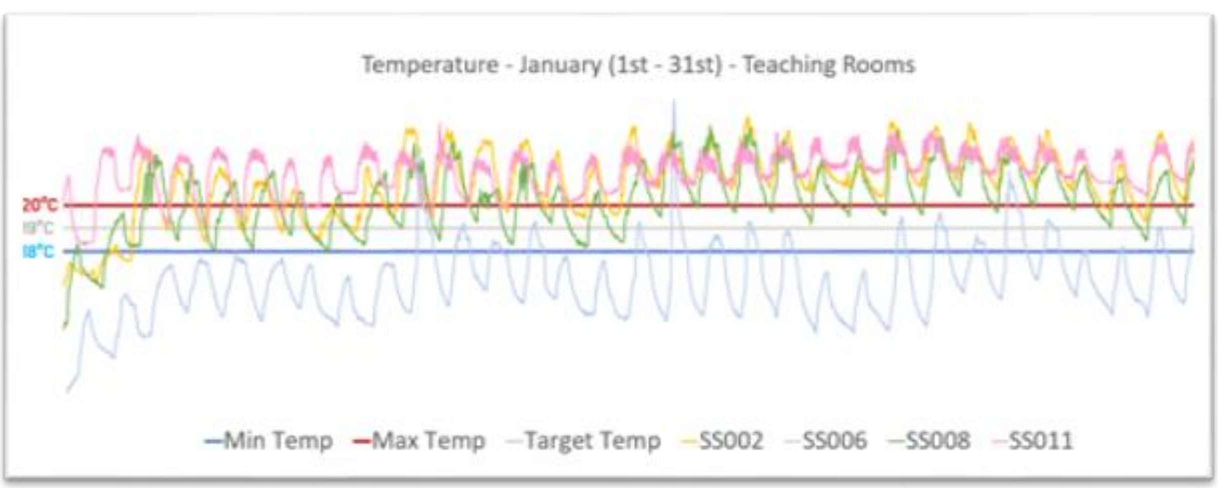

Figure 4.3: Data from twin representing the temperature throughout the month of January.

4.2 Energy Inefficiencies

The Sheila Scott Building was not designed for its current function of being a university building. The building itself has faced several challenges related to poor energy usage. This section will discuss the predicaments surrounding how the building was designed and the material used that would lead to multiple issues such as poor heat retention and feeble ventilation.

4.2.1 Digital Twin Analysis

Digital Twin technology allows for numerical verification of how the Sheila Scott building's rooms thermally behave. Since it was identified through the Heat Decarbonization Plan that the building insulation is poor, that was a main point of focus.

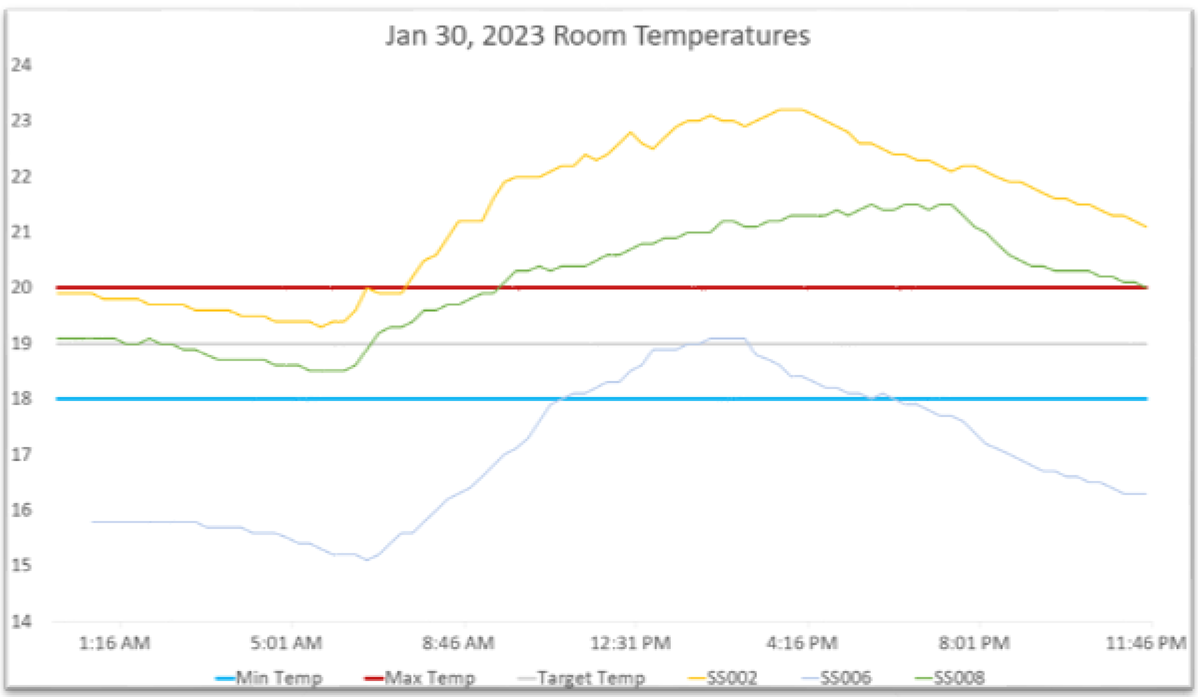

Figure 4.4: Graph of temperatures in the Sheila Scott Building for January 30, 2023

This graph reveals poor heat retention for rooms SS002, SS006, and SS008. Throughout this 24-hour span, rooms start to heat up at the start of the working day and cool down significantly at the end of the working day. Sensor data reveals how the temperature in the shown rooms above never plateaus for a significant amount of time throughout the day. It is also evident that it takes multiple hours for rooms to reach their maximum temperature. In fact, it's possible rooms never reach their target temperatures on abnormally cold days. These discoveries, found with the help of Digital Twin analysis, reveal a large problem in the Sheila Scott Building. As seen in Figure 4.4, rooms at the north end of the building exceed the maximum 20-degree Celsius temperature guideline, while rooms on the south end are still approaching the minimum. In its current state, rooms are extremely unlikely to stay within university guidelines in unison.

Digital Twin analysis also shows energy inefficiencies in the heating system. The vertical delta in Figure 4.4 gives quantitative proof that heating in the Sheila Scott rooms gradient down as the rooms get further from the water boilers.

4.2.2 Infrastructure

Through the investigation into the current state of the Sheila Scott building, the following were discovered as prevalent issues regarding the building's infrastructure:

The windows are a significant cause of heat loss. The windows installed in the Sheila Scott go from ceiling to floor along the backside of the building, where nine of the building’s lecture and skill rooms are located. Thermal imaging (as seen in Figure 4.5) and verbal testimonies from our interviews have made it clear that these windows are not helping rooms retain heat and explain why some rooms in the building are not at the suggested temperature of 19℃ according to sensor data obtained during the colder seasons. According to the Heat Decarbonization Plan, single glazed windows are used for windows and doors in the building. Single glazed windows are typically an inexpensive type of window used for construction, and this is because their quality is poor in reference to heat retention. The recommended thermal resistance, also known as the U-value, for windows in buildings is commonly in a range from 1.2 to 1.6, but single glazed windows have a U-value of 5.58 (Everest). This means that heat passes through them quite easily. This leads to heat escaping the building during the winter and substantial amounts of heat entering during the summer. The fire doors in the building are also made of the same material and have a slight gap in between the doors. An Infrared thermometer was used to test temperatures in various areas of multiple classrooms, and it was found that the temperature can vary significantly. The areas near where the heater was located away from the exterior was found to be around the set 19℃. However, the areas where the windows were located near the exterior of the building dropped steadily, with some areas near the windows measured at 14℃. This is further backed by the findings in section 4.2.1 where Digital Twin analysis shows how heat retention in the building’s rooms are poor. Staff members and students referred to the heating systems being weak, but this may be the reason why they believe that. The thermal images shown in Figure 4.5 visualize where is escaping the rooms and it is clear the windows are a major factor in how heat is escaping the building.

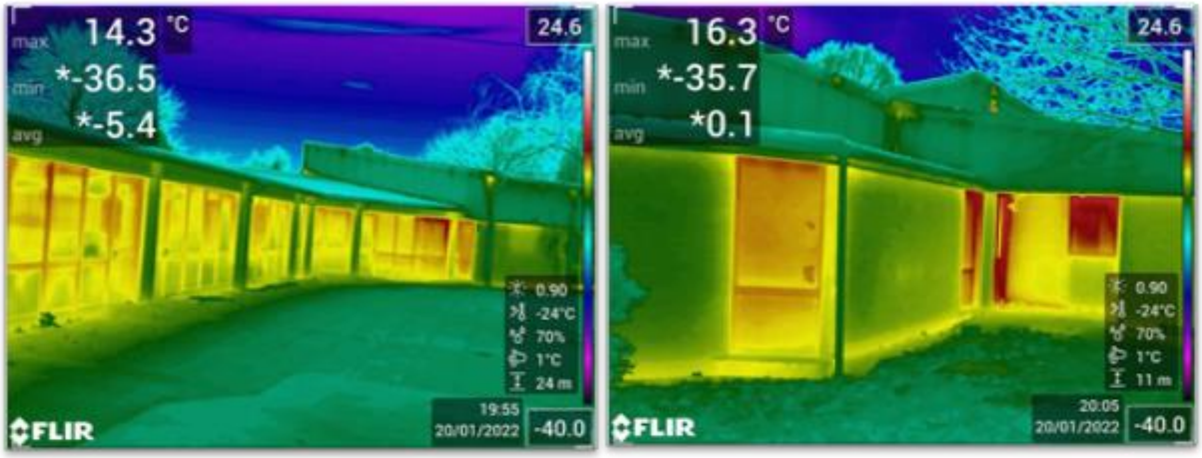

Figure 4.5: Thermal images show the exterior and the Sheila Scott building (University of Worcester)

The roof is not sufficiently insulated. The roof of the Sheila Scott building is made of a standing seam metal roof. These types of roofs are meant to be very energy efficient because they reflect the sun effectively while being lightweight and durable. However, due to the lack of maintenance and the poor insulation of the roof this is not the case. The roof is very thin and often leaks, with staff claiming they must place buckets in certain areas to collect water from said leaks. Staff also must cover some machines like the printer to avoid water damage. When it rains, the noise is undampened and makes the hallways and lobby of the building loud. Maintenance was done in the last couple of years to repair the roof, but the building's problem persists. Analysis of the Digital Twin sensor data has shown the lobby being colder than regulations would have it be, which the roof has been identified to be a contributor of.

The rear parking lot creates overheating the building. The Sheila Scott building was originally a school for children, and the area in the back of the school was a playground. When the university bought the building, they tore down the playground and paved over the area to create a parking lot. The problem comes from the fact that most of the rear exterior of the building provides little thermal resistance and very few cars tend to use the rear parking lot. During the summer and warmer days, the sun reflects off the asphalt and concrete and into the classrooms. The windows provide little resistance, and the poor ventilation leads to the classrooms being uncomfortably hot. Interviews with students and staff members of the building could verify that this was the case. They felt the area could be better utilized and was just a "dead space" according to an instructor in the building.

4.2.3 Building's HVAC

After looking over the physical building and consulting the Digital Twin of the Sheila Scott building, different concerns were observed regarding the heating and ventilation of the Sheila Scott.

The heat loss of the building prevents the HVAC from properly heating most of the building. There are 2 boilers in the plant room with enough room for a third. According to Dave Mourby, the infrastructure coordinator of the university, the building would be properly heated if it weren't for the factors that cause heat loss. Some of these factors relate to the infrastructure of the building, and some relate to the HVAC system in the building.

The heat pipes lack insulation making the system less effective. The Digital Twin has shown a significant temperature difference between the right side of the building and the left side of the building. We identified an average of 4°C difference between the two sides, although the difference can be large as 11°C. After further investigation, it was discovered that the boilers in the building are located on the north side, which forces heated water to travel the distance of the building to heat rooms. The pipes lack proper insulation, causing the water to cool as it goes further and further, making rooms become less heated and falling below classroom standards during colder seasons.

There is poor ventilation in the building. The building currently does not have an adequate ventilation system, with almost all ventilation coming from windows and doors. Some classrooms can often be over the maximum temperature for comfort, especially during the summer sessions. This can be caused by several factors such as the location of the classroom being near the plant room, the sun reflecting off the back packing lot into the classrooms, or the activity taking place within the classroom being very energy intensive like CPR training. When these classrooms get like this, the staff and students will want to lower the temperature, but the limited methods they have of doing this have a negligible effect. The most common way of reducing heat is opening windows. The problem with this is that the windows do not open very much and won't have a significant impact on the temperature. Some students and staff also reported that sometimes people don't close the windows due to the small openings. They said that the windows do not look like they are open when they are, so it is easy to forget they are open. Staff often open doors as a better way to vent the building as seen in Figure 4.6, but they still state that it is sometimes not enough.

Figure 4.6: A view of the back of the Sheila Scott building. The picture shows many open doors and windows.

Fluorescent light bulbs are currently being used in the Sheila Scott building. During the interview with the estate staff, we were able to identify that fluorescent light bulbs are currently used in the building. LED lights were partially installed in the building, but not fully. Finishing implementing LEDs throughout the building would be a relatively inexpensive way of reducing energy usage in the building.

4.3 Sheila Scott Building's Human Factors

Human interaction with this building is especially important since it would influence energy consumption and temperature imbalance that are currently an issue within this building. These interactions represent a major factor in controlling and maintaining building standards for the use of spaces in accordance with the University of Worcester's heating and comfort policy. The interview responses can be found in Appendices F, G, and H.

The target comfort temperature of the building varies depending on the student. After conducting focus groups with many of the students who use the Sheila Scott building, it was determined that students had very different opinions on the temperature of the building. Students, even ones in the same group, reported feeling both too hot and too cold in the classrooms in the building. There are two reasons this is believed to be the case: students coming from different backgrounds and the rooms being different temperatures. The university has many international students from around the world, so the idea of what the temperature may vary from student to student because of this. Students also reported that they believe classrooms on the left side of the building has a tendency to be cold in the winter and classrooms on the right side were too hot in the summer. Staff and technicians, who had more consistent answers compared to the students, were able to confirm these claims.

Students and staff often must break the policy of wearing uniforms. The university has a uniform policy for students in the building when participating in these practice seminars in the classrooms, but it was discovered that this policy is often ignored in the winter. This is due to students and staff becoming too cold in some of the classrooms so they will often wear winter jackets. This can have a negative impact on the learning experience of the students and the productivity of the staff.

Windows and doors are often left open for long periods of time to reduce temperature. As previously mentioned, there is no dedicated ventilation system in the building and instead they rely on opening windows and doors. From the Digital Twin's data and interviews with the building's users, it is apparent that some rooms are often above the maximum target comfort level in the building. The issue with this does not come from users opening the doors and windows, but rather the length of time as well as the outside weather when this occurs. From observations, staff and students often do not close windows and doors after the lessons are over, and they are sometimes left open all day long. They are also left open during days when the outside weather is colder than the temperature inside, which would lead to the heating system using more energy than needed. An instance of this occurring can be seen in Figure 4.6.

Space heaters are used in colder rooms during the winter. Rooms can sometimes go below 18℃ in the winter due to the various factors of poor heat retention. To provide a comfortable environment for the students, space heaters are brought into colder classrooms during this time. Technicians and some instructors confirmed that staff would supply their own heaters. The space heaters are not as energy efficient as the dedicated heating system in place and will often lead to overheating in a given room. When the space heaters are used, the heaters may create data that does not provide a good representation of the typical temperature readings in that room. In Figure 4.7, the temperature in one of the colder rooms can be seen reaching a much higher temperature than normal. Through interviews and this data, it can be inferred that a space heater was used during this day.

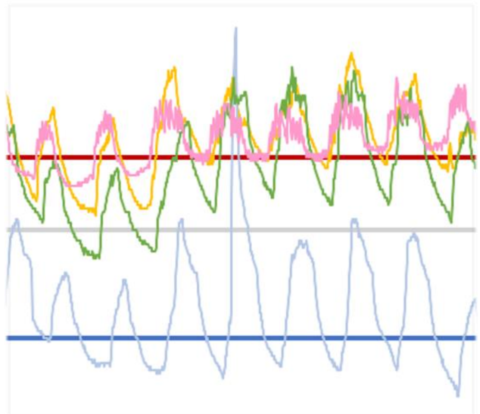

Figure 4.7: Temperatures of different rooms from the month-long dataset. The coldest room shown on the graph can be seen having a large increase in temperature during one of the days.

4.4 Reservation System

The reservation system currently in place across the University of Worcester is set up such that you must book rooms for classes 12 months in advance. From there, based off accounts from the faculty that has utilized the reservation system has described it as a lottery for rooms, as each room is assigned to instructors unbiasedly. In response to this situation, many of the staff would book many rooms at a time to increase their chances of getting a room. In the event they would have multiple rooms, the process to declaim rooms, in their opinion, is difficult to let it go back into rotation.

In the Sheila Scott Building, the technicians who oversee setting up equipment needed for classes, be it practice dummies and other simulation equipment. The equipment that needs to be set up is determined day by day based on which instructor will be teaching what subject in that room. This has been stated to be inconvenient for the technicians as some classes would be moved from room to room over the week due to the way the reservation system works. With how the schedules are set up, they would have to work fast with the little time permitted to set up rooms for the classes.

From the information we have gathered, the reservation system, when compared to data trends derived from the Digital Twin sensor data, has been identified to cause increased energy consumption within the Sheila Scott building. This causes excessive rooms being booked and setup to be on when vacant or causes classes to run longer due to the time needed to set up occasionally, not leaving much time for technicians to prep classrooms beforehand. Our team has determined that this is an issue that needs to be addressed for the building to be more energy efficient than it currently is.

5.0 Recommendations

In this chapter we present short and long term recommendations for both the Shaila Scott building and the Digital Twin.

5.1 Short Term Recommendations

Here we present short-term recommendations for energy savings based on the findings presented in Chapter 4.

Installation of thermal curtains. This is a low-cost easy solution to prevent heat loss from windows. The curtains would increase the thermal resistance of the area around the windows, which would reduce the amount of energy required to keep temperatures within the University standards.

Use material to block the lower section of windows. This would entail using inexpensive material to effectively block the lower portions of the windows to reduce heat loss from the windows. Covering the lower section of the window would decrease the area the windows take up on the buildings and therefore increase thermal resistance. This action can be seen in some of the offices of the building where some staff who occupy these rooms have blocked the lower panels with cardboard and other materials. This can be extended to the top part of the window frame that is not used by the room.

Insulation on the heating pipes. The heating pipes are not insulated well, and this can cause heat to be lost when heating the further part of the building. This insulation allows for heat to be retained within the pipes longer, allowing rooms further from the boiler room to be properly heated and its disparity from the rest of the building would be reduced.

Finish installation of LED lighting in Sheila Scott Building. We discovered that the Sheila Scott building does not have LED lighting in all the rooms. Our recommendation is to finish this so the building can move away from fluorescent bulbs that use more energy in comparison.

Green space instead of rear parking lot. To reduce increased temperatures in the rooms during the warmer seasons, the rear parking lot black surface should be reduced near the classroom. Our recommendation is to install gardens to absorb the heat from the black asphalt that would be reflected into classrooms. This action, however, would only make sense if the Sheila Scott building were to continue operation for an extended period of time, which the group understands may not happen.

5.2 Long Term Recommendations

In this section we recommend steps to advance the use of Digital Twin technology at the University of Worcester.

Organize data collection. The data obtained by the Digital Twin and its sensors are put into a spreadsheet and is currently organized in a manner that makes it hard to work with from a user's standpoint. Figure 5.1 is a clip from the data sheet that can be overwhelming to users and takes a long time for them to utilize it. One approach to make the datasheet more user friendly is through using Python or some other programming language to process and filter the datasheet into a format that would allow users to better comprehend the data in the sheet. This would also allow for the data to be exported into graphical forms such as graphs and charts.

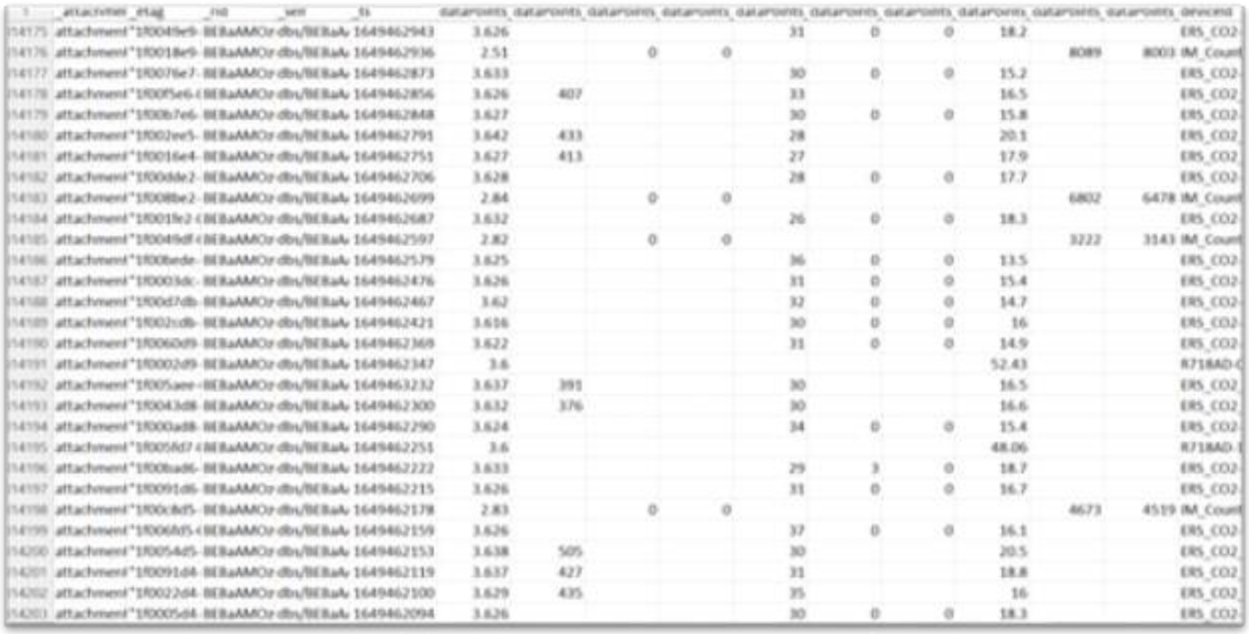

Figure 5.1: Clip from sensor data sheet from the Digital Twin in the Sheila Scott building.

Create accessible Digital Twin visualization. At this time, the Digital Twin model can only be viewed through the HoloLens headset. The HoloLens headset is a unique and interesting way to view the model, but it is not the most practical. The headset can only be viewed by one person at a time and has a tendency to give the user motion sickness. Connecting the headset to another device such as a monitor would allow more people to visualize the model and the information while avoiding motion sickness.

Slow implementation of the Digital Twin. The ultimate goal of the Digital Twin pilot program is to have the technology incorporated within all buildings across the university's campuses. Through talks with the estate staff, the most practical method of proceeding with this program would be by slowly implementing the technology in the other buildings. This is due to slow implementation is the most financially feasible option to implement the Digital Twin throughout the campus. Additionally, this would also allow the estate staff to look over and review the twins in each building individually as they slowly become more accustomed to the Digital Twin environment. This recommendation is only feasible if the previous two long-term recommendations are also implemented.

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Appendices

Appendix A

Focus Group for students who use Sheila Scott building.

Intro: Hello, we are students from Worcester Polytechnic Institute working under the University of Worcester regarding improvement of their Digital Twin Pilot Program in the Sheila Scott building. Do you have 5 minutes for us to ask you questions regarding your interactions with the building? The results of this interview will be kept anonymous should it be used in our paper. You will not have to answer questions you do not wish to answer.

(1 person asking questions and 1 note taker)

Focus Group Questions:

- Have you noticed any open windows or doors? How often?
- Has your instructor used a space heater in a classroom you were using?
- Have you noticed rooms using power when there are not people currently in them?
- How do you feel about the temperature in the building? Does it feel too hot or too cold? Does this vary per classroom?

Appendix B

Unstructured Interview with Estate Staff and Technicians

Intro: Hello, we are students from Worcester Polytechnic Institute working under the University of Worcester regarding improvement of their Digital Twin Pilot Program in the Sheila Scott building. Do you have 15-30 minutes for us to ask you questions regarding the building and its energy use? The results of this interview will be kept anonymous should it be used in our paper.

(2 people asking questions and 2 note takers)

Topics Questions for Interview:

- What are some problems involving the reservation system currently implemented in the university?
- What are factors that people may have noticed about the rooms that could affect energy utilization?
- Do you have any recommendations for methods of making the building more efficient with its energy usage?
- Have any of the recommendations that were made by the study last year put into effect? (Explain last year's study if interviewee is unaware of it)

Appendix C

Semi-structured Interview with Sheila Scott building's staff.

Intro: Hello, we are students from Worcester Polytechnic Institute working under the University of Worcester regarding improvement of their Digital Twin Pilot Program in the Sheila Scott building. Do you have 10-15 minutes to allow us to ask you a few questions about the building as well as your opinion on it? The results of this interview will be kept anonymous should it be used in our paper.

(1 person asking question and 1 person taking notes)

Topics Questions for Interview:

- What factors are you able to control inside the classroom in reference to energy usage (temp, bring space heaters)?
- Is the reservation system well designed and are there improvements that could be made to it?
- How many people are in the classrooms when classes are being held? Do you ever need to reserve multiple classrooms?
- Do certain activities cause classrooms to get too hot? (Such as CPR training) How often do seminars like this take place?
- Do you think staff members consistently turn off lights, close windows, and close doors when leaving classrooms?

Appendix D

Observation of Sheila Scott Building

This section will describe key data from the classroom and building observations during this study. The section will investigate different aspects of how the building is being utilized in the setting of a typical weekday.

Data points to be investigated:

- Are the windows open in the rooms?
- Are doors in rooms fully closed?
- Is the lighting on when people are not using the room or is the lighting system working properly? Are they automatic or turned on by a switch?
- Is the heater fully on when people are not using the room? Are rooms using too much heat? Is there a temperature the building is supposed to be at and is it at that temperature?
- Are the door sensors properly working in the building so entrance doors can stay closed?
- Are doors and windows properly sealed?
- How are individuals interacting with the building?

Appendix E

Semi-structured Interview with Timetabling staff members.

Intro: Hello, we are students from Worcester Polytechnic Institute working under the University of Worcester regarding improvement of their Digital Twin Pilot Program in the Sheila Scott building. Do you have 10-15 minutes to allow us to ask you a few questions about how the reservations system functions and the reasoning behind it? The results of this interview will be kept anonymous should it be used in our paper.

(1 person asking question and 1 person taking notes)

Discussion Points for Interview:

- Can you clarify how the reservation system works at the university?
    - Why does the reservation system work this way?
- Do you believe making changes for changing classrooms is difficult?
- Are there any changes that could be made to improve staff satisfaction with the reservation system?
- Why can people reserve a room for the entire day?
- What are your thoughts on a stricter reservation system?

Appendix F

Data collected from focus groups conducted from questions found in Appendix A

Name	Student 1	Student 2	Student 3	Student 4	Student 5	Student 6
Have you noticed any open windows, doors?	Yes	Yes, sometimes	Yes	No	yes	No, but yes during covid time
How often? ^	Very often, teachers tend to forget to close them		On hotter days	-	Often	Uncertain
Has your instructor used a space heater in a classroom you were using?	No	Yes	No	No	No	No
Have you noticed any empty rooms with lights on?	Rarely	Not really	Yes	Yes	No	No
How do you feel about the temperature in the building? (Too hot or too cold?) (Does this vary per classroom)	Tendency to be very hot	Cold	Usually too cold	Cold	Normally cold, yes to change temp.	really cold, yes

Name	Student 7	Student 8	Student 9	Student 10	Student 11	Student 12	Student 13	Student 14
Have you noticed any open windows, doors?	No	Yes, half of the time					Yes	No
How often? ^							Not that often	Not that often
Has your instructor used a space heater in a classroom you were using?	No	Not Sure					No	No
Have you noticed any empty rooms with lights on?	Yes	Sometimes					No	No
How do you feel about the temperature in the building? (Too hot or too cold?) (Does this vary per classroom)	More warm than cold	Sometimes					It’s okay	It’s okay

Appendix G

Data from interviews with Technicians and Estate Staff referenced in Appendix B:

Name	Alex	Jess	Eve
What are some problems involving the time tabling system currently implemented in the university?	Booking through timetabling system a year before Reservation system not great, limited by outside factors Nursing clinical skills limited to this building; system gets jammed up Relies a lot of human input It needs to be overhauled Fix one thing, something lese breaks	Rooms are booked in the building at the same time, while on other weeks nothing is happening. Staff book rooms without much of a plan. (Timetabling) Takes a long time to make adjustments to schedule.	The planning of it, the modules must put it in by march, don't time to handle it properly. Before that have to create planners for the year for each year and schedules tend to clash. Sometimes days have tons of classes and sometimes there's nothing. Nothing changes. Benefit from new software management system, overhaul. People book rooms they don't use. Book first, schedule classes and plan later.
What are factors that people may have noticed about the rooms that could affect energy utilization?	Windows open. Especially in summer, more active the class is Windows are annoying, don't open all the way so sometimes they forget Heat: Not official, helps when things get cold, usually not left on, very good about turning them off	Certain rooms are colder and hotter, heaters in buildings aren't good and possibly inaccurate reading temperatures. 16 is hottest in the building. They are colder usually than hot. In summer, there's not enough ventilation.	The roof is inadequate, water seeps through and lets out heat. Half is cold and half is hot. Issues controls when heat is on, it is not controlled by people in building. People sometimes faint during sessions or crowded rooms. Rooms are too small for sessions. Student numbers increase without room size increase. Staff

	Basic life support can be a workout, generate more heat Heaters are mostly in rooms 7 and 8, sometimes 20		will ring in sick so classes will double up (two classes in one room). 2 or 3 heaters are used sometimes but not very efficiently. Windows don't open much so no ventilation
Do you have any recommendations for methods of making the building more efficient with its energy usage?	Replace windows	Look at heaters building, heat retention is bad. Big glass windows may be letting out heat, fire exits may have slight holes that let out.	A new roof, possible air conditioning looked at but not enough power, not practical, Windows are too big (floor to ceiling instead of regular windows) looked at thermal imaging can be helpful. Building better used for offices instead of skills room, university says they're stuck with system
Have any of the recommendations that were made by the study last year put into effect? (Explain last year's study if interviewee is unaware of it)	No notable policies haven't noticeably been implemented Sometimes changes take place without technicians noticing	Not really within the last year, talked about air conditioning a couple years ag but talks have stopped.	They tried to repair roof but leaks continued.

Appendix H

Data from interviews with Sheila Scott building's staff referenced in Appendix C:

Name	Teresa S.	Sarah W.	Julie G.
Do you teach any classes in the building?	Yes, first year clinical skills instructor	Clinical Skills	Yes, clinical skills
What factors are you able to control inside the classroom in reference to energy usage (temp, bring space heaters)?	Not able to control anything in the classrooms themselves, the heating system in the classroom doesn't even seem to work.	Depends on the room, but the heater seems very ineffective. Students need to be in uniforms but is often too cold for that and instructors have to break policy to allow students to wear layers.	Just temperature on the room.
Is the reservation system well designed and are there improvements that could be made to it?	Must book rooms for 2 hour slots, sometimes wants to book rooms for more important seminars, sometimes need a breakout room.	Recommended for timetabling and technicians to have more communication. Technicians know more about the building and may have better solutions of scheduling things. Timetabling works for the entire campus and doesn't know exactly what is happening in Sheila Scott. Sometimes people in the building struggle to get	No, it's not useful.

		rooms so they book multiple rooms, people sometimes don't want to give up their rooms. Would like there to be some consequences for people who hoard rooms without use. She uses multiple rooms but usually needs both [cooldown rooms].	
How many people are in the classrooms when classes are being held? Do you ever need to reserve multiple classrooms?	Groups have gotten bigger over the years, recommended 20 students in a room but usually have 25 and have had up to 28 in one room.	Preference would be 16, usually have around 22 which makes things clustered. The size of rooms could be an issue.	The class is normally for 20-22 people. because they are practice/skill classes. They focus on groups. 4 groups in each team. 4 room 4 different group. they have to reserve multiple room at the same time due to the amount of people that they have.
Do certain activities cause classrooms to get too hot? (Such as CPR training) How often do seminars like this take place?	Summer causes buildings to get too hot, winter is too cold. Students and staff sometimes wear layers	Very loud when it rains,	clinical skill, so some time really get hot because they have too many students and sometime the

	even though nursing students are only supposed to wear nursing attire. International students sometimes struggle with how cold the building is.		room is not that perfect for the amount of people using the room.
Do you think staff members consistently turn off lights, close windows, and close doors when leaving classrooms?	They use buckets when it rains because roof leaks. Had to put cover over photocopier to prevent it from getting wet	Sometimes open windows but pretty good with closing them. Doors are left open during classes for ventilation. Wants to destroy building. Building not suited for purpose, doesn’t have the proper facilities for functions. Playground "dead space" could lead to overheating and wasted space.	Yes, they make sure to do a checking at the end of the day to doble check that lights are turn off properly.

Appendix I

Transcribed unstructured interview with David Mauby, Infrastructure Coordinator at the university, was conducted in a closed space and recorded with his consent:

0:04 So with regards to the roof, like I said, we bought the building at least 14 years ago.

0:11 The roof isn't the greatest roof in the world.

0:13 So we put a resin coating over the top which just seals it.

0:17 It's a fiberglass roof which becomes porous after a time.

0:20 So this resin basically gives it a new topcoat.

0:23 So apart from that, we've not done anything major to the roof, it's, it's not the greatest building in the world.

0:29 Yeah.

0:30 No, definitely.

0:34 Yeah, it's a lot of it.

0:35 But yeah, it's, it's one of those buildings you'd be better off knocking it down and trying to refer the shit and you're not starting from a good base.

0:46 So start from the beginning.

0:50 All new.

0:50 Yeah.

0:50 Makes sense.

0:52 That was one of the questions we had.

0:53 We also had another question.

0:55 Did, were you involved with the installation of Digital Twin?

1:00 No, I wasn't.

1:01 Unfortunately.

1:01 So that was done by colleague Matt Smith.

1:05 He was our energy manager up until about six months ago to the universe.

1:12 Got some time so I know he was involved, Simon was involved, but I've never actually got involved in the Digital Twin side of things.

1:20 So my role here is I look after the infrastructure, so all the boilers and systems and all that kind of stuff.

1:27 So I look after the boilers, the water, the controls for the boilers, the sort of suspect you see it in the plant room, you get a big boom box control and all those kinds of things.

1:41 But the Digital Twin, I've never really been privy to I probably should be because I also look after the universities, things like B M systems.

1:49 So it's something that I think we use it as a test bed.

1:53 And yeah, so far.

1:57 So, yeah, unfortunately, Matt left about six months ago.

1:59 We've got a new person in position called Jess.

2:03 She's been here for about three weeks now.

2:07 One of the technicians or someone else, Jess is the replacement for.

2:11 She's the new energy manager.

2:16 I think we had one sentence conversation with her.

2:21 So I'm not sure if Jess will know anything about it yet because like I say, she's only been here a short week, so a baptism of fire as well.

2:29 There's a lot to get your head around.

2:31 It would be really great as a documentation.

2:33 But I also I'm using I industry, we have a lot of documentation.

2:37 I can't trust that with every other industry though.

2:39 Yeah.

2:40 So have you asked Simon for that.

2:42 He said, ask Dave and then I'll give you up.

2:46 Yeah.

2:47 Ok, because when I spoke to Simon about it, he said he wanted to meet up to just go through systems.

2:51 I said, if it's anything to do with the, anything to do with the Digital Twin, I don't know anything about it.

2:59 I said to him that time nobody's ever showed me.

3:01 He said, oh, no, I think it's the systems within the building.

3:04 So the boilers and things like that.

3:05 And that is another question.

3:07 We have to see if we have, if you were asking questions about the twin, if you have any knowledge of that.

3:13 Unfortunately not, but I will try and find out as well.

3:18 We were also curious, this is actually sounds like it is actually how, what is this he situation in the building?

3:24 So it's supplied by two GB 162 boilers.

3:31 So Bud is part of Bosch, a German company, but they bought out a local company called Worcester boilers and that became Worcester Bosch.

3:42 But they, so it's all intertwined.

3:44 So we use those GB 1 62 boilers.

3:47 I think they're 65 kilowatts each.

3:50 We actually put in a header that was big enough to take a third boiler in the future if we ever extended the building.

3:57 But he's only got the two at the moment.

4:00 So those serve the radiator system within the building and then there's also some little sort of warm air blowers in some of the rooms.

4:08 So, they've just got an electric feed, a fan and blow the warm air through the room.

4:14 And then in other rooms it's got radiant panels within the ceiling.

4:17 They sit in like a ceiling tile.

4:20 and it's just a radiator over the ceiling effectively.

4:24 It's quite a simple system in that building.

4:27 It's not a huge amount of control or anything.

4:32 The control comes from like outside of the building.

4:35 So, yeah, so the, the, the controller that's in the room, the touch screen controller, that's the 8000 series control.

4:44 That basically it works like a sort of mini B MS system effectively.

4:49 So it's basically got an outside air temperature sensor on it and it's looking at the flame, we turn temperatures on the boilers and I'm not sure, but there may be a couple of room stats throughout the building, but very little in the way of thermostatic control in that way.

5:05 So, since it's all under the boiler heating system, have you noticed any temperature and radiation throughout the building?

5:15 It's, it's a difficult one.

5:17 That one because that a lot of that is we get, we do get a lot of people here saying rooms are too hot.

5:22 Some people are saying too cold, it is such a matter of opinion and I have this every day people, I can have people sat next to each other and swear blind.

5:31 It's completely different temperature building.

5:33 So some of the rooms we did actually do, I think somewhere there is a, a study on the values of the building because it's not a particularly well insulated building.

5:44 There's very little insulation in the roof, very little insulation in the cavity walls.

5:49 The windows are single glazed.

5:53 Yeah.

5:54 So, the, the building isn't great at retaining temperature.

6:01 But then also in the summer, it's an appalling building for heat gain because there's very little insulation, keeping that heat out and the direction that the windows are facing, the floors are ceiling, windows on the rear of the building, just stare at the sun all day long.

6:16 So the heat game is ridiculous.

6:18 So, yeah, it's, it's a pretty appalling building for heat loss of heat game.

6:24 I see.

6:24 Yeah.

6:24 So would you say the biggest energy consumers in that building are the heating system?

6:30 Yeah, undoubtedly, I see.

6:32 Do you have any chance to know what the statistics are on the light usage in the building and how much energy that takes out?

6:39 I wouldn't, I can probably if I looked at our metering system, if it's Jessie is just currently working through our me, we got a lot of meters that have failed, so they're not pulsing correctly.

6:54 So they're not going to miss the reports.

6:56 We could pop into my office in a minute.

6:58 And have a look at that.

6:58 We could have a look at, electricity usage and gas usage, but that won't break down small power and lighting.

7:07 It would be an overall consumption, I guess.

7:11 So, part of our, the majority of our study is setting human behavior and how their behavior affects the building.

7:18 And so, I suppose we're wondering if the usage of lighting like leaving lights on whenever people are in the rooms, if that provides a significant energy draw and if that's a recommendation we should provide against, yeah, it's, it's going to be a difficult one, you know, where we try and upgrade lighting.

7:35 So we've been doing this for several years now.

7:39 we're getting rid of old, fresh and fishing the five T eight.

7:43 we will only install led lighting now and when we do it, we're trying to do it with presence detection.

7:53 So that if people leave the rooms, it times out after 10 minutes turns the light off until they enter again because we do get a lot of places where people just walk out of rooms and leave lights on.

8:05 It's, it's one of those things that I don't know quite how you get over.

8:08 So, as we upgrade the lighting, we're trying to get the, the presence detection on it, in those rooms, it will be really difficult to try and find out.

8:18 You'd have to do a sort of,, a study of it, put people counters or something like that to see if the rooms are occupied while the light is on.

8:28 we don't have any of that kind of feeling.

8:30 Do you, by any chance have a list of the rooms that have the presence?

8:34 The pictures of, no, without looking at it.

8:39 I wouldn't, I don't know, I know in sort of, some of the buildings like every, just installed a lot of led lighting through there.

8:46 And we put that on presence, but I wasn't involved in the lighting upgrades in that building.

8:52 So to know, I just have to basically walk the building and check that.

8:57 What's, what really got it.

9:00 Sorry.

9:01 I don't feel like I'm being very harmful here.

9:03 Oh, no, this is extremely helpful and a lot of the stuff that we're hearing from you, like the expert on all this stuff is what we've been hearing from other individuals.

9:11 And so it's a nice, data validation tool as well.

9:15 Exactly.

9:17 Yeah.

9:17 Yeah, it's, we do some things well around here but we do some things appallingly badly and, consistency is one thing.

9:26 So we may have great lights in some of those rooms and others and then people lose track of which ones to be done.

9:31 Which ones haven't having that data recorded is, is so it's kind of really hard to give you the, the, the detail of what's, what in the building?

9:44 I see.

9:45 Do you So working with the building, do you by any chance have any recommendations that you would provide?

9:51 just off the top of your head for reducing energy.

9:55 One I would, if we were going to, if we're going to keep the building, I'd want to put a new insulated roof on it.

10:02 I'd want to upgrade grade the glazing to double glazing and I would probably the cloak the building by putting on external insulation rendered to, to try and create a thermal pocket with the building.

10:21 But obviously with budgets as they are, that's a huge amount of money to, to invest in one building, I suppose, in your opinion, do you believe that it's more cost effective to stop using the building or to do all these renovations?

10:40 And it's, it depends on the way you look at it.

10:43 If you're looking at sort of this, this simple route as such, we could, it could be cost effective to spend that money and just insulate the building.

10:56 But when you look at the building usage, it's not a particularly good building.

11:00 The footprint is massive for the amount of useful space inside.

11:05 So if you looked at it in the long term, if you demolish that building and built a new bespoke building with insulation from the ground up as you started and a more useful space, you'd get much better value out of it.

11:22 So in the short term, insulate, the building would be great.

11:24 In the long term, I'd want to build a building that we're going to use for 50 years.

11:30 But make a building that is going to be energy efficient for the next 50 years.

11:37 Whereas it's, if you, if you start modifying that building, it's going to be a sticking plaster, it's going to do a certain amount, but it's never going to be as good as a new building.

11:48 Technology has moved on so much in the building industry since that was built and it's only as good as the builders that built it and that wasn't particularly good, I suppose.

11:58 Speaking of technology you've worked with all the pretty much all the buildings on this campus.

12:04 Do you see any use for a Digital Twin in the rest of the campus?

12:08 Are there any metrics that you think would be useful in your day-to-day activity?

12:14 That's a difficult one.

12:17 It depends on how you're going to operate that Digital twin because there's obviously a lot of different things you can do it.

12:22 It is very useful to be able to wrap up all the systems in one.

12:29 So things like say lighting, for example, we are trying to use a local for emergency lighting.

12:40 So they've got an online dashboard, they'll put all the plot, all the emergency lights by any light that they manufacture but generally we try and stick to them for emergency lights.

12:50 They'll plot those on drawings of the buildings and those lights will self-test.

12:53 So they'll do their flick, test their drain down test.

12:56 They'll tell you if they're healthy, they're not healthy.

12:58 They'll even tell you which part is broken.

13:00 So you can order the new part in, fix it quite easily.

13:04 So that's one system.

13:06 Then I've got a BMS system that does, I've got two BMS systems that do build control.

13:12 There's lots of these systems.

13:14 So I end up with lots of different dashboards open and looking at various things.

13:20 So for me, the Digital Twin will be perfect if you can bring all those systems together.

13:26 It's all in one place.

13:28 It just simplifies life.

13:31 It's something I get slightly.

13:34 How do I put it politely, slightly annoyed about is when people suggested another system and said, oh, we can put it on this portal and we can put it on this portal.

13:46 I have to say I'm not dealing with that.

13:48 No, I've got enough to do as it is without having yet another password, another log in something else to do.

13:54 I said if it doesn't fit with what we got, don't do it.

13:57 I see.

13:57 So a Digital Twin because it should be able to pick up on everything, it actually becomes useful because I'm putting everything together, easily accessible.

14:09 It makes perfect sense in that way.

14:11 I think so.

14:13 And it will be useful in certain buildings.

14:14 So, the Bosch Brewer System we've got in there doing the heating, you can see it online.

14:24 But it's a bit awkward.

14:25 It's, it's their first generation of online controllers effectively.

14:32 And so they're still working on that, developing it, improving it.

14:36 So, actually, if you could bring that into the Digital Twin, it would probably be less clunky.

14:40 I see if that makes sense.

14:42 Yeah.

14:42 So with regards to metrics, I don't really, so have any.

14:48 So there's nothing really I'd want to see in it because I don't generally deal with the metrics.

14:57 I see.

14:57 I'm more because I deal with the hardware of our systems.

15:01 I want to know that it's working when it's not.

15:04 I want to know, you know, there are times when I want to see, make sure it's working and it's efficient and things like that.

15:08 So primarily if it's broke, I'll fix it.

15:11 If it isn't, I'll leave it alone.

15:14 Whereas other people in my team might be more interested in the metrics of the system.

15:19 Does that make sense?

15:20 Yes.

15:20 So, I guess to summarize that your recommendation would be to consolidate all the dashboards into one system.

15:28 Yeah, I see.

15:30 Yeah.

15:31 So I've got two different dashboards for B MS.

15:34 I've got one for lighting.

15:36 I've got one for metering.

15:37 I've got one for our battery storage and solar systems at the arena.

15:46 Which other ones?

15:47 So I got all these different dashboards, and it would just be great if they all fit into one point.

15:53 Yeah.

15:54 So do you think that it would be more work for your day-to-day work if the digital one was only, implemented into, let's say half the building on the Saint John's campus?

16:06 Or do you think that it would be all right, if half the buildings have the digital to win and half didn't, I don't think it would make a huge amount of difference actually because I think it's, there's a lot of constraints in that.

16:20 There's a lot of investment, time labor and financially it would be a lot of money but it's, it's one of those ones you'd have to do building at a time, bring it through and get them all done.

16:36 So the more it's done the better, but it, it wouldn't cause me any issues if half done and half weren't at the moment, most of them aren't.

16:45 So it will probably improve things in such.

16:50 But it's that initial investment in my time and energy trying to get that working.

16:55 I see what me to them.

16:56 So trying to get it working means kind of balance each other out.

17:01 It would improve things, but it wouldn't improve things, but I want more work to do to get there once the whole lots done.

17:06 Obviously, it would improve things, free up, time, free up energy, make life a lot simpler.

17:13 I see.

17:13 So if the university took the route of slowly implementing the digital rather than dumping huge amounts of money all at once, that would, that would be, I think that would be ok with you.

17:24 Yeah, that, that would be, to be honest, that would be my preferred route to go because so for instance, at the moment, we've, like I said, we just done a big lighting project in the building and the Charles Darwin building.

17:39 And alongside that, I'm also doing a project to install and upgrade B MS systems in five buildings.

17:47 So it takes a huge amount of time and a huge amount of energy to do that.

17:54 So doing five buildings for B MS systems at once when it's only me is a lot of work.

18:00 So if we did it a building at a time, I can make sure it's done properly signed off.

18:05 We move to the next one I see doing, throwing a huge amount of money at it is just gonna cause chaos.

18:10 I see.

18:11 Yeah.

18:13 Yeah, obviously if they, if they can bring in extra labor, external project managers, you know, experts in these things, that's fine.

18:22 As long as you know, I can be liaison with them, they can implement it and I can make sure it's fitting the university's needs.

18:29 But that means I have to devote less time to it.

18:31 If it's, if it's all sort of said my way, it's a huge amount of time.

18:40 This is extremely useful.

18:41 All this information is.

18:43 Yeah, I don't feel like that, but I mean, we actually, now we've been trying to figure out what was the heating system every time you ask them, hey, how is the building here?

18:53 They just get with the 50 yard and said, yeah, I'm kind of my own worst enemy.

19:02 because I, I do say to people at times I should walk around and stop looking at things every time I dig into things, I seem to find a little problem and another problem and it sort of spirals out of control and in the end where it should be probably somebody else dealing with it ideally because I want it done.

19:17 Right.

19:19 And, it started when I started here 12 years ago, I was looking at those things and there were no asset registers.

19:25 So when people were looking at all our and our lifts and our electrical systems, they were like, basically give you a shrug.

19:32 They didn't know what was there.

19:34 So, all the aspirations we got what I created.

19:36 I spent all that time sort of going around and updating it.

19:39 So I'm kind of my own worst enemy.

19:41 I've taken these, these roles off, but it does mean I'm probably in a position to tell you more about what's actually fitted out there.

19:49 Than most people.

19:51 And that's why everybody comes to me and say, yeah, that they, and I suppose another long term goal for our project is eventually implementing digital technology into a lot of other buildings.

20:04 So having your viewpoint on that, especially the person that's in charge of all these buildings, I think it would be useful.

20:12 Ok.

20:12 Yeah, I do think it would be useful because you can also, you can the amount of things you can bring into that.

20:17 I know on our new medical school that we're building down the road.

20:22 Elizabeth Garret Anderson building, they've done full modeling on that.

20:28 So you can obviously bring that into the Digital twin as well.

20:31 And it's just, it's just another, they're all layers within one system as opposed to being separate systems all over the place.

20:40 And that's where it become really useful.

20:41 It's just getting everything in one place.

20:45 And then I believe we have one, just one last question slightly different from what we've been talking about.

20:50 But we're hoping to do some temperature readings in the classroom in the classroom and we were wondering if you had a manual temperature device.

20:58 Yeah, I can either give you, I've got a little thermal hand held thermometer.

21:02 I've got some little probes.

21:05 I can show you take your pick if you like got a thermal imager.

21:09 I'm imager is necessarily required, but a handheld thermometer would be Yeah, so I got that in my car.

21:16 So we'll go and grab that in a second.

21:18 So much better than little Pat placard.

21:21 There.

21:22 Is it, those little papers that was for you?

21:27 And there was three of them.

21:29 And we all said like, Dave, please have something better.

21:32 Every time I, I've had that, I've had heating complaints everywhere.

21:35 People say, look at the thermometer and it's as much theme.

21:40 I see.

21:40 And I, I just say to them like, oh, please throw it away because it just, they can be affected by light, they can be affected by, moisture.

21:49 It, it makes no sense whatsoever to use those things and it just confuses people and they absolutely believe it.

21:54 And you think it's, I might as well just go and write the temperature on the wall.

21:59 So, yeah, I'll give you a proper, a proper, that'd be much better.

Appendix J

Authorship

Section Number / Section Title	Primary Author	Editing Author(s)
Acknowledgements	RT	RS, AF, JN
Abstract	RS	JN, RT, AF
Executive Summary	RS, RT	AF, JN
1.0 Introduction	JN, RT	RT, RS
2.0 Background		
2.1 Energy Usage in Buildings	JN	RS, JN, AF
2.2 Strategies to Reduce Energy in Buildings	RS	JN, RS, AF
2.3 Digital Twin Technology Application	AF	RT, JN, RS
2.4 The Sheila Scott Building	RT	AF, RS, JN
3.0 Methodology		
3.1 Understand the Design and the Future use of the Digital Twin.	AF	RS, RT, JN
3.2 Understand the Behavior of the Sheila Scott building's Users	RT	RS, AF, JN
3.3 Identify Energy Inefficiencies in the Sheila Scott Building.	JN	RS, AF, RT
3.4 Make Recommendations on how to Advance Digital Twin pilot.	RS	RT, JN, AF
4.0 Findings		
4.1 Sheila Scott Building and Twin Implementation	RT	RS, JN, AF
4.2 Energy Inefficiencies	RS, RT	RS, JN
4.3 Sheila Scott Building's Human Factors	AF	RS, RT, JN
4.4 Reservation System	RS	RS, RT, JN
5.0 Recommendations		
5.1 Short Term Recommendations	RS	RT, JN, AF
5.2 Long Term Recommendations	RT	RS, JN, AF
Appendices		
A Focus Group for Students who use Sheila Scott building	RT	RS
B Unstructured Interview with Estate Staff	RT	RS
C Semi-structured Interview with Sheila Scott building's staff	RT	RS, AF
D Observation of Sheila Scott Building	RT	RS, AF
E Semi-structured Interview with Timetabling staff at university	RT	AF
F Data from Students Focus Groups	JN	RT
G Data from Interviews with Estate Staff and Technicians	JN	AF
H Data from Interviews with Sheila Scott building's Staff	JN	RS
I The Interview with David Mourby	JN	AF,