Communicating HVAC Operation Through a Thermostat Interface: An In-Situ Implementation to Improve Perceived Control and Thermal Comfort in Offices

by

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Abstract

It is well understood that the ability to control the thermal environment through a thermostat interface can increase thermal comfort and productivity in offices. Less is understood about how the usability of thermostats, and more broadly the usability of building control systems, play a role in realizing these benefits. The field of human factors offers numerous techniques to design, test, and analyze interfaces; however, very few examples exist where these techniques were applied to thermostats.

This thesis contributes to understanding how thermostat interfaces and the operation of the heating, ventilating, and air-conditioning (HVAC) control systems can affect occupant's perceived control in offices. The research was carried out in three phases across two heating seasons on 25 academic offices of an institutional building in Ottawa, Canada. Phase 1 applied an analysis of building control logic, building automation system (BAS) sensor data, and thermostat interactions, combined with a survey to identify barriers to usability in the offices. The surveys indicated a low sense of perceived control among participants. Three primary usability issues were identified: (1) setpoint regulation was contextual and was affected particularly by neighbouring offices due to the zoning employed in the building, (2) response times to setpoint adjustments were slow and highly variant, and (3) control was removed from office occupants during scheduled setbacks, and this was not communicated to office users. In Phase 2, features were developed to address these issues and were designed to be implemented into the existing thermostats of the building. The features included displaying (1) HVAC operational information (e.g., heating), (2) a time-to-temperature estimate, and (3) when scheduled setbacks were in effect. These features were implemented in all 25 offices.

Phase 3 aimed to measure the operation and gather feedback about the implemented features. The feedback indicated that participants found value in the modifications to the thermostats and highlighted a need to include usability early in the design processes of the control system. In one instance, offering transparency to the system operation had an adverse effect, perhaps because the system was not designed to provide the level of individual control the participant expected.

While this thesis focuses on a single institutional building, it is expected that the issues found in this building are widespread. The thermostats in this building did not meet fundamental recommendations of usability found in the human factors literature. This thesis represents the first real-world implementation in an office building of a thermostat with the features developed. The identified issues, development of the features, and feedback are documented to inform future iterations of this design.

Acknowledgements

I first wish to acknowledge that this research was conducted at Carleton University, which is located on the traditional and unceded territory of the Algonquin Anishnaabeg People. This academic institution operates on stolen land abiding by the laws of an illegal colonial power that continues to occupy Indigenous lands while benefiting from the historical and the ongoing practices of genocide that perpetuate the oppression of Indigenous Peoples across Canada. As a graduate student of settler descent, I have conducted my research on this land for the benefit of my academic career. I wish to offer my recognition of, and gratitude for, the Indigenous lands on which I live and work, and the communities who still occupy the territory and continue to defend their rights as the traditional custodians of this land.

The academic and professional engineering communities for which this research contributes to are currently facing critique due to their longstanding under-representation of First Nations, Inuit, and Métis. This issue is of critical importance, as all peoples should have the right to design, build, certify, operate, and control the infrastructure they depend on. During my work on this project, I was unable to identify ways in which my research intersected with these issues; however, as engineers, we often claim objectivity and apoliticism while failing to address how the practices within our fields enforce colonial values. In my career going forward, I plan to seek advisement and expand my ability to recognize how colonial ideologies are influencing my work.

I would like to acknowledge the efforts of Professor Liam O'Brien and Professor Chantal Trudel. Without their guidance and support, this project would not have been possible. Their mentorship has allowed me to perform and showcase my research, and I credit their kindness and encouragement for making this research a rewarding and enjoyable experience.

I am thankful for the support of the students and professors who make up the Building Performance Research Center (BPRC) at Carleton University. They acted as my colleagues, friends and support network, enriching my experience in an incredibly positive way.

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Nomenclature

List of acronyms

AHU	Air handling unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAS	Building automation system
COV	Change of value
COVID-19	Coronavirus disease 2019
GUI	Graphical user interface
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
IEQ	Indoor environmental quality
IoT	Internet of things
ISO	International Organization for Standardization
MAE	Mean absolute error
MLR	Multiple linear regression
PI	Proportional Integral
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
VAV	Variable air volume

List of symbols

C	Thermal capacitance of an electrical analogous circuit
$\dot{Q}$	Heat flow of an electrical analogous circuit
$\dot{Q}_{OAT}$	Heat flow associated with outdoor air temperature
$\dot{Q}_{SOLAR}$	Heat flow associated with thermal gains
$\dot{Q}_{VAV}$	Heat flow associated with variable air volume operation
$\dot{Q}_{RAD}$	Heat flow associated with radiator
$\dot{Q}_{OCC}$	Heat flow associated with internal gains during occupancy
$\dot{Q}_{INT}$	Heat flow associated with internal gains present regardless of occupancy
T	Temperature
ΔT	Change in temperature
t	Time
Δt	Timestep
u_1	Indoor air temperature
u_2	Outdoor air temperature
u_3	Indoor illuminance
u_4	VAV flow
u_5	VAV supply air temperature
u_6	Radiator valve
u_7	Radiator supply water temperature
u_8	Occupancy

List of units

%	Percent
°C	Degrees Celsius
°F	Degrees Fahrenheit
K	Kelvin
L/s	Liters per second
lx	Lux
min	Minute
ppm	Parts per million
R	Rankine

Chapter 1: Introduction

1.1 Background

Across Canada and the USA, people are typically spending over 90% of their time indoors (~87% in buildings, ~5% in vehicles) [1], [2]. Therefore, indoor environmental quality (IEQ), and making buildings comfortable for occupants, has significant implications for the health and well-being of people. Typically, the comfort parameters considered in IEQ are indoor air quality (IAQ), thermal comfort, visual comfort, and acoustic comfort. The effects of the IEQ parameters on well-being are complex, come from multiple domains of comfort, and can be both long term and short term [3]. In office and education settings, the connection between IEQ, well-being, and productivity are of specific interest.

Thermal comfort is defined in comfort standards as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” [4]. In physiological models, thermal comfort is measured based on a heat balance of four environmental parameters; air temperature, mean radiant temperature, relative humidity, and air velocity, as well as two personal parameters; metabolic rate and clothing level. These parameters are widely used in standards to specify building operating temperatures [5], [6], with temperature ranges intended to satisfy 80% of occupants. However, in reality, the subjective aspects of thermal comfort are influenced by more than these parameters alone, and include, among other things, expectations of the environment, culture, age, gender, and availability of adaptive measures. Increasingly, attention has been put towards adaptive measures, such as the ability to change clothing or operate windows.

Personal control over the thermal environment refers specifically to the adaptive measures which influence the indoor air temperature and is typically done through opening windows and adjusting thermostats. Research has established that people will be more comfortable even in the same thermal conditions if they have access to some sort of personal control [7]–[9]. When performing large scale surveys, the level of personal control is often not known by researchers. Therefore, participants are asked how occupants feel about their level of control, referred to as perceived control. The availability of thermostats can have a strong influence on an individual's perceived control; however, people do not always view their thermostats as effective. It has been suspected that low perceived control can occur due to the usability issues with thermostats and heating and cooling systems; however, there is limited research in this area (e.g., [10]–[12]).

The field of human factors and human-computer interaction offers valuable insights regarding design principles in the control system and interface design. In this field, usability, user experience, and how such factors affect people's ability to operate complex physical systems are well researched. Heating, ventilation, and air conditioning (HVAC) systems are some of the most complicated systems office users interact with [13], and designers often overestimate the knowledge of users leading to usability issues [10]. This places an importance on interfaces, as people rely on their interactions with these systems to build a functional understanding of how a system works in order to effectively operate it, known in the field as a mental model. In the building used for this research, even the most basic principles suggested for consumer electronics interfaces [14], which include immediate feedback after an adjustment, and real-time system status information (e.g., the system is currently heating), were not followed.

Meanwhile, the increasing popularity of centralized building automation systems (BAS) has allowed for centralized operation, data collection, and advanced control strategies in commercial buildings [15]–[17]. These systems have been used to monitor building performance, measure occupant behaviour, and modify control systems by both researchers and industry. This technology, which is present in the building studied for this thesis, allows for a deeper understanding of building operation from the perspective of occupant's perceived control, as well as opportunities to monitor and communicate HVAC operational information to users.

1.2 Problem statement

This thesis aimed to identify issues, develop solutions, and obtain feedback to address barriers to usability related to the HVAC control system and the thermostat interface in offices. To achieve this, the relationships between thermal comfort, personal control, perceived control, and usability of the control system will be explored using theories of thermal comfort and human-computer interaction. This project takes advantage of the extensive access to 25 offices in an academic building located in Ottawa, Ontario, which acts as a living lab for this research. This building allows for direct measurement of thermal conditions and the ability to remotely modify what is displayed on the thermostat interface. Additionally, appropriate ethics clearance was obtained to survey participants about the comfort and usability in their offices.

1.3 Objectives

1. To apply a mixed-methods approach of combining historical building performance data, surveys of the occupants, and recorded thermostat interactions to assess and identify barriers to thermostat usability in 25 offices during the heating season. While this thesis focuses specifically on one institutional building, it aims to address issues that are expected to be common to other commercial or institutional buildings with offices.
2. Based on the identified barriers to usability, employ a human factors approach to develop features that may help support users' mental models of the heating system operation. The proposed features included communicating current HVAC operation by communicating heating control logic, setpoint schedules, and a time-to-temperature estimation. The implementation of the time-to-temperature estimation required the in-situ implementation of a grey-box room model. This design process was documented in this thesis and can be applied more broadly to buildings facing similar usability issues.
3. To implement and test the developed features in the 25 offices. This included using building performance, thermostat interactions, and survey results to gain feedback on the developed features. The feedback was reported and can be used in future iterations of thermostat designs.

1.4 Organization of thesis

This thesis is organized into seven chapters. Following this introductory chapter, Chapter 2 provides a review of relevant literature, and Chapter 3 presents the overall project structure, data collection methods, and an overall description of the building.

Chapters 4-6 describe the three phases of the project, (1) pre-implementation, (2) design, and implementation, and (3) post-implementation. Each of these chapters includes a discussion that summarizes and discusses the significant findings of these phases. Chapter 7 provides a final discussion, the major contributions, and recommended future work. A brief description of each chapter is listed below.

Chapter 2 provides a detailed literature review in three areas, the current state of thermal comfort in office buildings, relevant human factors theories, and advanced building automation systems and data-driven modelling approaches.

Chapter 3 describes the overall project structure, data collection techniques, test building setup, and survey techniques used to perform this project. This section gives a description of the technical features of the building studied, as well as an overview of how both the heating system and how the thermostats operate prior to any intervention. This chapter also describes the basic survey methodology, as well as the ethics clearance received to perform this research.

Chapter 4 describes the results from Phase 1 of the project. The chapter includes an assessment of the pre-implementation control system, thermostat interactions, and thermostat interactions to assess barriers to usability. This phase also consists of a survey to assess and baseline the occupant's thermal comfort and perceived control in the building. The results from these two methods are both used to inform the thermostat design.

Chapter 5 describes Phase 2 of the project and outlines the design and implementation of the thermostat features. This chapter includes both the rationale for the features based on a human factors framework and the technical implementation of these features. The implementation is also described in this chapter.

Chapter 6 describes Phase 3 of the project, which includes an assessment of the building performance during testing, an analysis of the technical performance of the implemented features, and the post-implementation survey.

Chapter 7 provides a final summary of the results of the project, highlights the contributions to the field, and presents recommendations for future work.

This work integrates two conference proceedings, one of which is published, and the other is accepted and in review.

1. C. Brackley, W. O'Brien, C. Trudel. "Evaluation of a modern commercial HVAC control system in the context of occupants' perceived control," in *ASHRAE 2020 Annual Conference*, 2020.
2. C. Brackley, W. O'Brien, C. Trudel. "Applying data-driven thermal modelling techniques to provide office occupants with time to setpoint estimates," *in eSim 2020.* (Accepted, in review)

In the co-author conference proceedings, Connor Brackley was the principal contributor to the design and execution of the research, presentation of the paper, and writing.

Chapter 2: Literature review

This chapter contains three sections. The literature on thermal comfort (Section 2.1) establishes the connection between perceived control, thermal comfort in offices, and the importance of thermal comfort to the productivity of office workers. The literature on relevant human factors theories (Section 2.2) gives several principles and strategies to improve interactions between people and the physical systems they interact with. Finally, the review of building automation systems and applications (Section 2.3) provides context on the technology available in modern commercial office buildings.

2.1 The current state of thermal comfort in office buildings

The goal of thermal comfort systems in office buildings is to provide comfortable indoor spaces for people while minimizing energy use and other costs. Improving the workplace thermal environment has benefits for office workers' health, well-being, and productivity [18]–[20]. This thesis focused on the thermostat interface and control system design to improve usability and perceived control in office spaces; however, the ultimate goal of improved usability is to improve thermal comfort. How thermostat usability affects thermal comfort is summarized in Figure 2.1. The importance of thermal comfort, along with the connections between usability and thermal comfort, will be elaborated on in this section.

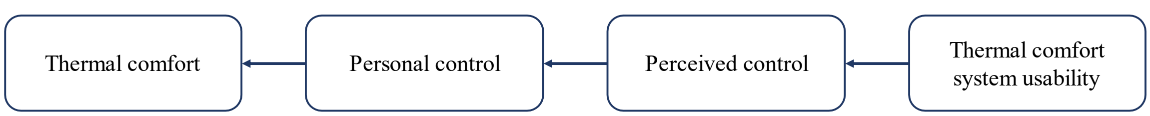


Figure 2.1 The path in which improved thermal comfort system usability can effect thermal comfort in offices

2.1.1 The importance of thermal comfort in offices

While many factors play into indoor environmental quality (IEQ), it is generally studied in four different domains: indoor air quality (IAQ), thermal comfort, visual comfort, and acoustic comfort. Each IEQ domain plays a complex and multiparameter role in health and productivity in office spaces [3]. Thermal comfort has explicitly been shown to play a significant role in a person's health, well-being, and productivity [3], [18], [21]. For example, Wyon [20] demonstrated that improving occupant thermal comfort in offices can directly increase productivity by up to 5%.

Thermal comfort is defined by ASHRAE Standard 55 as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." Thermal comfort research has typically been performed using two different techniques: climate chamber studies and field studies [22]. Climate chamber studies attempt to control all variables, including temperature, humidity, air velocity, activity, and clothing. One of the most famous and widely used studies of this type was performed by Fanger [6]. Fanger's research centred around the heat exchange equilibrium of the human body and the surrounding environment. Their research proposed that comfort was dependent on metabolic rate, clothing, indoor air temperature, humidity, and radiative heat transfer from the surrounding environment. Using a combination of all of these factors, Fanger generated an equation for the predictive mean vote (PMV), a scale between three and negative three, where three is "very hot" and negative three is "very cold." Fanger also developed an equation to convert this PMV score to the expected percentage of people dissatisfied (PPD).

The Fanger method was later used to inform building operational comfort ranges of ASHRAE Standard 55 *Thermal Environmental Conditions for Human Occupancy* [4], and International Organization for Standardization (ISO) 7730 *Ergonomics of the thermal environment* [5]. These standards are widely used for the design of HVAC systems and specify indoor thermal conditions in office buildings. The standards provide acceptable comfort ranges for clothing levels of 1 and 0.5 clo, based on operative temperature, humidity. Based on this guideline, the Canadian Centre for Occupational Health and Safety (CCOHS) recommends comfortable temperature ranges for office workers of 20-23.5°C in the winter and 23-26°C in the summer, assuming low air movement, and relative humidity of 50% [23]. The different temperature ranges between the seasons are based on the anticipated difference of clothing level.

The alternative method of research focusses on comfort using field studies. Fanger's method of treating the human body as strictly a heat balance item affected by purely physiological factors is limited in real-world applications. Thermal comfort is affected by several other factors, including behaviour adaptations (e.g., changing clothes or adjusting a thermostat), and psychological factors (e.g., expectations about the thermal environment, cultural differences). To address this complexity, De Dear and Brager [24] worked on updating ASHRAE Standard 55 to include an adaptive model of thermal comfort. Their work applied an empirical approach to create comfort ranges for naturally ventilated buildings, based on a previously collected database, which contained high-quality data from 160 naturally ventilated buildings in four continents. They found that comfort ranges in these types of buildings varied primarily by outdoor temperature and developed ranges intended to satisfy 80% and 90% of occupants. Importantly these temperature ranges are typically wider than those prescribed by the Fanger's thermal comfort model. In the adaptive model, the temperatures that provide comfortable indoor environmental conditions increase with increasing outdoor temperatures, offering the potential for more energy-efficient operation. This model is only specified for naturally ventilated buildings, which are primarily controlled by individuals through operable window usage. However, De Dear and Brager noted that some members of the Standard 55 technical committee argued that this model could likely also apply to buildings where individuals had other forms of control over their environment (e.g., thermostats).

Parkinson et al. [25] attempted to validate the adaptive thermal model on a larger, more recent database and determined they had sufficient evidence that the adaptive model could be used in mixed-mode buildings with air conditioning. This finding has not yet been reflected in the standards. The impact of personal control as an adaptive measure will be investigated further in the following section.

2.1.2 The impact of personal and perceived control on thermal comfort

Adaptive actions cover a variety of actions people can take to make themselves more comfortable, including changing clothing, drinking cold beverages, changing locations, and adjusting thermostats and blinds. Personal control in the context of this thesis refers specifically to adaptive actions that influence the thermal environment. Due to a variety of individual factors or human characteristics including preference, age, gender, metabolic rate, clothing level and expectations of the indoor environment, researchers have argued that personal control over the thermal environment has a strong influence on a person's satisfaction with their thermal environment [20], [26]. In Canadian offices, the common means of personal control are operating a thermostat and/or adjusting a window. Given the scope of this thesis, this literature review will focus only on control over temperature through thermostats; however, it should be noted that availability of operable windows also plays a significant role in personal control, and when available, can even be the primary means of intervention by occupants [27].

In their chapter of Creating The Productive Workplace [20], Wyon was critical of how PPV and PMD methods were calculated, noting that people participating in their development were not wearing their own clothing or performing their habitual office tasks. They also noted that knowledge about metabolic rates, mean temperature, and clothing levels are often unknown. To address this, Wyon and Sandberg [28] performed tests on 200 office workers, wearing their own clothes and performing their own work. Using this research, they associated various levels of personal control with the percentage of people satisfied, as presented in Table 2.1. While this table shows adjustment ranges, the research refrained from recommended the neutral value they should be centered about, noting that empirical research in each building would be required based on HVAC equipment and office setups.

Table 2.1 Wyon's findings for the required range of personal control corresponding to the percentage of people satisfied with their thermal environment. (Source: D. Wyon, "Individual control at each workplace: the means and the potential benefits," in Creating the Productive Workplace, 2000, pp. 192–206.)

% Comfortable	Range, K	Range, R
85	3.4	6.1
90	3.9	7.0
95	4.6	8.3
99	6.0	10.8

Beyond the direct physiological impacts of personal control on comfort, there is strong evidence that the psychological impacts of knowing that control is available can increase thermal comfort. When testing occupants in a climate-controlled chamber, Luo et al. [29] found that subjects in both cooler and warmer conditions reported higher satisfaction merely due to the availability of control, and the magnitude of this effect was higher for more extreme temperatures. Similarly, Zhou et al. [7] found that when testing in a thermally controlled environment, when people knew they could control temperature, their thermal comfort improved even when that control was not exercised.

For large scale studies, researchers' knowledge of personal control is typically unknown. The term "perceived control" is often used as a measure of occupants' perception of their ability to influence their thermal environment. Similarly to the lab-based tests which looked at the impact of personal control, Yun [9] performed field testing and found in seven office buildings, individuals with high perceived control were more comfortable even when experiencing similar operating temperatures. The importance of this perceived control was further highlighted by Boerstra et al. [30], who demonstrated through data from a database of over 6000 European respondents that a positive correlation can be drawn between perceived control and productivity.

Despite its importance, a large survey-based study of Finnish homes and offices suggests that both perceived control and thermal comfort in offices are significantly below that of homes [27]. Many reasons were speculated as to this discrepancy, including that people in homes have more adaptive actions, such as changing their clothes or moving rooms. It is also possible that the expectation of the thermal environment is lower in homes than in offices. However, correlations were found both between perceived control and thermal comfort, as well as perceived control and knowledge of the HVAC system [27]. These findings may suggest that how people perceive and understand their HVAC systems influences both their perceived control and thermal comfort.

2.1.3 The link between available personal control and perceived control

The availability of personal control via a window or thermostat interface is one of the primary factors that influence perceived control in an office [8], [31], [32]. For example, Huizenga et al. [31] found in a survey of 215 buildings in the US, Canada, and Finland that 76% of occupants who had access to a thermostat reported that they were satisfied with their thermal environment vs. 56% of people without access.

Despite their importance, some studies have revealed that the availability of thermostats alone does not guarantee the benefits of perceived control. In one survey of 22 Dutch offices, complaints regarding thermal comfort decreased if personal control options via thermostats were both available and considered effective; however, if the personal control was not deemed effective, the number of complaints was the same, or in some cases, higher [19]. Similarly, in a field study performed by Boerstra et al. [32], surveys were combined with tests of the building performance, finding that while the average office worker had access to a thermostat, only 31% indicated that they were satisfied with their control over the environment. In another study of 170 university workers, Tamas et al. [33] asked about the ease of usability of each of their office features. They found the ease of adjustment of thermostats was rated the lowest, with many participants saying they thought their thermostat adjustments had no impact on temperature. It has been suspected by some researchers that his gap may be caused by usability issues with thermostats [10]–[12]. The impact of thermostat usability will be further discussed in Section 2.2.4 in reference to a human factors and usability framework.

2.1.4 Thermostat interactions

When deemed effective, thermostat adjustments are one of several primary adaptive opportunities provided to people for times of discomfort [27]. For this reason, measuring thermostat adjustments are, in some cases, used as a proxy to understand satisfaction with the thermal environment. As an example, Gunay et al. [34] used the temperatures to which individuals adjusted their thermostat to create individualized setpoints based on user preferences. In this study, they observed that people only infrequently interacted with their thermostats, approximately once every 56 hours on average. Through surveys, Boerstra et al. [32] found a connection between perceived control and exercised control. People who adjusted their thermostats more frequently (on a daily to monthly basis) report higher perceived control than those who made adjustments less than once a month or never. The authors note that they are uncertain as to the cause and effect of this observation: are people not interacting with their thermostat due to a belief that it does not work, or do people not perceive they have control because they do not interact with their thermostat? It may, therefore, be difficult to associate interactions to satisfaction with the thermal environment, particularly in cases where users do not view their thermostat as effective.

The way people interact with thermostats as a proxy of understanding usability is also of interest in this thesis. For programmable residential thermostats, Perry et al. [35] developed several metrics that related button presses to usability. The number of buttons presses, pauses between presses, length of time of interaction, and the success rate of various tasks were suggested as ways to infer usability. In general, devices with short interactions, with few button presses, and few pauses between button presses were seen as easier to use. These metrics were intended to be used in a lab setting, where the intent of the individual's interaction was known. This limitation is a crucial consideration for fieldwork in cases where button presses are monitored without knowledge of the user's intent.

2.1.5 Summary of framework

This literature review presents the ways perceived control, personal control, and thermal comfort are connected. It is well established that improving the workplace thermal environment has benefits for office workers' health, well-being, and productivity. The connection between personal control over the thermal environment through personal thermostats is also well established in the literature, in two primary ways. First, personal control allows individuals to adjust to their preferences based on their characteristics and state within a given environment, and second, simply the knowledge that control interventions are available appears to lead to a higher satisfaction with the environment (even if those controls are not exercised). However, to realize the benefits of personal control (e.g., through the use of thermostats), the literature suggests that occupants must perceive that they have control. While there is evidence to suggest the connection between available control and perceived control using personal thermostats is strong, availability alone may not guarantee higher perceived control. Several studies indicated that there is a distinction, and perhaps a disconnect, between available control and perceived control; however, limited studies were found in the literature which have investigated the reason for this. A review of the principles of human-computer interactions and how it applies to current thermostats interfaces and HVAC control systems is covered in section 2.2.

2.2 Relevant human factors theories

While thermal comfort is primarily studied within the context of the relationship between IEQ and comfort, to the best of our knowledge, few studies exist that directly study the impact of the interface or control system design in the context of usability. The Fundamental design principles of interface design are reviewed in this section, and relevant theories are used to structure a framework of thermostat design. This framework is then used to review the limited literature on usability studies related to thermostat interface design.

2.2.1 Interface definition and interactions

Defining a thermostat interface by interaction and type within the context of the human-computer interaction field helps understand how to approach the design of these devices to support people's experience. In their book, Interaction Design – Beyond Human-Computer Interaction [14], Preece, Rogers, and Sharp define several interface categories, including touch, web, wearables, graphical user interfaces (GUIs) etc., and note that many interfaces we interact with likely fall into more than one of these categories. Thermostats may be button-based, touch screens, or in some cases, may be categorized as mobile (e.g., smart connected thermostats in the residential sector). However, they broadly meet the category of the home or consumer appliance, defined as machines designed for everyday use in homes or public spaces. When people interact with these types of interfaces, they are typically trying to achieve a task within a short period of time. They should be designed with short interactions in mind. Users will be likely uninterested in exploring how the systems work, and the design should focus on simplicity and visibility. Status information and feedback regarding how long a machine will be running are considered fundamental design principles.

Preece, Rogers, and Sharp also define four types of interactions: instructing, conversing, manipulating, and exploring. Given their categorization as an appliance, thermostat interactions are exclusively instructing-type interactions, where users issue instructions to a system via buttons, touch screens, or in some more advanced residential thermostats, even speaking. Conversing involves people having an interactive dialogue with a system; manipulating consists of changing the nature of objects in virtual space and exploring is where individuals explore a virtual space. Conversing, manipulating, and exploring-type interactions are all absent from current generations of thermostats. These fundamental principles and associated design approaches are important to understanding and advancing thermostat designs. Improvements should be with the premise that individuals will naturally expect quick and straightforward instruction-based interactions with thermostats and will likely not be interested in other types of interactions.

Preece, Rogers, and Sharp also define a cognitive framework regarding how people interact with interfaces. The role of cognition in interaction design includes designing for attention, perception, memory, learning, and problem-solving. Attention refers to the mental load required to perform a task, and this load can be reduced by making necessary information easily available, avoid cluttering, and using techniques such as animated graphics or colouring to highlight necessary information. Perception refers to how information is interpreted and can be improved by making text legible, and graphical representations familiar and recognizable. Memory is the extent to which carrying out an operation or understanding an interface relies on recalling information from other sources. This should be reduced to not overload users, and interfaces should be designed to promote recognition. Finally, since people may prefer to learn through doing, rather than reading instructions, interfaces should be designed to facilitate learning and problem solving the interaction through the system itself. The authors suggest that interfaces should be designed to encourage exploration, and additional information should be provided through menus and manuals for users who would like to learn more. Due to the long delay between adjustments people make to thermostat settings and completion of the setpoints they select, designing an interface that encourages exploration poses a particular challenge for thermostat interfaces, as the effects on the environment are not immediately apparent. This concept is explored further in the following section (Section 2.2.2).

2.2.2 Framework of Interaction and Feedback

In their book User-Centered System Design [36], Norman and Draper introduce a framework highlighting the importance of interfaces as the medium that bridges the gap between a person's goals (e.g., achieving a particular setpoint temperature) and the physical system responding to their goals (e.g., the HVAC system achieving the particular setpoint temperature). This gap represents the difference between the psychological expectation of the system and the physical manifestation of the system. Ideally, this gap does not exist; however, this typically only occurs with very simple systems or when users of the systems can be considered experts. According to Norman and Draper, the interface helps bridge this gap in two ways, through what they call the execution bridge and the evaluation bridge. People use the execution bridge to specify and execute actions and issue commands to the physical system. They then rely on the evaluation bridge to perceive, interpret, and evaluate how the system is responding to their actions. This framework is visualized in Figure 2.2 the authors note that there are two ways to provide these bridges and increase the usability of systems: move the system closer to the users' expectations by improving the accuracy of their psychological representation of the system (by helping them understand how it works), or bringing the person closer to the system, by improving the ease in which they can input and execute their actions. Both strategies are important and work in tandem to help people effectively interact with their systems.

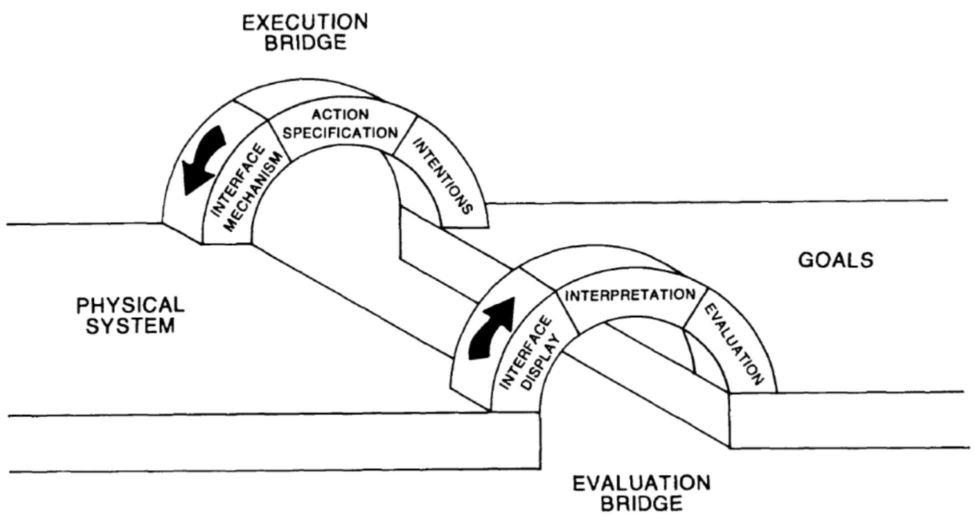


Figure 2.2 A visualization of the framework introduced by Norman and Draper. The execution bridge and evaluation bridge represent how interfaces can bridge the gap between a user's goals and the physical system (Source: D. A. Norman and S. W. Draper, User-Centered System Design. 1986.) [36]

A concept that describes the psychological representation that people have of physical systems is known as mental (or conceptual) models [14], [36], [37]. As people interact with systems, they build an idea of how that system works. When a person interacts with a complex system, they rely on the feedback of the system to understand how they can achieve their goals. According to Preece, Rogers, and Sharp, if people can develop better mental models of how a system works, they are in a better position to interact with that system effectively. The transparency of a system can help people build effective mental models and can be aided by interface design by providing useful feedback in response to user input. This is represented in the framework as improving the evaluation bridge. Additional assistance through instructions or online help can also assist users. However, it should be noted that a fully technical mental model is not always required for users to achieve their goals. The example given by Preece, Rogers, and Sharp is a TV: while a technician may need a detailed mental model of how a TV works to fix it, an average person only needs a limited understanding to operate it to their needs. In the context of heating system operation, which may not be of interest to office users, system transparency should be presented only to assist individuals to reach their specific comfort settings.

Interestingly, Norman and Draper point out that if there is a delay between an input and a perceived change to a system, this can “severely impede” the process of evaluating the effects of one’s action. This undesirable phenomenon is inherent to current thermal designs due to the system’s lag in responding to a person’s input. In their book The Design of Everyday things [38], Norman states that modern systems should generally provide feedback about 0.1 seconds after a request was received, and notes that this is particularly important for operations which take considerable time. They also note that when possible, systems should provide time and progress estimates. When times are hard to predict, it is recommended that a range of times be shown, or if this is not possible, display the worst case or longest time, so that the system exceeds expectations. Since thermostats and associated thermal comfort systems are slow to respond, this is a very important consideration in thermostat design.

2.2.3 Interface design process

In their book, Interaction Design [14], Preece, Rogers, and Sharp describe four basic activities of interaction design; establishing requirements, designing alternatives, prototyping, and evaluation. This process is not intended to be done linearly, but instead iteratively as shown in Figure 2.3. Defining design requirements is done through data gathering in order to identify people's needs and create requirements for the interface design. Data gathering can be done in several ways, including data recording, interviews/questions, and observing users' activities. Prototyping is the process of creating a version of a design that users can interact with. This can be as advanced as a finished product, or as simple as a paper-based representation of an interface. Evaluating involves collecting information regarding users' potential experiences with the designs. Types of evaluation can include several techniques and can be narrowed down to three broad groups: controlled settings involving users, natural settings involving users, any setting not involving users. This basic design process will be considered throughout this thesis when developing an improved thermostat interface.

Rather than just looking at the thermostat as an independent interface, it is important to see the impact of the entire thermal comfort system and its design implications on usability. In their book Evaluation of Human Work [37] Wilson and Sharpe discuss the importance of ergonomic and human factors in system design and discuss when and how human factors should be integrated into the design process. In systems ergonomics, it is important to move beyond the technology and consider the complexity of the whole system, interactions with other systems, and how the environment and context can affect the system. On a system design level, ASHRAE Standard 55 - Thermal Environmental Conditions for Human Occupancy [4], is one of the most well-used standards when specifying comfort demands of buildings, which is then used to design system equipment. While this standard covers comfortable temperature ranges, humidity control, and air flow rates in detail, it makes no mention of usability or other human factors concerns in the system. It can therefore be speculated that usability is left out of the design process when specifying the system unless it is of particular interest to the specific designers involved. This represents a major gap and is a significant motivation for this thesis.

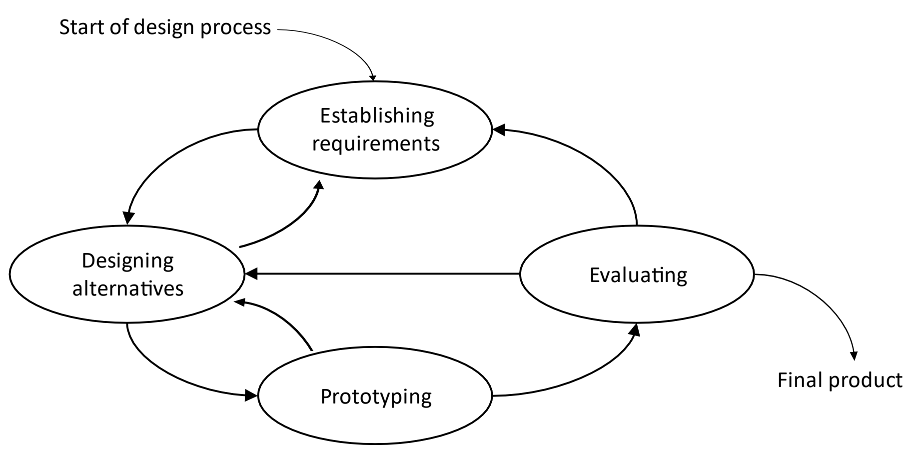


Figure 2.3 Interaction Design Life Cycle Model. The arrows show the suggested iterative design paths. This figure has been slightly from the original source to include "start of design process" text.
(Source: J. Preece, H. Sharp, and Y. Rogers, Interaction Design - Beyond Human-Computer Interaction (Fourth Edition). 2015) [14]

Ergonomic system and interface design is a well-developed field in human-computer interaction, and relevant theories have only been briefly summarized here. More information can be found in the primary references for this section [14], [36]–[38].

2.2.4 Analysis of current commercial thermostat design

While research analyzing commercial thermostats in the context of usability is limited, some studies do explore interface and system design within the context of usability and perceived control. To some extent, the usability of both commercial (primarily focused on office space) and residential thermostats have been researched. The two domains have very different challenges: in general, people have a better understanding and are more satisfied with their home thermal comfort systems [27]. However, users are often entirely in control of their heating system, and therefore fully in charge of the energy use that results. As a result, the research in the residential sector is primarily focused on intuitive interfaces that promote understanding and utilization of energy-saving features of programmable thermostats [35], [39]–[43]. Conversely, in offices, people have limited knowledge of their HVAC systems, and typically limited control over their thermal comfort systems, which are increasingly becoming more automated. People generally operate thermostats during periods of discomfort, and those interactions with thermostats are typically more focused on alleviating discomfort as quickly as possible [12]. Given the commercial scope of this research, only the literature on commercial thermostats is highlighted here.

Karjalainen and Koistien [11] performed an extensive interview-based field study of 13 buildings to understand how people use controls and found several usability issues relating to temperature controls. Some people were unaware of the thermostat's existence, were unaware of the purpose of the control, or thought control was to be left up to services personnel only. It was also noted that the symbols on the thermostats were frequently not understood, and users did not know if systems were for heating, cooling, or both. Some of these issues are likely also caused by a failure in the evaluation bridge. For example, the author notes that any sort of feedback was typically not given, or when given (through a coloured LED), the user did not understand it. Building on this research, Karjalainen [12] developed and tested a thermostat prototype based on several usability guidelines. These included simplicity of the interface, a clear way to adjust the temperature, and instant feedback regarding the systems operations followed-up by feedback when the system reached its goal. The researchers developed an interface through several design phases, working from paper prototypes to a computer interface that affected system-level controls. They found that the interface shown in Figure 2.4 could be used effectively by even novice users. The thermostat interface developed in this thesis draws from the characteristics of this thermostat.

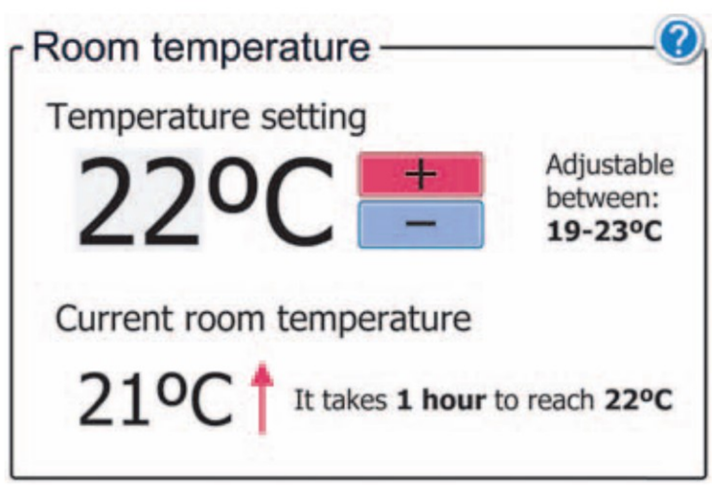


Figure 2.4 Interface prototype designed through several iterations of user testing. This interface was found usable by even novice users (Source: S. Karjalainen, "Usability guidelines for room temperature controls," Intell. Build. Int., vol. 2, no. 2, pp. 85–97, 2010.) [12]

Beyond the interface itself, the design of the control system can also influence perceived control. The speed of the system, availability of thermostats, and automation all play a role in the usability of thermal comfort systems. While Karjalainen and

Koistien [11] mention the value of immediate feedback in their thermostat usability guidelines, they also recommend that the control system should have a fast and effective impact on room temperature. These two types of feedback can work together to improve overall feedback (i.e. what Norman and Draper refer to as the evaluation bridge) for these systems to improve perceived control in buildings. Boerstra et al. [32] found that people were generally aware of how quickly buildings reacted to setpoint changes, with occupants reporting slow response times in slowly responding buildings. While the effect of this speed on perceived control was not reported, it can be concluded that occupants are at least aware when their buildings are underperforming.

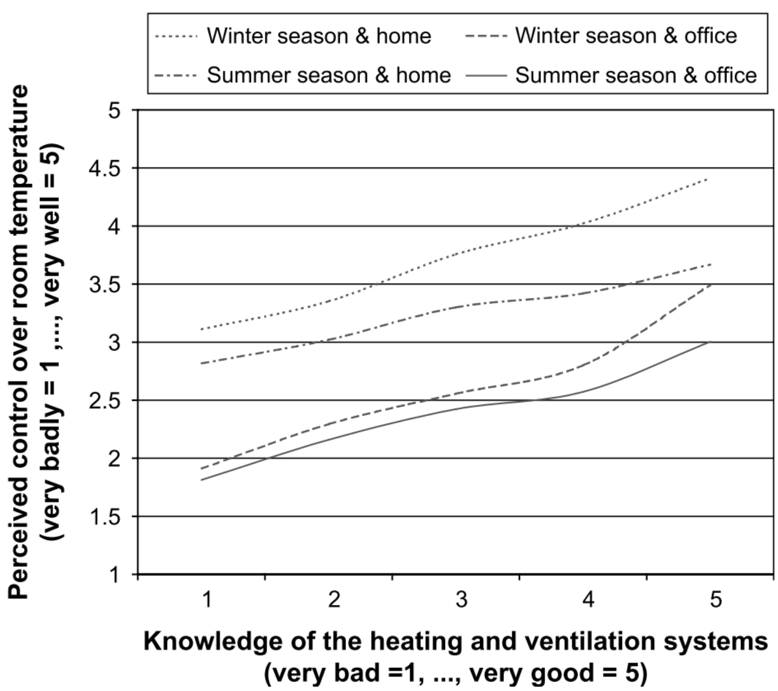


Figure 2.5 The correlation between knowledge of the HVAC system and perceived control over temperature.
(Source: S. Karjalainen, "Thermal comfort and use of thermostats in Finnish homes and offices," Build. Environ., vol. 44, no. 6, pp. 1237–1245, Jun. 2009.) [27]

There is evidence that improving the understanding, or mental models, of thermal comfort systems improve perceived control. Karjalainen [27] demonstrated a positive correlation between the self-reported understanding of the HVAC system, and perceived control, as shown in Figure 2.5. It was also noted that people generally have a better understanding of their HVAC systems in their residential settings compared to their office settings.

There is current interest is the effect of automation on building usability. Over 20 years ago Boradass and Leaman [44] expressed concern that increased automation will not always lead to better performance, and suggest that users through intentional automation, and increase the likelihood of building malfunctions as operators become less knowledgeable and able to maintain the building systems due to increasing system complexity [44], [45]. More recently in an interview of 170 university employees, 89% of employees said that they would prefer their lighting and HVAC systems to be slightly more manual or much more manual (40%, 49%, respectively) than their current situation [33]. Since automation efforts in buildings are typically targeted at centralizing control and reducing energy, without simultaneously considering the human-computer interaction effects of these efforts, automation can have an adverse effect on perceived control.

This thesis will apply the frameworks, analysis methods, and design process discussed in the human factors literature to examine how thermostat interfaces may affect perceived control and thermal comfort and also develop potential improvements to the interface.

2.3 Advanced building automation systems for data collection and control

Increasingly commercial buildings are equipped with advanced building automation systems (BAS). These systems are installed in commercial buildings to allow centralized control of the building services, such as HVAC equipment, lights, automated blinds, and alarms [15], [16]. Building automation is achieved with a distributed controller architecture, through which sensor inputs are processed, and control outputs are generated and used to operate the various building systems. The primary purpose of BAS is to provide occupant comfort systems at a reduced operational cost. Modern BAS typically presents the control logic through a user interface, allowing operators to generate, interpret, and modify the building control logic [16], [17]. These interfaces provide access to all building services and allow for some faults to be diagnosed and corrected with minimal personnel effort.

By centralizing building operation, BAS systems also centralize methods for data collection from the sensors within the building. This allows comprehensive data collection and enables the market in building data analytics in both industry and research [15], [17], [46], [47]. The availability of data through BAS has been used for an array of purposes, including diagnostics for building operators, automated fault detection, load forecasting, control system strategies, and studying occupant behaviour.

2.3.1 Review of data-driven modelling approaches

One application of building data particularly relevant to this thesis is the use of historical data to develop data-driven models, the usefulness for which has been demonstrated for advanced control strategies, energy monitoring, and calibrated modelling [47], [48]. As an example, optimal start algorithms that use the historical building data to estimate time to recover from setback temperatures have existed since the early 1970s [49]. Some recent applications of data-driven models include next day heating/cooling load estimation for better operation of heating plants and model predictive control to reduce energy demand from the heating and cooling system [50], [51].

Broadly, the two categories of data-based modelling are hybrid or grey-box and black-box [52]. Black-box models are purely data-driven and can be developed without knowledge of the source data. For this reason, they can be applied to building data without knowledge of the building dynamics or sensor locations, making them more versatile and easier to apply. By their nature, their internals are unknown, uninterpretable, and can perform unpredictably if not trained on a large or well-varied training set. The alternative grey-box (or hybrid) modelling uses a combination of measured data and an understanding of the expected effect of the input parameters to create representative models. The primary advantage of these models is they can act predictably, and the parameters can be interpreted by people.

Gunay et al. [53] provided a comparative analysis of various electrical analogue room models and had several key findings. By training various models with real building data, they found that increasing parameters without increasing the number of sensors decreases the model predictive accuracy. Also, they found the simplest model that provided satisfactory predictive accuracy included the parameters of indoor and outdoor temperature, indoor light intensity, motion sensors, and heating system status, using 15-minute timesteps. These findings represent the basis for the model formulated in this thesis.

While many examples exist of using data-driven models for control, few applications have provided this information to office users. This thesis includes the development, training, and implementation of a model used to estimate time-to-setpoint in a commercial building. Because this time-to-temperature estimate will be displayed on the thermostat, the model developed needs to provide robust, predictable, and consistent estimations.

2.4 Summary of the literature review

The literature on thermal comfort established a connection between perceived control, thermal comfort in offices, and the importance of thermal comfort and how it related to the productivity of office workers. The thermal comfort literature also notes that while providing a means of personal control through thermostats may have a significant effect on one's perceived control, people do not always perceive their thermostats to be effective. The literature on relevant human factors theories provided a framework and gave several principles and strategies to improve interactions between people and the physical systems they interact with. Finally, the review of building automation systems and applications provided context on the technology available in modern commercial office buildings.

Chapter 3: Project structure, data collection methods, and building description

This chapter describes the overall project structure (Section 3.1), the building in which this research was conducted in (Section 3.2), the survey administration (Section 3.3), and the ethics clearance obtained to conduct this research(Section 3.4).

3.1 Project structure

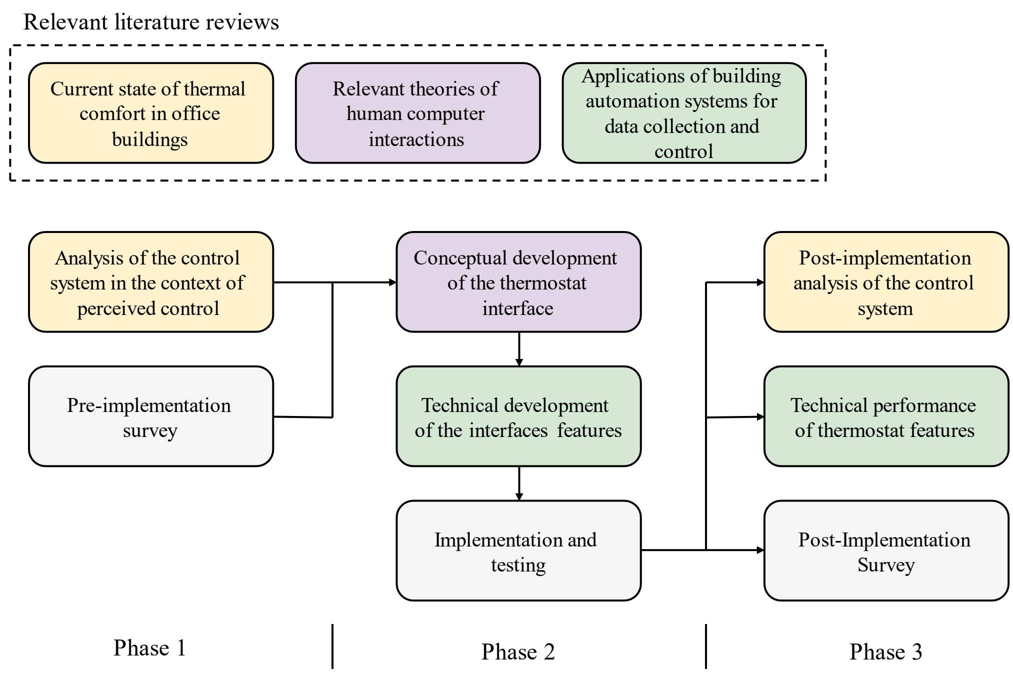


Figure 3.1 Project overview. The colours correspond to the relevant literature reviews. The grey refers to project steps for which there is no specific literature review.

The goal of this project is to identify issues, develop solutions, and obtain feedback to address usability issues related to the HVAC control system and thermostat interface in commercial office buildings. While the building studied is an institutional building, this study focused only on the offices within this building, making the results applicable to both commercial and institutional buildings with offices. This project was carried out in three phases, as shown in Figure 3.1. Due to the interdisciplinary nature of this project, the relevant literature reviews are colour coded into the various stages of the project overview.

In Phase 1, an analysis of the current implementation of the thermostat and control system operation was performed. A data-driven approach was used to measure environmental conditions, personal control, occupancy, and thermostat interactions. This data-driven approach was followed by surveys to understand and baseline occupants' perceived control over the thermal environment and further understand the usability of the heating system. The results from these two methods of data collection were analyzed to understand potential barriers to usability that may be impacting perceived control.

Phase 2 involved the development of several features that aim to address the potential barriers to usability found in Phase 1 and informed by the broader scientific literature. The revised thermostat features aimed to improve the feedback given to people regarding the operation of their heating system. Phase 2 also included the technical development and implementation of the features, which required processing HVAC operational outputs from the BAS and displaying the relevant information through the interface. These features included communicating current HVAC information, when scheduled setbacks were in effect, and future time-to-temperature estimates to office occupants, the latter of which required data-driven room level modelling.

Phase 3 aimed to gain feedback and assess the performance of the implemented thermostat features. To do this, the same techniques applied in Phase 1 were used to assess the control system performance to ensure there were no significant differences between the pre-implementation and the post-implementation so that any user perceived changes could be identified as such. The operation of the implemented thermostat features was monitored to ensure they performed as expected. Finally, surveys were then used to obtain feedback regarding participants' satisfaction with the implemented features.

This project took place over two heating seasons, occurring in the winters of 2018-2019 and 2019-2020. Due to timing and scope limitations, this thesis does not focus on the cooling season. During the pre-implementation phase (2018-2019), the heating season of this year lasted approximately from mid-October to mid-March. During mid-January to mid-March of that year, the control system was temporarily modified for another research project, which was intended to save energy without affecting occupant comfort. Since the purpose was to measure the typical control system operation, the pre-implementation assessment only includes mid-October to mid-March.

During the development of the time-to-temperature model, a training data set and validation data set were used. The training set was the same period used for the pre-implementation analysis of the control system during the 2018-2019 winter, and the validation set was the same months in the 2019-2020 winter.

The developed features for the thermostat were implemented in the following heating season (2019-2020) on February 10th. While the updated thermostats remained in place until early April, Carleton’s work from home policy as a response to the coronavirus disease of 2019 (COVID-19) took place on March 16th, making March 15th the official end of the test period.

In the post-implementation analysis, the heating system performance of the 2018-2019 and the 2019-2020 winter were compared to identify any differences. For this analysis, the entire heating season between approximately October 25th and March 25th was used for each year. Shown in Table 3.1 is a summary of all the time periods and will be referenced throughout this thesis.

Table 3.1 Summary of the analyzed time periods

Date and Duration	**Associated Analysis**
October 15th, 2018 – January 15th, 2019 (3 Months)	Pre-Implementation assessment of the heating control system performance and time-to-temperature training
October 25th, 2018 – March 25th, 2019 (5 Months)	Full heating season as perceived by the occupants
October 25th, 2019 – March 25th, 2020 (5 Months)	Full heating season as perceived by the occupants
October 15th, 2019 – January 15th, 2020 (3 Months)	Time-to-temperature validation
February 10th, 2019 – March 15th, 2020 (3 Months)	Testing period for the thermostat

3.2 Building and office level HVAC description

3.2.1 Building description

The analysis, implementation, and survey data were all completed using 25 offices of an institutional building in Ottawa, Canada. The offices are single occupancy and used by university professors. The offices are nearly identical in footprint and orientation, with a window located on the only wall exposed to the outdoors, on the north-east oriented façade. The only exceptions are two corner offices, which have an additional window on the north-west façade. The building was recently constructed, with occupancy beginning in May of 2018.

During the construction of these offices, extensive building sensors were installed to study building control, occupant behaviour and building operation. While researchers were heavily involved with the specification of sensing equipment, they intentionally were not involved in designing the HVAC control logic. The building HVAC control logic is therefore considered to be representative of typical industry implementation. A photograph of the office layout is shown in Figure 3.2. The thermostat can be seen on the right.

Figure 3.2 Photo of one of the offices, showing the thermostat.(immediately above the door handle)

3.2.2 Data collection

The building HVAC system is controlled through a centralized building automation system (BAS). All the continuous data (e.g., room air temperature) was collected in five-minute time intervals, and all event-based data (e.g., from motion detectors) was collected based on the change of value (COV) by the BAS and data archiver. This data was securely uploaded onto a cloud storage device for analysis. With ethics clearance, this unobtrusive method of data collection allowed for the studying of room performance and occupant behaviour to be done without the occupants' knowledge, meaning the Hawthorne effect is not a concern. The Hawthorne effect refers to the change in behaviour of individuals in a study based on their knowledge that they are being observed. Table 3.2 shows the list of sensors used in this study.

Table 3.2 List of room level sensors

Parameter description	**Collection frequency**	**Unit**
Blind position	Change of value (COV)	(%)
Time and date	5-Minutes	(date and time)
Illuminance (measured at three different depths away from the window)	5-Minutes	(lx)
Indoor carbon dioxide concentration	5-Minutes	(ppm)
Indoor relative humidity	5-Minutes	(%RH)
Indoor air temperature	5-Minutes	(°C)
Lighting state	COV	(%)
Motion detector on thermostat panel	COV	(on/off)
Motion detector in ceiling	COV	(on/off)
Outdoor air Temperature	5-Minutes	(°C)
Radiant heater flow rate	5-Minutes	(L/s)
Radiant heater inlet temperature	5-Minutes	(°C)
Radiant heater outlet temperature	5-Minutes	(°C)
Radiant heater valve position	5-Minutes	(%)
VAV Reheat coil flow rate	5-Minutes	(L/s)
VAV Reheat coil inlet temperature	5-Minutes	(°C)
VAV Reheat coil outlet temperature	5-Minutes	(°C)
VAV Reheat coil valve position	5-Minutes	(%)
Return air temperature	5-Minutes	(°C)
VAV airflow	5-Minutes	(L/s)
VAV supply air temperature	5-Minutes	(°C)
Window state	COV	(open/closed)

3.2.3 Description of the room level heating system operation

The HVAC system in these offices uses a combination of a variable air volume (VAV) system and hydronic perimeter heating to condition the space. Each office has an individual hydronic heating unit, and the VAV system is shared between two to four offices, referred to as a zone. Shown in Figure 3.3 is a schematic of the heating system. The intended design of the dual heating system was to provide individual room level control based on user-prescribed setpoints; however, when VAV heating is required, each room is heated at approximately the same rate. The ability of this system to provide room-level control is quantified in Section 4.1.

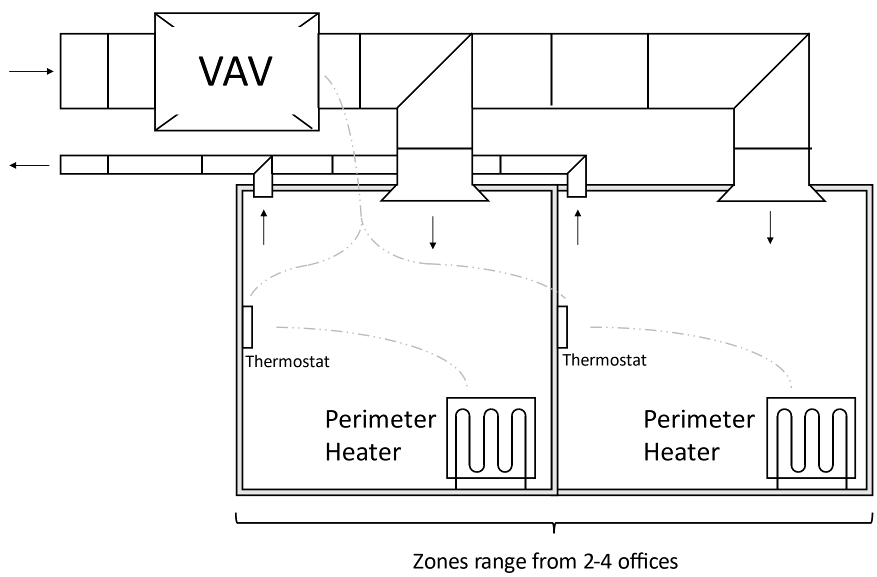


Figure 3.3 Schematic of the room level heating system. As shown, each room is equipped with perimeter heating. The VAV system is shared by between 2 and 4 offices.

Each office is equipped with a wall-mounted thermostat control panel, allowing occupants to control their setpoints. The operation of these thermostats is described in detail in Section 3.2.5. During the heating season, the occupants can request a temperature from 18°C to 24°C, a ±3°C range. Each week, on Sunday at midnight, the setpoint resets to 21°C, unless the setpoint at that time is between 20.5°C and 21.5°C. This measure was implemented by the facility managers and is intended to prevent energy-intensive setpoints during long periods of vacancy.

The rooms are controlled using a simplified proportional-integral (PI) controller. The farther the office temperature is below the setpoint (proportional), and the longer the office temperature is below the setpoint (integral), the more the control system considers the room to need heating. When heating is required, depending on the need (as determined by the PI controller), the system will switch on the perimeter heating or use the VAV system and the perimeter heating simultaneously to heat the office.

The VAV system receives air from the air handling unit (AHU). This air is typically provided at 18°C in the heating season. When no heating is required, the VAV system runs at its minimum flow, with no reheating of the air. When VAV heating is needed, the VAV flow is increased, and a hydronic reheat coil controls the VAV supply air temperature between 18°C and 35°C, based on the PI control input. The VAV system design flow is sized to provide a similar flow to each office and is therefore scaled depending on how many offices are in a given zone. The minimum flow provides approximately 30 L/s to each room, and the maximum flow provides 70 L/s to each room.

This building is equipped with scheduled temperature setbacks. In the evenings and weekends, the VAV system provides no heating or ventilation to the rooms, and the hydronic heating is only operated by the control system to keep the temperature above 18 °C. During this scheduled setback, the indoor air temperature can float away from the user-prescribed setpoint, even though, in some cases, the offices are still occupied.

During the 2018-2019 heating season, the scheduled setbacks operated outside of what was considered “occupied hours,” between 6:30 am to 5:30 pm Monday to Friday. Prior to the 2019-2020 heating season, due to occupant complaints, facilities management changed this schedule to 7 am to 10:30 pm seven days per week.

Very little documentation existed regarding the control system operation, so a review of the logic as coded into the building controllers was performed to understand the HVAC control scheme. Due to the researcher’s involvement with the sensor implementation in this building, sensor names were consistent between rooms; however, this is not typical of most BAS.

3.2.4 Known control system issues

Errors in programming and faulty hardware in buildings are generally understood to be common occurrences affecting both comfort and energy. Due to its recent construction, this building is still in its commissioning phases, meaning that increased faults can also be expected. These issues were reported to facilities management; however, they were not corrected during the time period of this study. Table 3.3 shows the list, description, and implications of these issues.

Table 3.3 List of observed issues.

Issue	Description	Implication
VAV flow primarily operates in cooling mode regardless of season for all rooms	When the VAV is in heating mode, it is designed to increase flow between its minimum flow and its maximum flow based on the PI controller when heating is required. Conversely, in cooling mode, the flow increases when cooling is needed in the room. The modes change based on the AHU temperature; however, the AHU temperature does not exceed the threshold required to switch into heating mode at any point in the heating season. The reason for the discrepancy between the AHU setpoint temperature and the chosen heating threshold for the VAV is unknown	Low flow when heating is required caused slower heating rates than what the designer intended.
Water flow is measured at the hydronic heater when the valve position control signal is set to 0%, or fully closed	When heating is not required in this room, the control system sets the valve position to 0%, or fully closed. During this time, no flow should be measured through the radiator; however, flow is still measured at close to its maximum flow rate.	Heating occurs through the hydronic heater in this room even when no heating is needed, affecting performance and likely affecting perceived control. This room was included in the pre-implementation and post-implementation analysis of the control system. None of the survey responses came from this room.

3.2.5 Wall-mounted thermostat control panels

The wall-mounted thermostat in each office was selected by researchers based on its flexibility and functionality. The thermostat control panels have no internal logic, and instead, act simply as a sensor array and input device for the building automation system. This differs from thermostats people are familiar within their homes, where the panel acts as both an input device and a controller with internal logic. The product manuals provided by the manufacturers describe these devices as a network sensor with a customizable button overlay to adjust individual comfort. However, the terminology thermostat or thermostat control panel will be used interchangeably throughout this thesis to be consistent with existing literature and terms commonly used in the industry.

A photo of the thermostat control panels is shown in Figure 3.4. The company which manufactures these thermostats offers approximately 100 faceplate variations with different button layouts. Programming of the thermostat is done using the building automation system. The digital display is designed with specific display information in mind; however, it can be programmed to display anything within the flexibility of the LCD screen. The thermostat control panels are also equipped with a backlight. This backlight can be displayed at any brightness between a minimum and a maximum level and can also display any colour using an RGB input. The existing design significantly limited changes made to this thermostat control panel, but the panel was determined to be flexible enough for the purposes of this project.

The existing wall-mounted thermostat control panels tie into the building automation system and allow people to set their temperature preferences in the form of setpoints, turn their lights on and off, adjust the light brightness, and control the level of their blinds. The thermostat features six buttons; the names for these buttons starting from the top left are eco mode toggle, occupancy toggle, information scroll, blind adjustment, temperature adjustment, and light adjustment. Below the buttons and display is a continuous adjustment toggle with a plus and minus button on each side. As shown in Figure 3.4, these will be referred to as the minus button, slider, and plus button. The large number on the display (line 1) is the current indoor air temperature and remains there regardless of the buttons pressed. The smaller number (line 2), is displaying the indoor air temperature setpoint on the figure shown, and changes as various buttons are pressed.

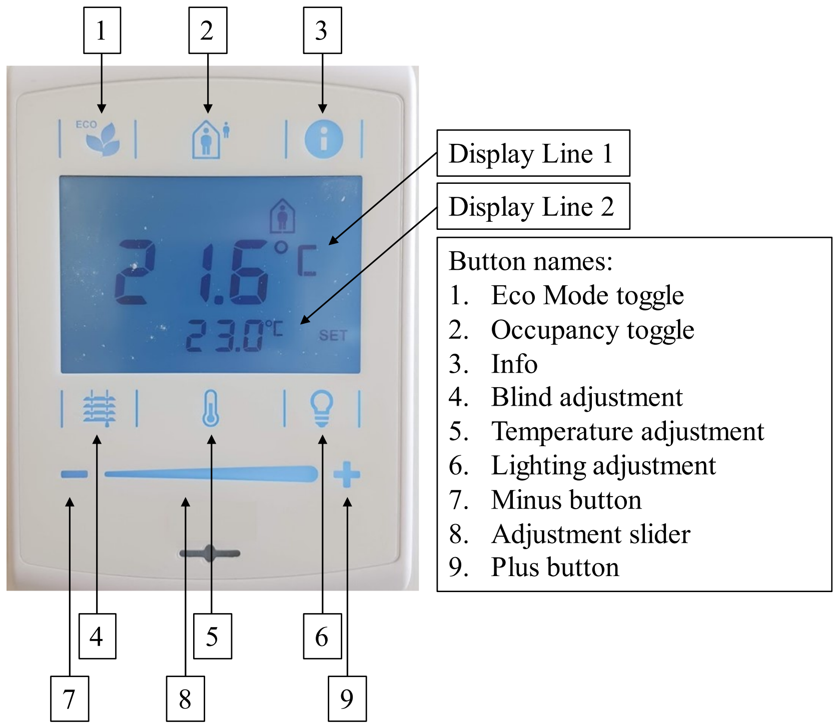


Figure 3.4 Photo of the thermostat interface in the offices. The interface is shown is in "thermostat mode" and shows the current indoor air temperature on display line 1, and the setpoint on display line 2.

To adjust the various visual and thermal comfort settings, users can press either the blind adjustment, temperature adjustment, or light adjustment buttons to activate the corresponding mode. When this happens, the current setting appears on line 2, for example, Figure 3.4 shows the thermostat state after the temperature adjustment button is pressed, and the indoor air temperature is shown in °C. Occupants can then press the plus or minus buttons or slide their finger along the slider to adjust. When this happens, the "SET" (as shown in the figure) appears to indicate that the setting has been set, and no further button presses are required. The same process occurs for blind adjustments; however, the number shown on line 2 will be between 0%, indicating that the blinds are fully retracted and covering none of the windows, and 100% indicating that the blinds are covering the full window. For light adjustments, repeatedly pressing the light adjustment will toggle the lights between OFF (0%) and the previous ON setting. If the previous ON setting was over 50%, the light setting will round down to 50%. This is meant to be an energy-saving measure. Alternatively, after the light adjustment is pressed, the user can use the slider or plus buttons to set the light levels between 0% and 100%.

The eco mode toggle feature toggles a leaf to appear on the top left of the thermostat display, and currently has no effect on the control system. Similarly, the occupancy toggle currently does nothing, and the corresponding symbol of the person in the house on the thermostat is continuously on, regardless of occupancy, thermostat interactions, or control system operation. The inclusion of these buttons was selected for future purposes; however, currently, these buttons have no impact on the control system, and the purpose of the feature is not well defined in the documentation. Finally, the info button cycles through various displays. The first press activates the backlight, without causing any other changes to the display, while any button presses after that cycle through the following information, which is displayed on line 2 of the thermostat: outdoor air temperature, indoor humidity, indoor CO_2 concentration, and backlight brightness. When occupants have toggled to the backlight brightness, they have the ability to adjust this between 0% and 100% using the plus, minus buttons, or slider, similar to the other setting adjustments. After one minute of inactivity, the thermostat resets and goes to the light mode by default. This means that if an occupant's first interaction is with the light button, it will toggle the light on or off, in the same way that it would in light adjustment mode.

After a setting is adjusted, aside from the new setting being displayed, there is no feedback from the thermostat that would indicate that a setting change was successful. For lights and blinds, the effect is nearly immediate, unless the systems are not operating as expected. For setpoint changes, the only form of feedback through the thermostat is the indoor air temperate reading, which is displayed to the nearest 0.1°C. Due to the inherent delay in thermal response, there is a delay between when the setpoint is changed and when the thermostat displays a change in temperature. The length and implications of this delay are explored in Section 4.1.

These thermostats are provided for people to use without any instructions regarding how to operate them. In the pre-implementation survey, some participants left comments which mentioned this lack of an instruction manual, noting that they were unsure of the thermostat's full capabilities.

3.3 Survey administration

Two surveys were conducted during this research, a pre-implementation survey and a post-implementation survey. In both cases, the survey responses were used both for research purposes and for facilities management in charge of operating the test building. The questions were developed in conjunction with facilities management goals. Facilities management distributed the surveys to all 25 offices studied using email. The surveys could be filled out online at the participant's convenience within three weeks after the original send date. One week before the final day for completion, a reminder email was sent.

Based on the recommendations from Robson's and McCartan's book, Real World Research [54], several techniques were used to maximize response rate and accurate answers. Personal questions were avoided, with the exception of obtaining the office number to cross-reference with the data collection. Efforts were taken for wording to be simple and non-technical, to keep participants from feeling the survey was beyond their expertise. For example, questions were asked about satisfaction with the temperature, use rather than satisfaction with thermal comfort. The survey was administered through Google Forms, which is likely a familiar and easy to use platform. It was created using the university colour scheme and branding and was designed to appear visually pleasing and professional. An additional recommendation from Robson's and McCartan's book suggests that questions should be structured with interesting questions at the beginning to initiate interest, more specific questions in the middle, and finishing with an interesting question to promote participation in further surveys. Each survey started with questions about overall comfort in their offices, and it is suspected that due to the partnership with facilities management, participants' ability to communicate their issues would be a motivator for filling out the survey. The question design for each implementation will be detailed in Section 4.2 (Pre-implementation survey) and Section 6.3 (Post-implementation survey).

3.4 Ethics clearance

Ethics clearance was obtained from the Carleton University Research Ethics Board for data collection, thermostat modifications, and surveys conducted throughout this research. Based on the clearance, the name of the building was not included in this thesis and is just referred to as an institutional building in Ottawa, Canada. For the data collection and modifications to the control system, it was determined that the impact on the office users was low, particularly as the data was in most cases aggregated between the 25 offices before being presented. Therefore, no consent was required by the occupants to perform that BAS related aspects to this research. This avoided concerns about the Hawthorne effect, for both this and future research in the building.

For the surveys, express consent was obtained from the participants before using the results for research purposes. Since the surveys were also an opportunity for occupants to provide feedback to facility management, people were given the opportunity to choose to opt-out of the research part of the surveys and still have their results sent to facilities management. For both surveys, participants who consented to allow their answers to be used for research were offered a small incentive. The incentives of $10 for the pre-implementation survey and $20 for the post-implementation survey were provided as Amazon gift cards and were administered by email.

Chapter 4: Phase 1 - Pre-implementation

This chapter covers Phase 1, which occurred before any changes were made to the interface operation of the building. Included in Section 4.1, is a thorough assessment of the control system in relation to the thermal environment and controllability in the room. Following this assessment, a survey of building occupants to assess perceived comfort, perceived control, and satisfaction with their office control systems was conducted and covered in Section 4.2. These two methods were to be used to baseline comfort and controllability, as well as determine suspected barriers to usability in these offices. Barriers were reported and used to inform the features in the updated interface developed in Phase 2.

4.1 Analysis of control system within the context of perceived control

4.1.1 Setpoint control

This analysis aims to investigate control individuals have over the environment, which is expected to have an effect on both perceived control and thermal comfort. Given that individuals control the setpoint temperature (within the permissible range), the focus of this metric is the ability of the control system to regulate the indoor air temperature to the setpoint temperature. As exact control of the air temperature is not possible; this study considers thresholds of ±0.5°C and ±1°C from the setpoint.

The data collected from the 25 offices was aggregated for this analysis. The indoor air temperature and deviations from setpoint were investigated in each individual room and then combined. Figure 4.1 shows the results of this analysis and includes the three months of collected data. Since the building systems do not attempt to regulate the temperature during setback periods, the scheduled setbacks were excluded from this analysis. The office temperature was within 0.5°C of the setpoint 54% of the time and within 1.0°C 78% of the time.

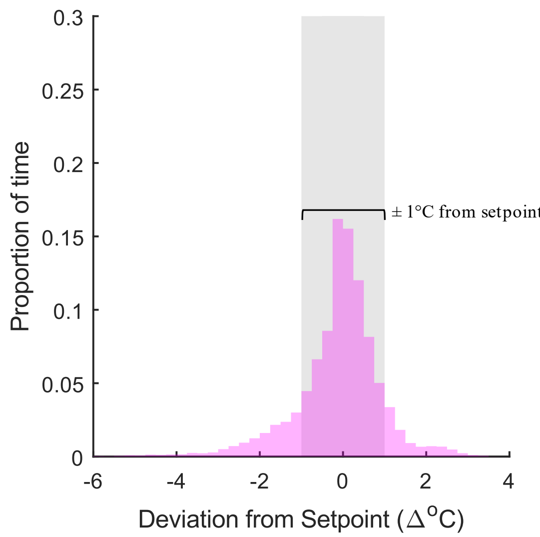


Figure 4.1 Aggregated office indoor air temperature deviation from the setpoint temperature. The times where setback temperature was in effect were excluded from this analysis. October 15th, 2018 – January 15th, 2019.

With no known standards or guidelines regarding the rooms' ability to control the temperature, it is difficult to establish the acceptability of this setpoint control. However, three major causes of prolonged periods of poor setpoint control were identified, which likely add to a case of low perceived control in the offices.

Case (1) occurs as a result of zoning in the building. Due to the shared VAV systems among zones, the system can not always regulate the temperature based on the room setpoints when there is a significant difference in heating demand in offices within a single zone. This difference in heating demand can happen for several reasons, such as varying occupancy, equipment use, and opening windows. Importantly, actions taken by an individual in one room can affect the setpoint deviation in the other rooms in the zones. A common and easily measurable example of this is when there were different setpoints between two or more rooms within a zone. Shown in Figure 4.2 is the same analysis when there is a greater than a 2°C difference between the setpoints of offices within the same zone. A drastic decrease in performance is observed. On average, the setpoint is controlled within ±0.5°C 23% of the time, and within ±1°C 46% of the time.

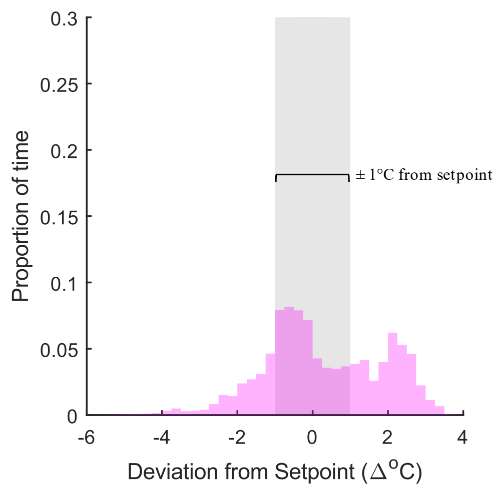


Figure 4.2 Aggregated deviation from the setpoint temperature at times when the differences between the setpoints in between two or more rooms in a zone are great than 2°C. October 15th, 2018 – January 15th, 2019.

As an example, Figure 4.3 (a) shows two adjacent offices in the same zone, where the relatively higher setpoint of the first office causes the second to overheat. In general, Case 1 explains the high frequency of setpoint deviation of approximately 2°C above the setpoint observed in Figure 4.2.

Case (2), as shown in Figure 4.3 (b), occurs when the HVAC system is not able to meet the heating needs of the room. In these cases, both the VAV system and the hydronic perimeter heating are acting at their maximum design capacity. This typically happens when the outdoor temperature is below -10°C; however, it depends on a combination of outdoor air temperature, thermal gains, and HVAC operation. This issue, along with Case (3), was the primary reason for the portion of time the temperature is lower than the prescribed temperature. While this is not directly related to high zone differential setpoints, differential setpoints of 2°C are typically caused by higher setpoints, which are harder to attain by the control system. This contributes to the large drop in performance when the zone setpoint differential is high.

Case (3), as shown in Figure 4.3 (c), is a prolonged period of poor setpoint regulation due to the VAV system schedule. Due to setback scheduling, the VAV provides no heating prior to 7:30 am, and the hydronic perimeter heaters are only used to regulate the temperature above 18°C. At 7:30 am, the VAV system is turned on, and the offices act similarly to a setpoint change. The building responds slowly, sometimes taking until noon to reach the setpoint threshold. This issue occurs regardless of zone temperature differential, but the building takes longer to reach higher setpoints.

These cases reveal how setpoint control is affected by temperature preferences, outdoor weather conditions, how neighbouring offices are used, and energy-saving features of the BAS system. These factors are likely not understood by the occupants and represent a significant barrier to perceived control.

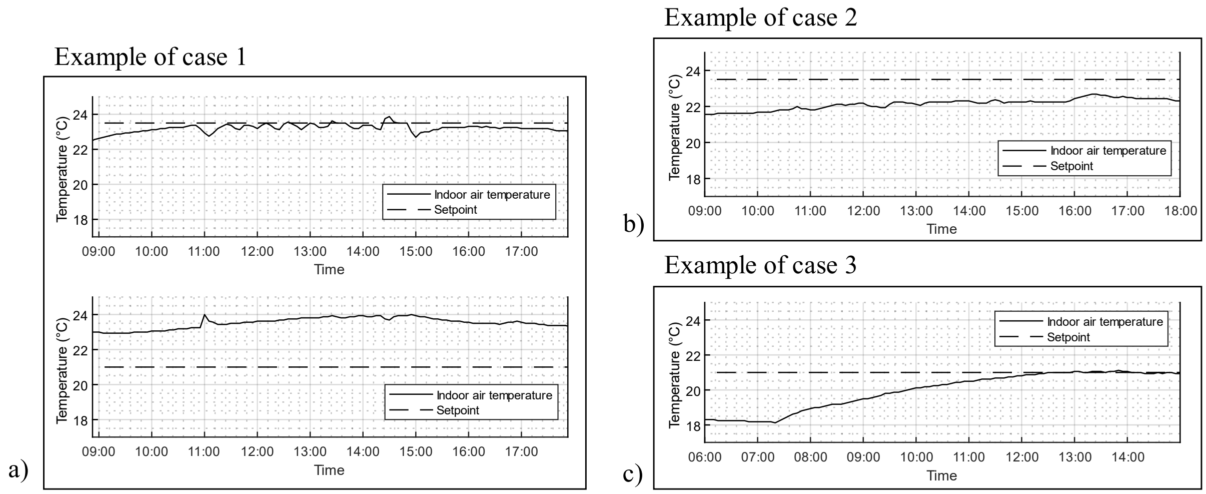


Figure 4.3 Examples of three major causes of prolonged periods of poor setpoint control.

4.1.2 Setpoint response

The lagging thermal response of such systems to setpoint changes is a key usability factor of personal thermostats. Typically, people interact with their thermostats in times of discomfort; therefore, the control system should be able to respond fast enough to alleviate this discomfort [12]. While this is acknowledged in the literature, there is little guidance regarding what is acceptable and little information about what is common. For this building, the time for the control system to reach the setpoint after an adjustment made by the occupant was measured. The setpoint response time is defined as the length of time from when an individual adjusts the setpoint to when the temperature reaches within ±0.5°C of the setpoint. The setpoint change is only considered a success if it is reached before the scheduled setbacks are in effect (5:30 pm). The results are binned into three categories: the setpoint was reached, the setpoint was not reached before the scheduled setback, and the occupant changed the setpoint before the previous setpoint was reached. Table 4.1 shows the results. The results show users made more than twice as many setpoint increases as decreases. This is because the setpoints reset to 21°C each week, and many occupants adjust it to a higher setpoint sometime after this reset.

Table 4.1 Binned results of setpoint changes during the pre-implementation period. October 15th, 2018 – January 15th, 2019.

	Total Setpoint changes	Setpoint reached	Setpoint not reached	Setpoint changed before reached
Setpoint increases	98	62 (63%)	25 (26%)	11 (11%)
Setpoint decreases	44	37 (84%)	6 (14%)	1 (2%)
Total	142	99 (70%)	31 (22%)	12 (8%)

Figure 4.4 plots every setpoint change for all 25 offices in the pre-implementation field based on the difference between the setpoint and the indoor air temperature at the time of the setpoint change. Linear regression was used to characterize response time. By this measurement, the room takes approximately 83 min/°C to respond to an increased heating setpoint, and 53 min/°C to respond to a decreased heating setpoint. Viewing the response time in this way is important, as this is the only information immediately available to users through the thermostat as they adjust the setpoint. However, it is clear that other factors play a significant role, as the linear coefficient of determination is 0.41 and 0.05 for setpoint increases and decreases of respectively. Therefore, when occupants decrease their setpoint, the information provided on the thermostat (i.e., setpoint and indoor air temperature) gives them almost no indication of how soon they can expect their preferred temperature, if at all. Even for setpoint increases, heating by 1°C can be as fast as five minutes and as slow as three hours.

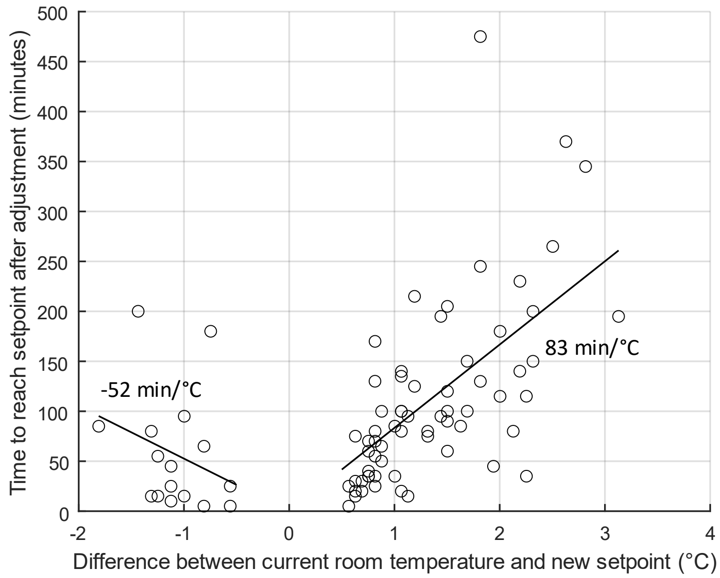


Figure 4.4 Setpoint response time after adjustment for all 25 offices. October 15th, 2018 – January 15th, 2019.

Due to the high variance of setpoint responses, multiple variable linear regression (MLR) was used to understand further the effect of outdoor air conditions and control system operation on response times. Three groups of parameters were considered. Group 1 only considers the difference between the setpoint and current IAT. This is relevant as this is the only information displayed to users through the thermostat interface. Group 2 includes the outdoor air temperature and the illuminance readings from the room sensors, which are used as a proxy for thermal gains. The limitations of using illuminance as a proxy for thermal gains are further explored in the development of the time-to-temperature estimations (Section 5.2.3). Occupants may have a sense of how the outdoor conditions affect the indoor environment, but likely are unaware of its full effect. Group 3 considers how the HVAC system reacts to the setpoint change (measured 15 minutes after setpoint change). Table 4.2 shows a summary of these cases, and Figure 4.5 shows the coefficients of determination of the three cases for both increasing and decreasing setpoint changes.

Table 4.2 Parameters used in multiple linear regression for setpoint response times

Description	Parameters considered	Description
Setpoint difference	Setpoint, indoor air temperature	Difference between the SP and IAT
Outdoor conditions	Outdoor air temperature, light intensity	Outdoor temperature and solar gains
Heat system status	Radiator valve position, VAV airflow, VAV supply air temperature	Hydronic radiator and VAV system current operation status

Since the control system is in heating mode, the way in which the control system reacts to an increase in setpoint is predictable based on the deviation from the setpoint. While outdoor conditions provide some context, the capacity of the VAV system dominates the effects of outdoor weather conditions. For this reason, adding context regarding the outdoor conditions or the heating system status only increases the coefficient of determination from 0.41 to 0.47. When the setpoint is decreased since there is no active cooling, the rate in which the room cools down depends heavily on the outdoor conditions. It also depends heavily on how the VAV system is operating, as it may continue to operate in heating mode to meet the requirements of other rooms in the zone. For this reason, adding this context increases the coefficient of determination from 0.05 to 0.44. In phase 2, a more sophisticated gray box model was developed and used to present time-to-temperature predictions for building occupants.

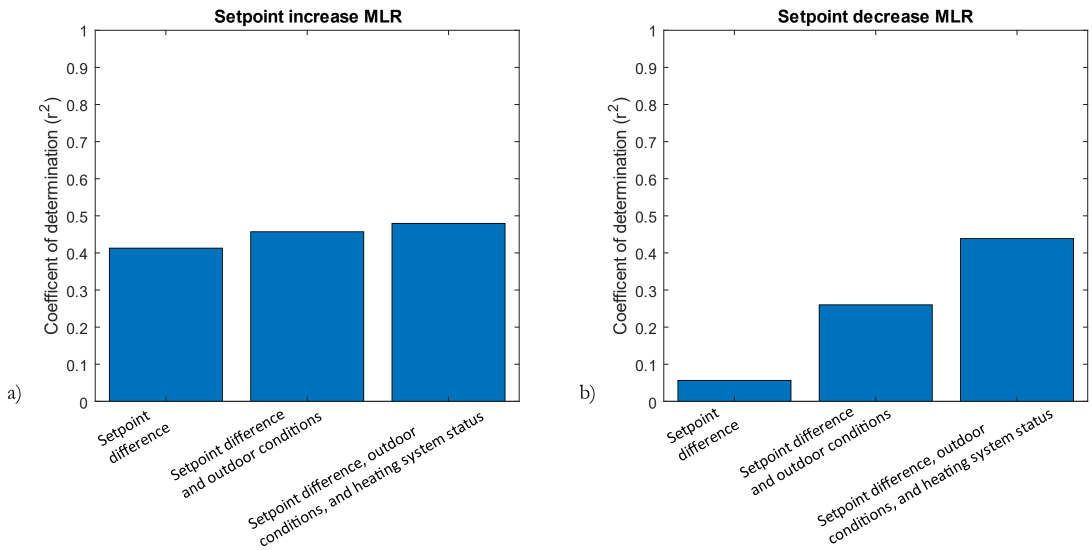


Figure 4.5 Multiple linear regression of setpoint response time for setpoint increases or decreases. October 15th, 2018 – January 15th, 2019.

4.1.3 Schedules and occupancy

As described in the description of the room level heating system (Section 3.2.3), during the evenings, nights, and weekends the system does not attempt to reach the user prescribed setpoints but instead only uses the radiators to prevent the room from dropping below 18°C. Figure 4.6 shows the aggregated weekly occupancy distribution compared to the current setback schedules. The schedule captures 91% of occupied hours within the regular HVAC operation; however, some people stay past 5:30 pm during the week and/or are in on weekends, leading to occupancy during times of scheduled setbacks.

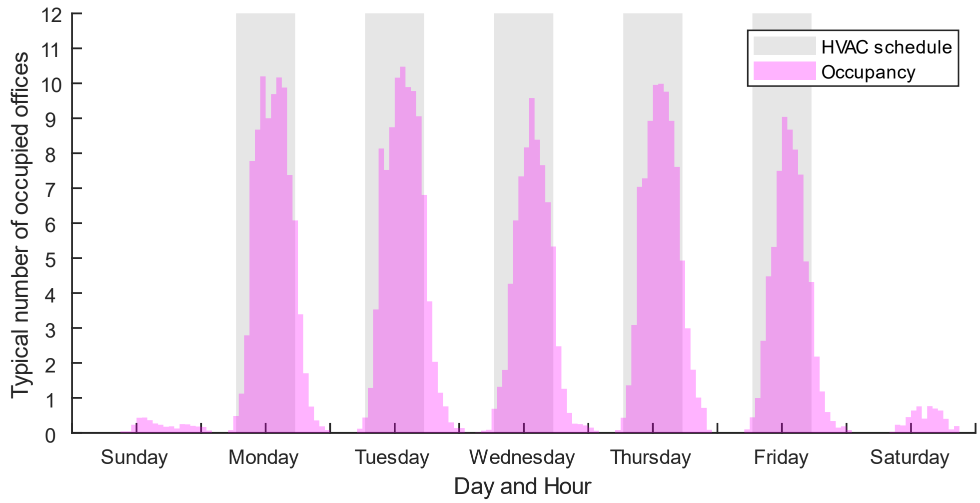


Figure 4.6 Aggregated weekly occupancy distribution for all 25 offices. October 15th, 2018 – January 15th, 2019.

Evaluating the appropriateness of this schedule involves a balance between energy and comfort, and is beyond the scope of this project. However, the effect on control during scheduled setbacks is significant. Figure 4.7 shows the level of control occupants have during regular work-day hours (8 am-5:30 pm) on the weekend. The time the temperature is within ±0.5°C and ±1°C of the setpoint is 30% and 56% respectively, significantly lower than when the scheduled setbacks are not in effect. During this time, the system would have no response to setpoint changes. Given that these schedules are in no way communicated to occupants, this likely affects the occupants' overall perceived control of their thermal environment.

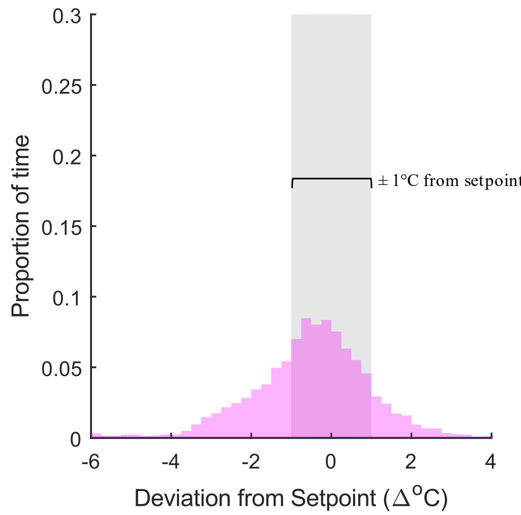


Figure 4.7 Distribution of temperature and setpoint control between the times 8 am and 5:30 pm on the weekend when the scheduled setback is in effect. October 15th, 2018 – January 15th, 2019.

4.1.4 Thermostat use, button presses, and feedback

Button presses were monitored during the entire test period; however, due to technical limitations, the use of the slider and plus/minus buttons was not monitored. Two metrics were developed; the first looks at how many buttons were pressed during an interaction, while the second looks at which button was first pressed during an interaction.

An interaction, in this case, is defined by a period of time where a person is interacting with their thermostat by pressing one or multiple buttons and reading the display. Because only button presses are monitored, these interactions are measured by observing clusters of button presses that occur within a short period of time. Based on observation, nearly all of these clusters of button presses were limited to 2 minutes. Therefore, a two-minute interval was used as the monitoring length to define a single interaction.

The number of buttons pressed per interaction is shown in Figure 4.8. It is important to note that the building has been occupied since the summer of 2018. Therefore, the office users have likely gained some familiarity with the thermostats. Of the 1424 interactions observed, over 77% of them involved only one button press, and 97% of them involved three or fewer button presses. Based on Perry et al. [35] (as discussed in Section 2.1.4), if people take fewer buttons presses to achieve their task, it likely means they find the thermostat easy to use. However, that metric is intended to be used when the task of the user is known, and the success can be measured. It is unknown if individuals achieved their intended tasks during these interactions, and it is also possible that users are uninterested in figuring out how to complete their tasks or intimidated by the interface. This analysis was followed up by asking the occupants directly about the ease of use of the thermostat in the pre-implementation survey, covered in Section 4.2.

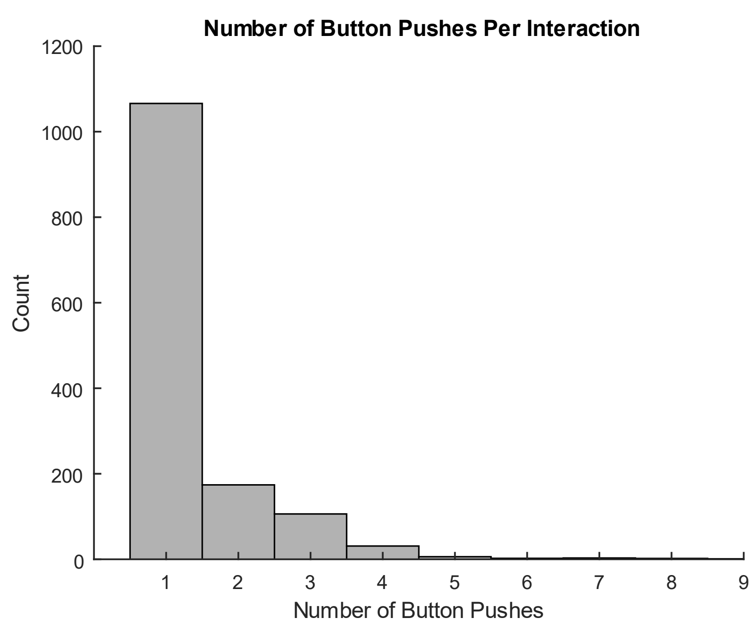


Figure 4.8 The number of button pushes per interaction with the wall mounted thermostat control panel. October 15th, 2018 – January 15th, 2019.

To further understand how people are operating their thermostat, the first button pressed in each interaction is shown in Figure 4.9. People rarely interacted with the Eco Mode Toggle and the Indoor/Outdoor Toggle. It could be that people were unaware of their function, and either did not want to or did not care about interacting with them. It is also possible that people have interacted with these buttons and noticed they had no perceivable effect, and have stopped using them as a result. The light mode, temperature mode, and blind mode make up 53%, 24%, and 12% of button presses, respectively. Interestingly, the info button contributed to 11% of button presses. Upon further investigation, nearly all those interactions were associated with single button presses. When the info button is pressed once, the backlight turns on. By default, the thermostat displays the indoor air temperature and the current light level, so it is likely the office's users are using the single info button press to view this information.

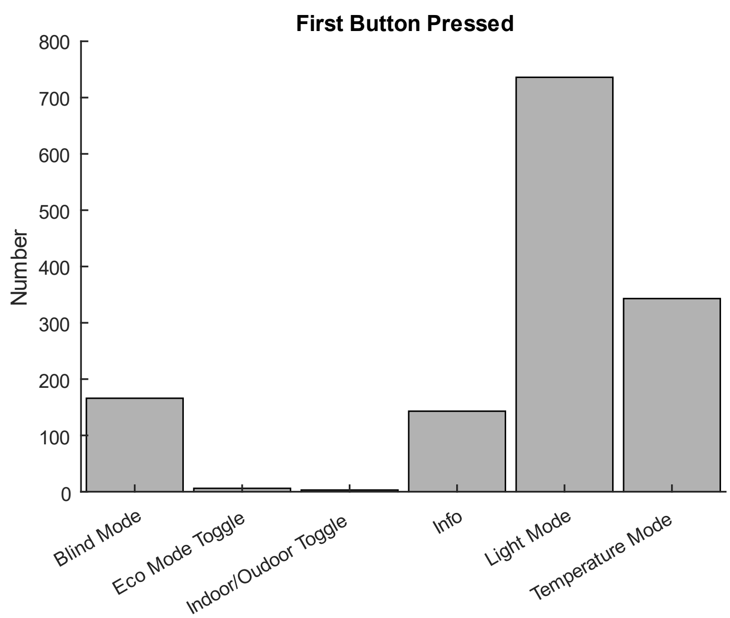


Figure 4.9 The first button pressed in the observed interaction. October 15th, 2018 – January 15th, 2019.

While button presses give insight into how users are instructing with their thermostats, the feedback given by users was also investigated to understand the two-way interaction between thermostats. Currently, there is no indication beyond the effect on the office environment that indicates to occupants how the system is operating. From the perspective of the display, the only indication that individuals could use to recognize that the system is working to their needs is a change of temperature towards their setpoint. Since the indoor air temperature is displayed in increments of 0.1°C, feedback was measured as the time between when the person adjusted the thermostat and when the thermostat displayed a change of 0.1°C towards the setpoint. Since indoor air temperate is measured at 5 min intervals, this can only be analyzed at a resolution of 5 minutes. The results of this analysis are shown in Figure 4.10. In general, 75 percent of the interactions result in this type of feedback within 20 minutes for setpoint decreases, and within 15 minutes for setpoint increases. Sometimes it can take up to 30 minutes for setpoint decreases, and 35 minutes for setpoint increases. This type of feedback is inherently limited to the control system's capacity to affect temperature. Therefore, more immediate feedback through the display would likely reassure people regarding the impact of their control actions.

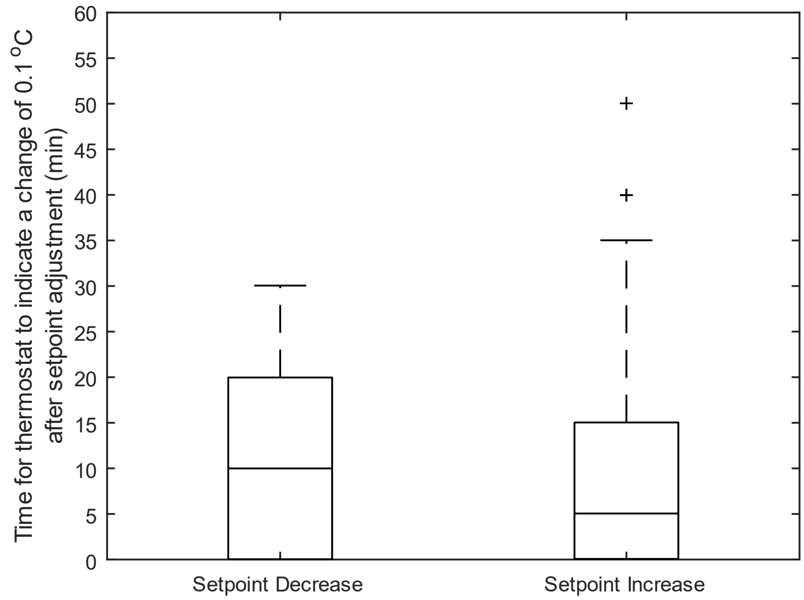


Figure 4.10 Box plot representing the measured time between a setpoint adjustment and the time until a change of 0.1°C was displayed on the thermostat. October 15th, 2018 – January 15th, 2019.

4.2 Pre-implementation survey

Surveys provide valuable insight from participants to better understand their comfort, motivations behind their behaviour, and insights into comfort and usability issues on both the physiological and psychological levels. While the office temperature, and setpoint response, are the result of building operation systems, it is not possible to understand the actual user comfort or intent of button presses without considering survey data. This section describes the survey administered before any changes were made to the building systems. The survey was deployed to understand the comfort, sense of control, and usability issues from the perspective of the users during the heating season. Due to the partnership with facilities management, additional questions were asked based on their request.

The survey was distributed during September of 2019. The timing of this survey represents a limitation of this study, as people were asked to recall their comfort conditions from the previous winter months. Additionally, comfort during the cooling season may have had an effect on their overall perception of building systems.

The results from this survey were analyzed in relation to a data-driven analysis of potential comfort issues to inform design decisions regarding the upgrades to the thermostat, as well as to provide a baseline for future improvements that were to be implemented into the thermostats. The full survey is located in Appendix A. The survey questions are described below.

1. Two questions were aimed to address the occupant's current satisfaction with their thermal comfort in the winter, as well as when times of discomfort occurred. In the analysis of the control system, the ASHRAE Standard 55 temperature range was maintained 94% of the time the setpoint was not active. Based on the standard, this range aims to satisfy 80% of occupants. However, as covered in the literature review focused on thermal comfort (Section 2.1), thermal comfort may be a psychological state of mind, and depend on other factors beyond strictly environmental settings, including the expectation of the environment, adaptive actions, and perceived control. These survey questions were used to provide a baseline for occupant comfort, as well as map comfort to the indoor air conditions and control system performance measured through the building automation system. While the heating season was the primary target of the survey, since it was administered in the cooling season, a question was

asked about overall comfort in the cooling season as the participant's comfort at the time of the survey likely affects their perception towards their offices.

   a. Question 2 asked what their overall satisfaction was with regards to thermal comfort during the cooling season.
   b. Question 4 asked what their overall satisfaction was with regards to thermal comfort during the heating season.
   c. Question 5 asked at what time of day did discomfort arise during the heating season

2. Three questions were used to assess people's perception of the performance of the control system. In the analysis of the control system (Section 4.1), likely barriers to perceived control were identified. These barriers included contextual setpoint regulation, uncommunicated scheduled setbacks, long and highly variant setpoint response times, and delayed feedback from the thermostat. These questions aim to map the participants' perception of the control system onto the measured performance, as well as provide a baseline of perceived control.
   a. Question 6 asked how effective they found their room is at maintaining their setpoint temperature.
   b. Question 7 asked how satisfied they were with the speed at which the building responds to their setpoint changes.
   c. Question 13 asked about the primary reasons people adjust their thermostat. The following reasons were suggested: do they adjust their thermostat never, when they are uncomfortable, based on a setting they

know they like, or have they given up due to a lack of perceived control. Participants could also select other and give their own reason.

3. In Section 2.2.2, Norman and Draper's framework was discussed, which states that better mental models of the system will provide an improved ability to operate systems. One question was asked to assess participants' current understanding of the system.
    a. Question 14 was a multi-part question which asked people to assess the impact of various parameters on the office temperature. These parameters included setpoint temperatures, radiator operation, VAV operation, occupancy, time of day, and the conditions in neighbouring offices.
4. Based on the usability issues found by Karjalainen and Koistien [11] as discussed in Section 2.2.4, several people in those offices were confused when interacting with their thermostat, and in some cases, were not aware of it, or assumed it should only be operated by maintenance employees. To address this, two questions were asked about the ease of use of the current implementation of the thermostats.
    a. Question 15 asked how easy it was to adjust the temperature setting, lighting level, and blind position and the wall-mounted thermostat control panel.
    b. In Question 16, participants were given a picture of the wall-mounted thermostat and asked to answer questions about what the thermostat was communicating.

5. Finally, open ended questions were asked to gain further insight on comfort and usability of the thermostats.
    a. Question 12 asked participants to add any other comments regarding thermal or visual comfort in their office.
    b. Question 17 asked participants for any suggestions or complaints regarding the operation or interface of the wall-mounted thermostat.

In addition to the research-based questions, facilities management also requested additional questions about when discomfort occurred during the cooling season (Question 3), satisfaction with humidity (Questions 8 and 9), satisfaction with air movement (part of Questions 3 and 5), as well as satisfaction with the artificial and natural lighting in the office (Questions 10 and 11).

4.2.1 Results

A total of 10 participants (of 25 possible) both filled out the survey and opted to allow their survey responses to be used for research purposes. All of the participants opted to answer each research-focused question. The only exception to this was question 14. Only seven participants responded to this question, which aimed to assess participants' overall understanding of the heating systems.

Results from the comfort and control portion of the survey are summarized in Table 4.3. Only two of the 10 respondents expressed dissatisfaction with the thermal environment in the winter, with three expressing neither satisfaction nor dissatisfaction. On the other hand, only one respondent expressed satisfaction with the level of control and with the response of the heating system after an adjustment. These survey results map to the measured building performance, as while the building generally maintained standardized comfort ranges, the measured setpoint regulation was found to be contextually dependent, and response times were slow and unpredictable.

Table 4.3 Summary of the pre-implementation survey responses related to satisfaction with the thermal environment and control.

	Overall Satisfaction with Comfort in the heating season	Overall Satisfaction with Comfort in the cooling season	Effectiveness of the thermostat at controlling the temperature to the participant's comfort preferences?	Satisfaction with the speed that the temperature of your office changes after you change the temperature setting on your thermostat?
Very Satisfied / Very Effective	0	0	0	0
Satisfied / Effective	5	5	1	1
Neither	3	2	1	1
Dissatisfied / Poor	1	2	4	4
Very Dissatisfied / Very poor	1	1	4	4

The satisfaction with the thermal environment in the summer was lower than satisfaction in the winter. Therefore, given the timing of the administration of this survey, participants may have had a lower overall impression of their building system compared to if this survey was administered in the winter.

Question 5 asked participants to identify which times of day do they typically feel comfortable, too hot, and too cold, the results of this are shown in aggregate in Figure 4.11. On this question, participants could select as many boxes as they want. The low participant count, combined with the requirement to recall their conditions, make it difficult to draw conclusions. However, it is notable that mornings and weekends correspond to the coldest complaints. As noted in Section 3.2.4, the scheduled setbacks allow the building to get cold overnight and it is frequently slow to respond in the morning. These scheduled setbacks also remove control during evenings and weekends, leading to lower comfort conditions for those who choose to work at that time.

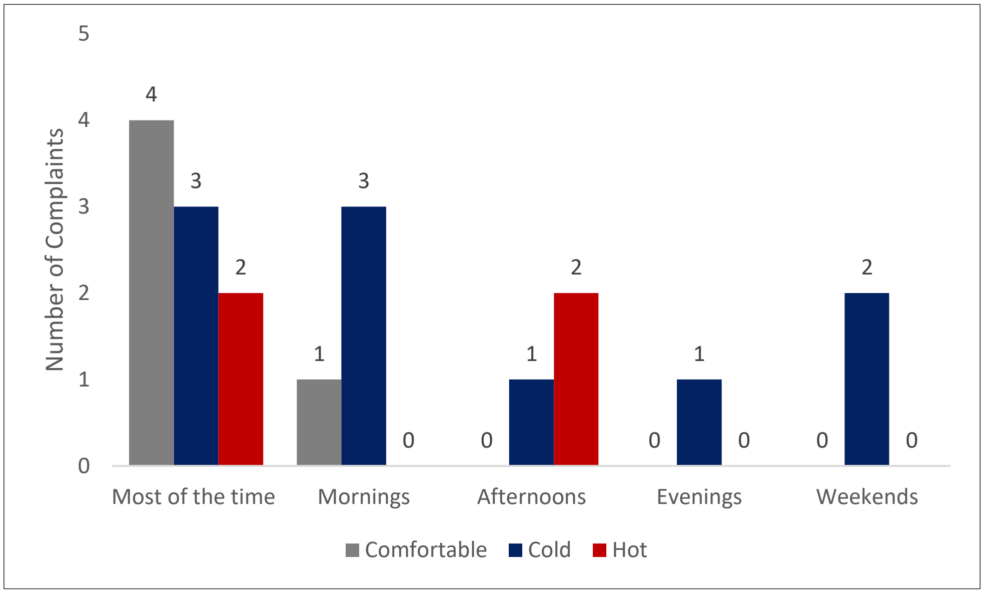


Figure 4.11 Summary of times of the day participants reported being comfortable, too hot, too cold from the pre-implementation survey.

The survey results were cross-checked with the actual conditions of these offices to investigate if the measured temperature was, in fact, hotter or colder than the user prescribed setpoints during the times of complaints; however, no significant correlation was found between complaints and real conditions. One contributing factor to this could be the motivations behind the user prescribed setpoint. Ideally, if people felt that they had control over their system, setpoint preferences could be used as a proxy for a comfortable temperature. However, when participants were asked what motivates them to adjust their thermostat, six out of the ten stated that "(they) have given up on adjusting (their) thermostat as it does not seem to work." Of the remaining participants, two stated that they changed the thermostat only when they felt uncomfortable, and two stated that they adjusted the thermostat both when they feel uncomfortable and when they notice it is not at their preferred setting.

The participants were asked to rate the impact various factors had on their office temperature. The purpose was to assess their understanding of the heating systems. Figure 4.12 shows the results of this question based on the 7 participants who answered this question. Several notable things can be taken from these results. Participants rated their setpoint setting as having a low impact. They rated a significantly higher/lower setting as having more of an impact; however, the median was still quite low at 2 out of 5. This supports the result that users do not feel they have control in these offices. While in Section 4.1.1, setpoint control was analyzed and found to be contextual, the setpoint still has a significant impact on the room's temperature. The building schedule, which activates setback temperatures in the evenings and weekends, appears to be noticed by the participants, as they rated time outside of working hours (evening and weekends) as having a significant impact on room temperature. Another major contributing factor influencing the setpoint control discussed in Section 4.1.1 was the impact of zoning and neighbouring preferences on control. This factor appears not to be perceived by the participants, as the impact of neighbouring offices was rated as having no impact by five out of the seven participants.

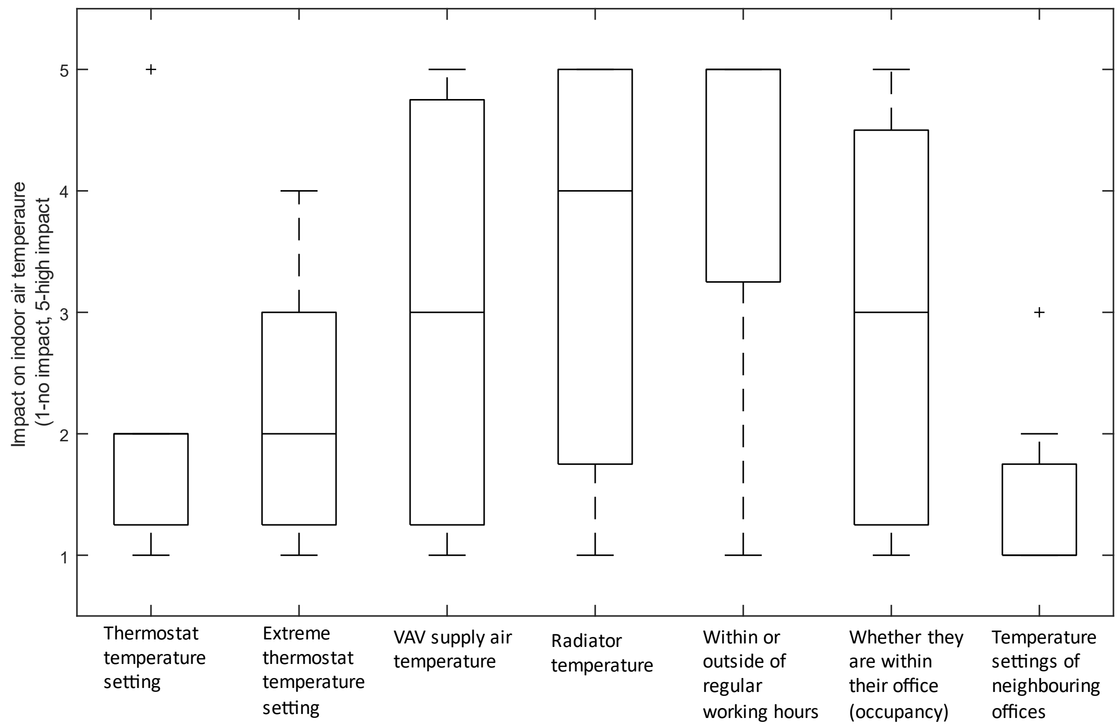


Figure 4.12 A box plot of showing participants' ratings of the impact of various factors on the indoor air temperature of their office from the pre-implementation survey.

Participants were asked to rate the ease of adjusting their thermostat comfort settings. Nine out of the 10 participants rated setting the setpoint as easy, while one rated it as difficult. It should be noted that the person who rated it as difficult also responded negatively to overall thermal comfort, and their ability to control the temperature in previous questions. It is, therefore, possible that this person misunderstood this question and answered it based on their ability to affect temperature. It is also possible that this participant equated the lack of system response to their poor thermal comfort. This question was followed up with an image of the thermostat, and users were asked to identify the measured indoor air temperature, setpoint, and whether there was information displayed regarding whether the system was heating or cooling (not indicated in the current implementation of the thermostat). In all cases, participants successfully identified the indoor air temperature and setpoint. Since in the picture given, the setpoint was higher than the indoor air temperature, three out of the 10 participants stated that the office was being heated. While logical, heating is in no way communicated through the interface, and this answer was not necessarily correct as the system would not heat outside of scheduled times.

The open-ended questions provided further insight into the temperature and thermostat usability issues. The responses are summarized in Table 4.4; only temperature and thermostat related complaints are shown in Table 4.4.

Table 4.4 Open-ended comments from the pre-implementation survey

Issue	Description
Do you have any other comments regarding thermal or visual comfort in your office?	Thermostat is only a placebo
	Last winter my heat register did not work (stone cold) and the only heat comes from having my door open. It worked about 10% of the time.
	I do not have control over my blinds. They are seemingly stuck in their current position. I have been in that office for just over a year (and reported this issue multiple times) but they have never worked. Having the blinds fixed would help optimize both thermal and visual comfort in the office.
	It would be helpful to be able to override the default temperature settings during the early morning, evening, or weekend hours. Since this is a research building, I/we can expect to be in the office at any given time.

Are there any suggestions or complaints you have regarding the operation or interface of your wall-mounted thermostat?	It works fine for controlling the lights and blind in my office. It does not to affect the temperature.
	So far, we have received no training or manuals on how to use the thermostats.
	A "user-guide" on how to use the thermostat would be helpful so that we may take advantage of all the features it comes with
	It works fine for controlling the lights and blind in my office. It does not to affect the temperature.

4.3 Phase 1 Discussion

Phase 1 consisted of two parts, an assessment of the control system in connection with perceived control, and the pre-implementation survey. The assessment of the control system was performed by measuring the performance of the HVAC control system. The analysis included how well the building was controlled to user-prescribed setpoints, how quickly the building responded to setpoint changes, how scheduled setbacks aligned with real occupancy, and how people interacted with their thermostat.

The level of control users had over the temperature was found to be contextual and dropped significantly when the differential between the highest and lowest setpoint was 2°C or higher. The contextual nature of setpoint control is likely not understood by office users. Zoning, in particular, is not communicated to the occupants either verbally or through the thermostat interface. As it has such a high impact on control, it represents a potential gap in the individual's understanding of the HVAC system and likely leads to reduced perceived control.

Adjustments to setpoint changes were slow and highly variable, and the system did not always successfully achieve the setpoint before the end of the occupied day, after which scheduled setbacks took effect. While few guidelines exist, it can be speculated that the slow response times observed in this building do not alleviate discomfort quickly enough or reassure the office users that the HVAC system is functioning as expected or in response to thermostat adjustments by occupants.

No feedback was given to occupants when scheduled setbacks were in effect, even as some offices are still in use. During scheduled setbacks, there was a significant drop in setpoint control as the control system would not react to setpoint changes. Any interactions with the control system during scheduled setbacks likely contribute to poor perceived control.

The measurement of button presses indicated short interactions with thermostats; however, without knowing the intent of the interactions, it is difficult to infer usability. The smallest increment of temperature displayed on the thermostat typically took over 5 minutes to change towards the setpoint after an adjustment. Given that Norman [38] recommended that these types of devices should provide feedback within 0.1 seconds after an adjustment, this adds a possible cause of low perceived control in these offices.

Overall, the survey results support the findings in the analysis of the control system. Results indicated that the participants were overall somewhat satisfied with their thermal conditions; however, they felt little ability to control the room. While some of their complaints were hard to verify, many complaints regarding thermal comfort and control matched what was expected based on the data. It is also notable that with one exception, participants reported no difficulty adjusting their setpoints and were generally aware of the information displayed by the current implementation. This further supports the premise that the primary issues leading to the lack of poor perceived control lie within the control system operation, and not within a lack of knowledge on how to operate the thermostat to set their preferences.

Chapter 5: Phase 2 – Design & implementation

The usability issues found in the assessment of the control system, coupled with the low perceived control reported by the survey participants, situate this building well for improvement. This section will describe the development and implementation of the updates to the existing thermostat design, which aimed to address the identified usability issues. Phase 2 included the conceptual development of the thermostat interface (Section 5.1), development of the technical aspects of the interface (Section 5.2) and implementation of the developed features to the existing thermostat control panels (Section 5.3).

5.1 Conceptual development of the thermostat interface

During the prototype stage of the design processes, the human factors literature recommends an iterative design process alternating between establishing requirements, design alternatives, prototyping, and evaluating performance. The evaluation can involve several techniques and can be narrowed down to three broad groups: controlled settings involving users, natural settings involving users, any setting not involving users.

Due to the access to both the control system data and occupant surveys, the primary goal of this implementation was to test a working prototype in a natural setting with occupants. Based on the time constraints of the project, and the desire to not affect occupant behaviour during the implementation of the design, the iterative process of the design did not involve occupants. Design requirements were established based on the data collected in Phase 1 and were coupled with the expertise of the researchers involved in the project. Facilities management was also consulted and gave comments based on their experience of working with occupants.

While implementing the features into the existing thermostats has the advantage of retaining familiarity with the thermostat, it also imposes significant limitations to the design. The button layout and screen functionality are limited to what is shown in Figure 5.2. The building automation system allows for flexibility in the display configuration of the LCD screen, such that any symbol or number can be displayed at any time; however, the design is still quite limited by screen size and icon placement.

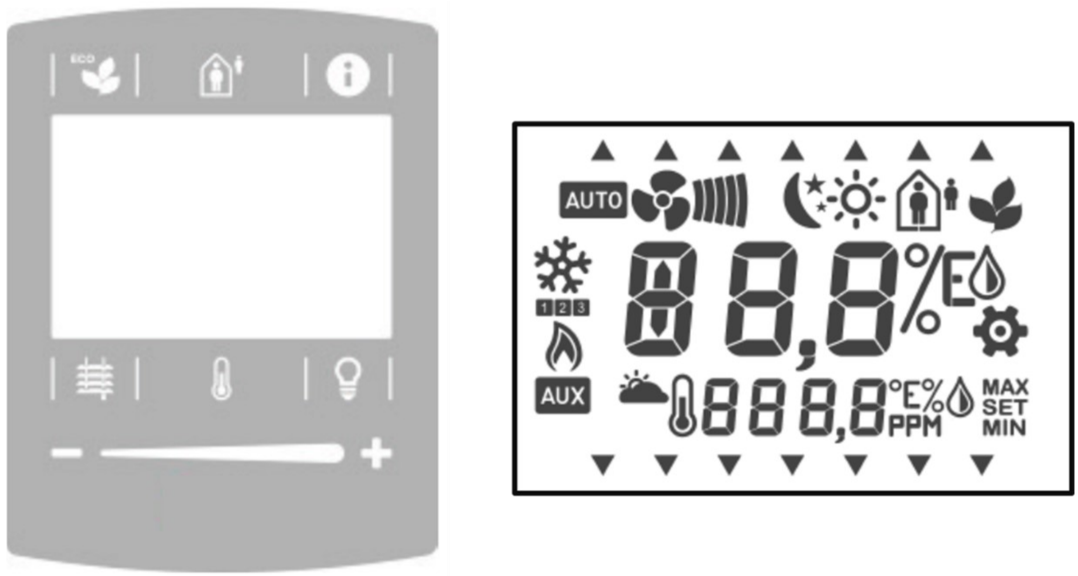


Figure 5.1 Thermostat control panel and the layout of the digital display (Source: Delta Controls Inc, "eZNS Network Sensor Button Overlay Design Guide - Edition 1. 3." 2016, and "eZNS enteliZONE Network Sensor Application Guide - Edition 1.41." 2017. [55], [56]*)*

5.1.1 Framework

The thermostat interface features were primarily developed based on the framework introduced in section 2.2.2. This framework suggested that a gap exists between peoples' understanding of the operation of the system and the actual system operation. Two bridges work in tandem to help bridge that gap, the execution bridge, which describes how individuals are able to give commands to a system, and the evaluation bridge, which is the way individuals are able to perceive the results of their command. An interface that is well designed in both of these areas equips users with functional mental models, which positions them better to use the system effectively.

Given the complexity of the heating system, having room level setpoints as the only means to adjust the temperature is likely misleading, as it does not reflect how the system works in reality (i.e. the execution bridge). However, setpoint adjustments are common to almost all thermostats, and participants in the pre-implementation survey were already familiar with how to adjust the setpoints of the thermostat in their offices. Since the participants in our study were not directly involved in the research, they may not be particularly interested in learning a new thermostat input layout. Additionally, any changes to the setpoint adjustment methods may appear to users as removing features or functionality they may have become accustomed to, which may cause frustration and a negative impression towards the thermostat.

How feedback is delivered through the interface (i.e. the evaluation bridge) was seen as a major gap in the current thermostat implementation, and can help individuals create a functional mental model of the system, leaving them in a better position to interact with their thermostat and overall HVAC system more effectively. To support this, Karjalainen [27] provided evidence that better knowledge of the heating system can increase perceived control. Our updates to the thermostat were designed to communicate the functioning of the system more explicitly in an attempt to address the potential causes of poor perceived control as identified in Phase 1. The potential causes are listed below:

1. The ability of the control system to regulate the indoor air temperature to the setpoint was contextual based on the control system logic and the settings in other rooms.

2. The building was equipped with scheduled setbacks during evenings and weekends such that the building no longer attempts to reach the occupant's selected setpoints. These scheduled setbacks are in no way communicated to the individuals in the offices.
3. The rooms exhibited slow and highly variant thermal responses to setpoint changes, and minimal feedback was communicated to occupants regarding if the control system was working to meet the setpoint.

In addition to the above issues, the upgraded thermostat was also designed to provide fundamental feedback for these types of devices, according to the literature. This included providing immediate feedback to the occupant after they make a setpoint adjustment to the thermostat, and if there is a significant delay between the adjustment and when the desired setting is reached, a time estimate would be provided [37], [38].

5.1.2 Implemented features

The features implemented are summarized in the sections below, and include communicating heating system status information (Section 5.1.2.1), communicating scheduled setbacks (Section 5.1.2.2), and providing time-to-temperature estimations to office users (Section 5.1.2.3). Section 5.1.2.4 provides an example of the operation of all of these features throughout a day.

5.1.2.1 Heating system status

This feature aimed to provide real-time display feedback regarding the HVAC system. This feature was intended to address two issues found in Phase 1; the contextual nature of the setpoint control and the lack of feedback after an adjustment. The HVAC operation is communicated in two ways: 1) the backlight colour changes to represent different types of operation, and 2) the flame appears and displays a number (1 or 2) to indicate which heating system is active. By default, the backlight was set to be activated in a dim state when the occupant is not using their interface and scale up to 100% when they interact with the buttons on the interface. Both of these backlight intensities were adjustable through the interface to support individual preferences.

The colour of the backlight was explored as the primary method to communicate the heating system functions. If the display was white, this would indicate that no heating is active in the room. If the display was red, this would indicate the system is operating to meet the occupant's preference. If the display was yellow, this would indicate that the VAV was heating to meet the needs of another room in the zone. A flame on the display was used as a secondary method to communicate the heating functions and help occupants understand which heating system was currently active. A one above the flame indicated the radiator was on, and a two above the flame indicated that both the radiator and VAV were active.

5.1.2.2 Schedule information

This feature was intended to communicate the lack of control users have during scheduled setbacks. During these setbacks, the building systems are no longer being controlled to their desired setpoint temperature, and are instead controlled to maintain the building at above 18°C. When a scheduled setback is in effect, the passive backlight is switched off, the active backlight colour switches to white, and the word "OFF" appears on the screen. When a user presses the thermostat button, a scrolling text reads "Heating system is OFF," and then displays the setpoint, which users can still adjust so that they can set their preference for the when the scheduled setback is no longer in effect. When the heating system returns to its normal operation, the thermostats revert to communicating the heating system status.

5.1.2.3 Time-to-temperature estimations

The final feature is a display of the time-to-temperature, i.e., the time it will take from the current time and when the indoor air temperature will reach the setpoint. This aims to address the issues of slow, highly variant, and contextual warm-up times identified in Phase 1. The primary goal of the time-to-temperature readings is to display a time estimation directly to the occupants on the thermostat in their office. The purpose is to inform users of the time-to-temperature under two key situations, (1) when the user increases their setpoint, and (2) during the morning warm up time. While these are the primary targets, there may be other times throughout the day that this information is relevant. For example, if a window is open, and the room cools down, the occupant may be interested in how long it will take after the window is closed for the room to heat back up. Time-to-temperature estimations will be displayed as the time it will take from the current temperature until the time the indoor air temperature will reach within 0.5°C of the setpoint. This information will only appear when the temperature is less than 0.5°C below the setpoint, and the scheduled setbacks are not active.

5.1.2.4 Example operation of thermostat features

Figure 5.2 shows an example of the thermostat operation. In Room 1 of this figure, prior to 6:30 am, the scheduled setback is in effect, and the room is not being controlled to the setpoint temperature. When the scheduled setback ends, the VAV opens and provides airflow to ventilate the room with slightly cool air (≈18°C), and the radiator switches on and off to maintain the setpoint. During this period (between 6:30 am and

9:30 am), the user would see the thermostat toggle between red and white, and the number 1, which appears above the flame symbol on the thermostat display, would similarly toggle, to indicate only the radiator is cycling. At approximately 9:30 am, the occupant changes the setpoint from 21 to 24. Based on the control system response to this action, the thermostat turns red (if it was not already), and the number above the flame on the thermostat display turns from one to two. When observing room 2, the radiator is not required to maintain the setpoint temperature, so the thermostat would appear white for the period between 6:30 am and 9:30 am. When the person in room 1 changes the setpoint in the first room, the VAV would activate which adds heat to both Room 1 and Room 2. While the user in Room 2 would not have any increased real control over this situation, at least they are now provided with the information as to why their room is being heated, despite their room already being hotter than their setpoint.

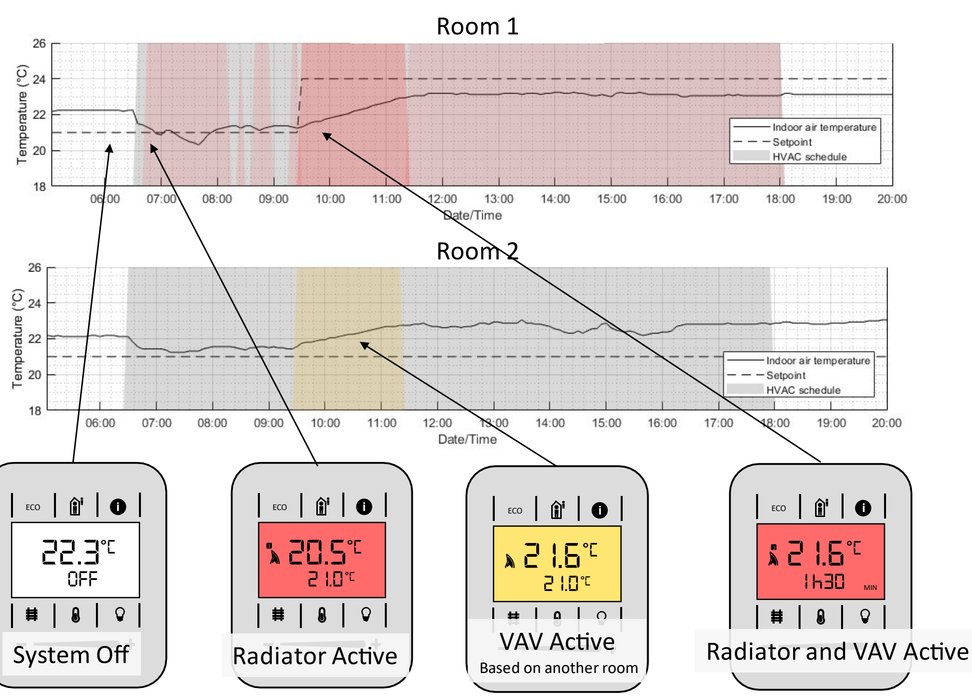


Figure 5.2 An example operation of the implemented features of the thermostat. A one-day snapshot of two rooms that are zoned together and share the same VAV airflow is depicted here.

5.1.3 Instruction manual

While the updates to the thermostat were designed to be as intuitive as possible, due to the limitations of the thermostat interface, it is unlikely that users could fully understand what the updates were intended to communicate without additional resources. To address this, an instruction manual that describes the new features in detail was created in collaboration with facilities management. This resource was emailed out to the occupants of these offices prior to the implementation of the updated thermostats. The instruction manual is located in Appendix B.

5.1.4 Interaction context of thermostat features

Based on the descriptions of interfaces provided by Preece, Rogers, and Sharp [14], thermostat interfaces were defined as an appliance based on the human factors literature review (Section 2.2), where people only have short interactions, and will likely be uninterested in exploring how the system works. The interface should, therefore, be designed with simplicity in mind. As mentioned, the main information recommended by the literature is system status and how long the system will be running for. While simplicity was used as a design principle, the developed features display significant detail as to which heating system is active, and the reason. This has the risk of confusing users; however, the value of adding this context was considered important to reflect the complexity of the control system and support greater transparency about factors which may be contributing to occupant's lack of perceived control.

In the literature review of relevant human factors theories (Section 2.2), cognitive interactions were described and included attention, perception, memory, learning, and problem-solving. In retaining the interface's functionality with regards to various features, the cognitive load to perform tasks such as setpoint changes should be relatively unaffected. The new features were designed to be as intuitive as possible within the context, such as using warm colours like red and orange to signify heating conditions; however, the specific meaning behind the colours presented, or the meaning of the numbers above the flame, are likely not easy to understand immediately. Therefore, to obtain an accurate perception of the features required occupants to rely on reading and understanding the instruction manual. By doing this, the individuals' ability to understand the features would then rely on memory (recall), which likely limits their ability to understand the system in the absence of the instruction manual. This is particularly true for people who are uninterested in reading the manual.

The features are also intended to encourage learning and problem solving by letting occupants change settings and see how the thermostat reacts. During setpoint adjustments, occupants receive immediate feedback after an adjustment so that they can observe how the system behaves in real-time. More broadly, the passive status updates with the changing colours and flame icon, which occurs even when users are not interacting with the thermostat, also allow for people to explore how the system works. This task of understanding the system may require prolonged attention to the thermostat’s status updates. As an example, a person’s room may be overheated due to the VAV operating based on the needs of another room; however, they may not be paying attention (or not in the room, or not in view of the thermostat) when the thermostat is yellow. If they missed this cue, the user would have no way of knowing why their room is overheated. It was determined given the limitation of the interface, and the possible limitation of people’s general interest in the system operation, the implemented features were still the best solution. However, the requirement for people to pay attention to a thermostat's interface to fully understand the room's current state is a significant limitation to this design.

5.2 Technical aspects of the interface features

5.2.1 Heating system status

This thermostat feature displays heating system status through the use of colours and a number above the flame symbol on the display. To achieve this, the real-time heating information from the BAS was interpreted and displayed through the thermostat. A full description of the heating system operation can be found in Section 3.2. To briefly summarize, the system works on a PI control scheme. When a room requires heat as determined by the PI controller, the radiator switches on, and the valve modulates to maintain a difference of 3°C between the inlet and outlet water temperature. The VAV supply air is reheated between the air handling unit supply air temperature, typically approximately 18°C, and the maximum reheat temperature, 35°C, based on the PI input. The designers intended for the VAV flow rate to also increase when heating is required; however, due to coding errors, this does not happen for these offices. Therefore, VAV flow remains constant regardless of the heating needs of the room.

One major design consideration was whether to connect the thermostat output with the control variables or the measured variables. For the radiator, the control variable is the valve position output, and the measured variable is the radiant heat flow. For the VAV supply air temperature, the control variable is the setpoint, while the measured variable is the measured VAV supply air temperature. The advantage to using the control output is that it is quick to respond and acts in a predictable and consistent way. The advantage of using the measured output is that it is more connected to the user experience.

For the radiator, when comparing the valve position to flow, no discrepancy was observed between the flow and valve position when the valve was completely closed. Therefore, the radiator valve position was considered appropriate to use. There was an exception to this in one room, where the radiator would still allow water flow even if the valve position was closed (see Section 3.2.4 for known control system issues). Since the radiator operates on an on/off basis, with the valve position having a range between 0% and 100%, a simple rule was implemented; if the valve position was 0%, the radiator was considered off, if the valve position output was anything else, the radiator was considered on.

For the VAV, due to issues related to the control system, the control output and measured input did not always match. The reason for this was not identified as part of this research. As an example of this issue, an observed scenario is shown below, where the control system does not act based on the control inputs.

In this scenario, between 8:30 am and 12:30 pm, the supply air temperature setpoint and measured value are controlled within approximately ±3°C. Soon after 12:30 pm, the measured temperature momentarily drops, and then immediately returns to its normal operation. Then at approximately 1:30 pm, the control system begins to malfunction, and the temperature supply air temperature drops. Therefore, if the control input was used, users may be told that their air-based system is heating; however, they would not observe any heat from the vents, which may cause distrust in the system. Alternatively, if the measured output was used, small fluctuations may cause the thermostat to communicate that heating has stopped, even though it should not have.

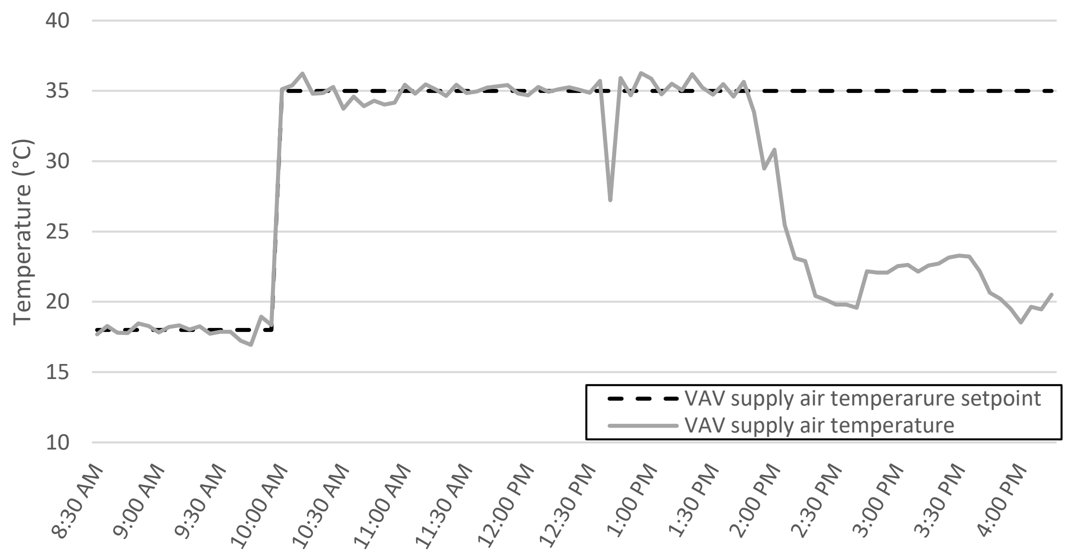


Figure 5.3 Example comparison between the VAV supply air temperature setpoint and the measured supply air temperature. This example shows a frequent issue that occurred where the supply air temperature deviates significantly from the setpoint.

Since the data was collected on a 5-minute interval, one final issue with using the measured supply air temperature was only discovered during testing. The measured supply air temperature lags several seconds behind the supply air temperature setpoint. This is particularly important during a setpoint change because the thermostat feedback would take several seconds to respond to a button press if the measured supply air temperature was used; however, the control variable generally took less than a second to respond if the supply air temperature

The solution used was a hybrid approach; under normal operation, the VAV supply air temperature setpoint was used to dictate the thermostat display. This allowed for quick feedback to setpoint changes and consistent operation. To mitigate the observed control malfunctions, the measured supply air temperature was monitored when the thermostat displayed that the VAV was in heating mode. If the temperature remained consistently more than 5°C lower than the supply air temperature setpoint for 10 minutes, the system switched the thermostat mode to not display VAV heating. Figure 5.4 shows the pseudo-code implemented into the BAS, which allows the thermostat to display the heating system status.

A final consideration for implementation was the frequency at which the heating system status was updated. Since the backlight changes based on status updates, there was concern that frequent changes would annoy occupants. When the heating system status logic applied to the historical data used for the analysis of the control system (2018-2019 season), in extreme cases, the number of status changes exceeded 150 times a day. This primarily occurs when the supply air temperature is close to the setpoint for most of the day, and the radiator valve cycles on and off to maintain the setpoint temperature. Since it is expected that people will have limited interest in the control system operation, a 15-minute filter was applied to the status updates. This measure was intended to balance the potential annoyance caused by providing occupants with accurate heating system information. The exception to this 15-minute filter occurs after the user changed adjusted the setpoint. For 5 minutes after the setpoint was adjusted, the operating system data was displayed in real-time so that the users could observe the effect of their interactions.

```
// This script constantly loops during thermostat Operation
Loop

// Step 1, Check if radiator is on
if Radiator Valve > 0%
          Radiator Heating = On
else
          Radiator Heating = Off
end

// Step 2, Check if VAV is on, and is heating properly, and the VAV is operating correctly
if VAV Supply Air Temperature Setpoint > 30°C
          VAV Heating SP = On
          if [[VAV Heating SP = On]
             …and [VAV Supply Air Temperature Setpoint - VAV Supply Air Temperature > 5]]
             …for 10 minutes
                    VAV Heating = Off
          else
                    VAV Heating = On
          end if
else
          VAV Heating SP = Off
          VAV Heating = Off
end if

// Step 3, Display backlight colour and symbol based on heating system operation
if [Radiator Heating = Off] and [VAV Heating = Off]
          Thermostat Backlight Colour = White
          Flame Symbol = Off
          Number Above Flame Symbol = Off
else if [Radiator Heating = On] and [VAV Heating = Off]
          Thermostat Backlight Colour = Red
          Flame Symbol = On
          Number Above Flame Symbol = 1
else if [Radiator Heating = On] and [VAV Heating = On]
          Thermostat Backlight Colour = Red
          Flame Symbol = On
          Number Above Flame Symbol = 2
else if [Radiator Heating = Off] and [VAV Heating = On]
          Thermostat Backlight Colour = Yellow
          Flame Symbol = On
          Number Above Flame Symbol = Off
end if

end Loop
```

Figure 5.4 Pseudo-code of the implementation control logic for the heating system status feature

5.2.2 Schedule information

The purpose of this feature was to inform people when a scheduled setback was occurring. Similar to the heating system status, building data was obtained through the building automation system. The building level schedules were already communicated to the room level controllers, and this input was used to change the mode of the thermostat. When observing historical data, no discrepancies were found where the schedule indicated off, and the VAV was still active. Therefore, this feature was simple to implement. Figure 5.5 shows the pseudo-code required to implement this feature.

```
// This script constantly loops during thermostat Operation
Loop

// Step 1, Check if radiator is on
if Schedule = Setback Mode
        Overwrite Heating System Status Feature
        Thermostat Backlight Colour = White
        Previous Thermostat Passive Backlight Intensity …
                = Current Thermostat Passive Backlight Intensity
        Thermostat Passive Backlight Intensity = 0
        Number Above Flame Symbol = "Off"

        if Temperature mode button is pressed
                Scroll text = "Heating System Is Off"
                Display Setpoint
        end
else
        Resume to Heating System Status Feature
end

end Loop
```

Figure 5.5 Pseudo-code of the implementation control logic for the schedule information feature

5.2.3 Time-to-temperature estimations

The time-to-temperature feature was the most complex feature to implement and required the development of a data-driven model for the offices. The time-to-temperature is displayed directly on the thermostat interface any time the indoor air temperature is

0.5°C below the setpoint temperature. Since there is no active cooling, no estimation was provided when the setpoint was below the indoor air temperature, as this was difficult to predict and depended heavily on the setpoint in other rooms. In future iterations of this design, further explanation to occupants could be provided to explain the full implications of set points in other rooms; however, it was determined that was not feasible given the constraints of the interface and the scope of the project. The model development, training, assessment, and implementing this feature is described in this section.

5.2.3.1 Model formulation

To build the data-driven grey-box model of the room, each room was modelled using an electrical analogous thermal network model. This model is based on the recommendations of Gunay et al. [53], who provided a comparative analysis of several grey-box models. They suggested the simplest model that provided satisfactory predictive accuracy included the parameters of indoor and outdoor temperature, indoor light intensity, motion sensors, and heating system status. The parameters used in this model are the effects of outdoor air temperature, solar thermal gains, radiator and VAV operation, occupancy, and internal gains (e.g., plug loads). Figure 5.6 shows the room model and inputs. Table 5.1 lists the parameters collected from the BAS system.

This model assumes that the air in the room is fully mixed, and therefore uses a single node to represent the indoor air temperature. The rationale for this assumption comes from Gunay et al. [53], who found that if the number of temperature nodes exceeded the number of sensor measurements, the accuracy of the model decreased, rather than increased. Since only thermostat temperature is used in this analysis, a one node model was deemed most appropriate.

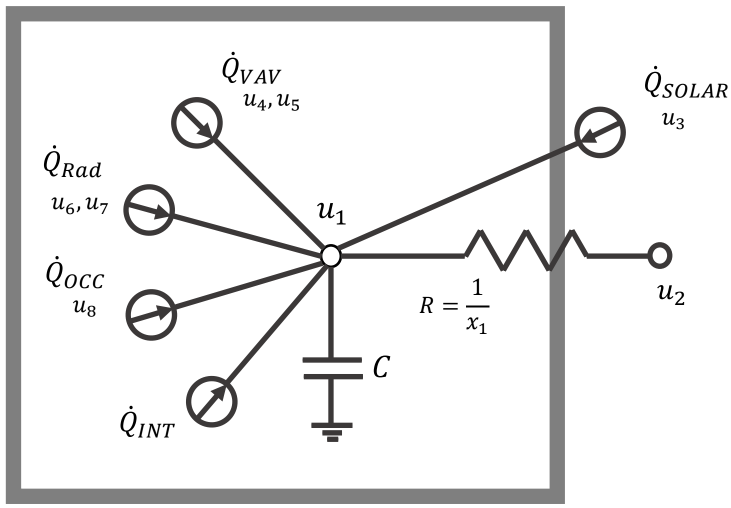


Figure 5.6 Electrical analogous RC room model.

Table 5.1 List of input parameters used in the electrical analogue room model.

Inputs	Description of measured parameters	Unit
u_1	Indoor air temperature	°C
u_2	Outdoor air temperature	°C
u_3	Indoor Illuminance	Lux
u_4	VAV flow	L/s
u_5	VAV supply air temperature	°C
u_6	Radiator Valve	open/closed
u_7	Radiator supply water temperature	°C
u_8	Occupancy	yes/no

The heat losses due to the outdoor air temperature ($\dot{Q}_{OAT}$) are shown in equation (5.1) and are modelled as a thermal resistor between the indoor and outdoor air temperature. The indoor and outdoor air temperatures are measured directly by the building automation system. The resistance incorporates the combined resistance of the window and wall assemblies, as well as the convective coefficients on the inside and outside of the building. With the simplifications made to this model, this parameter also captures infiltration and exfiltration between the room and the outdoor air. The equivalent resistance is represented in the model as ($R = 1/x_1$).

$$\dot{Q}_{OAT} = x_1(u_1 - u_2) \quad \text{(eq 5.1)}$$

The solar gains ($\dot{Q}_{SOLAR}$) are shown in equation (5.2) and are inferred by using an average of three illuminance sensors at three depths within the room. The model assumes that there is a linear correlation between the measured illuminance and the solar gains of the room. This approach has limitations, as the relationship between illuminance and solar thermal gains is inherently non-linear and affected by the position of the blinds, the state of the artificial lights and whether the is incoming radiation is direct or diffuse. Despite these limitations, assuming a linear correlation still provides some insight regarding thermal gains. In one study, Bursill et al. [51] performed an analysis of this assumption on an office room and found a 0.42 linear correlation between the illuminance sensor and the expected solar irradiation at the office. In future iterations, the model performance could be improved by disaggregating the natural and artificial light using the blind position and lighting level. Additional accuracy could be added by incorporating weather station data and sun position to improve this disaggregation and further understand the solar gains from diffuse or direct solar irradiation. For this thesis, the model assumed a simple correlation between solar gains and measured illuminance, which is represented as the parameter (x_2).

$$\dot{Q}_{SOLAR} = x_2 u_3 \quad \text{(eq 5.2)}$$

VAV heat input ($\dot{Q}_{VAV}$) is shown in equation (5.3) and is captured using basic thermodynamic principles with the heat input modelled using mass flow rate from the incoming air, the specific heat of the air, and the difference of temperature between the air entering and exiting the room. ($\dot{m}C_v\Delta T$). While the mass flow rate is not directly measured, it is assumed that the volumetric flow rate is proportional to the mass flow rate. In reality, this relationship between mass and volumetric flow would vary based on the density of the air, which is affected by both supply air temperature and pressure. The mass flow rate in the room is assumed to be steady-state, where the mass flow provided through the VAV is equivalent to the mass flow through the return vent. It is also assumed that the return air temperature is equivalent to the indoor office temperature. This second assumption is based on the previously mentioned assumption that air within the room indoor air temperature is perfectly mixed. The VAV heat input can be represented in the following equation, where the fitted parameter (x_4) is representative of the heat capacity and density of the incoming air.

$$\dot{Q}_{VAV} = x_4 u_6 (u_7 - u_1) \qquad \text{(eq 5.3)}$$

Heat input due to the radiator ($\dot{Q}_{RAD}$) is shown in equation (5.4) and is captured by measuring the radiator supply water temperature and valve position. During operation, the valve actuates to maintain a temperature difference of 3°C between the water temperature of the inlet and outlet of the radiator. For the purposes of this model, it is assumed that during operation, if the radiator valve is open (u_6=1), the radiator surface temperature is the same as the water temperature, and if the valve position is closed, the surface temperature is the same as room temperature (no heat transfer occurs). This assumption has limitations, as some heat loss occurs between the water and the metal of the radiator, and the radiator has heat capacity and thus a transient effect that is not considered. Depending on the control system operation, the radiator may switch on and off several times within a 5-minute period or remain on or off for most of the day. This may lead to numerous examples where the radiator is considered off, but the radiator is still hot, limiting the accuracy of this model. Additionally, heat transfer will occur both through both convection and through radiation to the room surfaces. The heat transferred to the room surfaces will ultimately affect the room temperature through convection. While the fundamentals equations behind these two modes of heat transfer differ, for simplicity, the radiator heat input is only modelled as convection. The trained parameter x_4, therefore, is representative of the convective heat transfer coefficient and area of the radiator associated with that convective heat transfer.

$$\dot{Q}_{RAD} = x_4 u_6 (u_7 - u_1) \qquad \text{(eq 5.4)}$$

Finally, internal gains are represented using x_5 and x_6, where x_5 represents the gains associated with occupancy ($\dot{Q}_{OCC}$), and x_6 represents the internal gains from other equipment in the room ($\dot{Q}_{INT}$). Occupancy was inferred using two PIR sensors, one located on the thermostat panel, and one on the ceiling above the occupant's desk. Occupancy was assumed for 60-minutes after the most recent motion detected either by the ceiling mounted or wall mounted PIR sensor. Reducing occupancy to a binary variable likely fails to capture the complexity of how occupant behaviour affects the gains in this office. For example, it does not capture how many occupants are in the room or what kind of equipment they are using. Despite these limitations, this simplification to a binary variable was necessary given the available data.

All of these input parameters are applied to the room temperature node of the RC grey-box model. The thermal capacitance, represented by C, characterized the thermal response time of the room. This included both the capacitance of the air, and the solid objects in the room. While the response time between these would be different, it is assumed they can be represented by a single thermal capacitance. Heat flow through the capacitor is defined by equation (5.5).

$$\dot{Q} = C\left(\frac{dT}{dt}\right) \quad \text{(eq 5.5)}$$

Applying Kirchhoff's law, that heat flow into a node is equal heat flow out of that same node. Therefore, the heat flow through of the thermal capacitor is equal to the sum of all the other heat flows associated with the temperature node. The heat flow through the capacitor can be written as equation (5.6).

$$C\frac{dT}{dt} = x_1(u_1 - u_2) + x_2(u_3) + x_3u_4(u_5 - u_1) + x_4u_6(u_7 - u_1) + x_5u_8 + x_6 \quad \text{(eq 5.6)}$$

Since the thermal capacitance (*C*) is assumed constant, it can be incorporated into the trained parameters. Additionally, the room data is discrete timestep data, therefore (dT/dt) is estimated as ($\Delta T/\Delta t$). These final simplifications are represented in equation (5.7).

$$\frac{\Delta T}{\Delta t} = x_1(u_1 - u_2) + x_2(u_3) + x_3u_4(u_5 - u_1) + x_4u_6(u_7 - u_1) + x_5u_8 + x_6 \quad \text{(eq 5.7)}$$

5.2.3.2 Time-to-temperature estimation

Once trained, predictions of the temperature of the next time step (T_{i+1}) are found by adding the calculated change in temperature to the temperature of the current time step (T_i), as shown in equation (5.8).

$$T_{i+1} = T_i + \Delta T \quad \text{(eq 5.8)}$$

Time-to-temperature is determined by repeating this process (marching forward in time) until the predicted temperature reaches within the threshold of 0.5°C of the setpoint. The number of timesteps required provides an estimate of the amount of time it will take to reach the setpoint. If the prediction exceeds the threshold temperature, linear interpolation between the current and previous timestep is used to determine a precise estimate. For each timestep the input parameters ($\boldsymbol{u}$) may be updated based on predicted parameters. For this application, outdoor conditions and HVAC operations will be assumed constant for the duration of the prediction horizon. However, indoor air temperature is updated based on the prediction. A conceptual model of this process is shown in Figure 5.7.

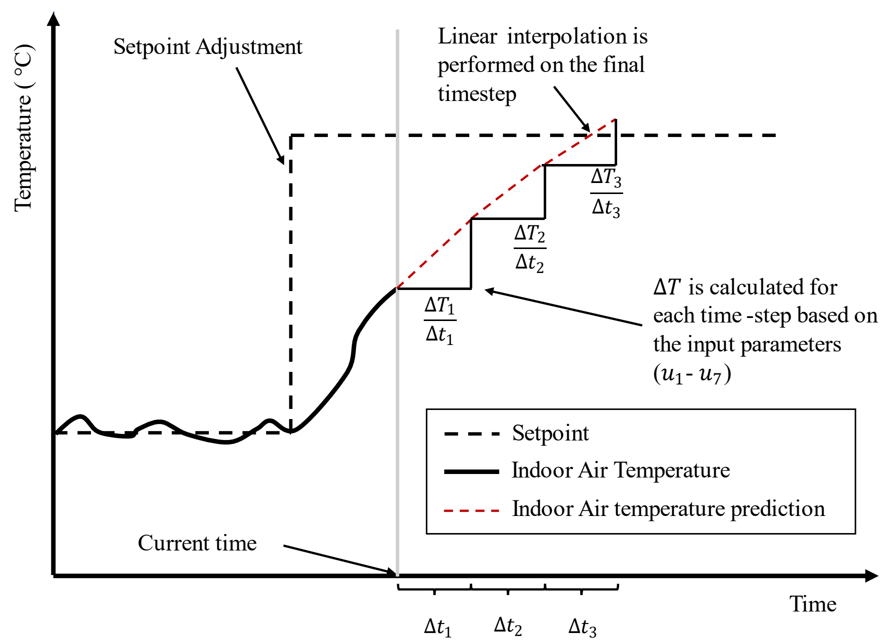


Figure 5.7 A conceptual diagram depicting the time-to-temperature estimation.

5.2.3.3 Training and validation data

The parameters of the electrical analogous room models were trained based on three months of data from mid-October 2018 to mid-January 2019. Setback periods (evening and weekends) where removed from the training data. Since these offices are equipped with window sensors, times that the window was open were also removed from the training data, as the room dynamics would change significantly during this time.

Aside from these exclusions, all other operation data were used to train the parameters. The choice to use all data, rather than focusing on warmup and setpoint changes, was made to ensure room models were robust regardless of how often morning warmups and setpoint changes occurred. The performance of these models was assessed based on the ability to predict time-to-temperature on a validation set.

The validation set is made up of the same three-month period in the following year, from mid-October 2019 to mid-January 2020. model performance, the time-to-temperature of each warmup and setpoint change is calculated. An example of a morning warmup time is visualized in Figure 5.8.

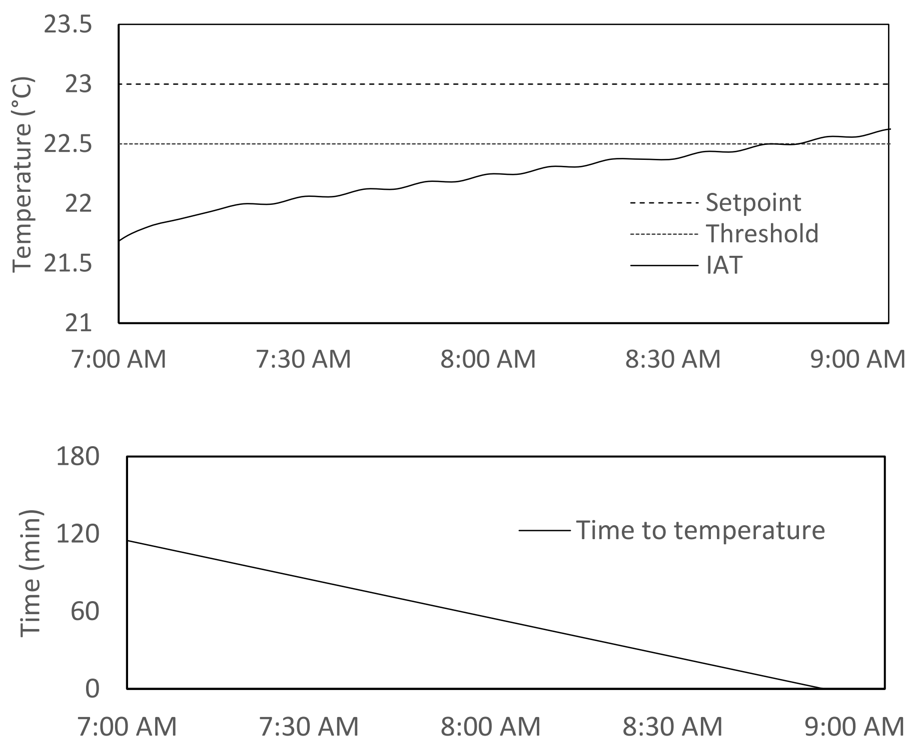


Figure 5.8 Example of validation data for a morning warmup. (Above) indoor air temperature, and the threshold for the estimation. (below) the measured time-to-temperature.

Model performance was assessed based on the mean absolute error (MAE) between the validation data and the time-to-temperature estimates. An individual MAE is calculated for the time horizon when the validation data is heating and is 30, 60, and 120 minutes from the setpoint threshold. In total, across all the rooms, 848, 717, and 406 examples of 30, 60, and 120 minutes time horizons were collected from the validation data. For the assessment of model performance, MAE between predicted and measured time-to-temperature is calculated for each room using equation (5.8). and an average MAE between the rooms is used to determine the overall performance.

$$MAE = \frac{\sum_{i=1}^{n} |y_i - x_1|}{n} \qquad \text{(eq 5.9)}$$

Where y_i is the measured time to temperature (either 30, 60, or 120 minutes) based on the validation set, and x_i is the estimated time-to-temperature based on the model input parameters at that time step.

Five rooms were removed from the validation set. Three of these rooms were removed as they had fewer than 10 cases where the indoor air temperature was lower than the setpoint threshold for more than 30 minutes. The other two were removed due to erratic heating behaviour that was unrepresentative of the rest of the offices. The office temperature in these offices fluctuates significantly during heating, in ways which were unexplained by the parameters measured. Onsite inspection of the sensors and heating system operation would be required to further understand the issues in these offices.

5.2.3.4 Training time step determination

Determination of the room model training timestep was performed by comparing the measured data from the validation set with the time-to-setpoint estimates of the electrical analogous room model. The room model was trained using 5, 15, 30, and 60-minute time steps. When the resulting predictions from these room models were compared to the validation set, for all (30, 60, 120 minute) prediction horizons, increasing the timestep increased the MAE; however, the effect was small (<15%). Only a small difference was observed between the five and 15-minute timestep (<3%), and therefore a 15-minute timestep was used as this information is more likely available in other buildings. In general, this strategy would work for increased timesteps, and should typically be selected based on the minimum BAS collection frequency.

5.2.3.5 Forward selection of parameters

A forward selection process was used to investigate the effect of each parameter on predicting time-to-temperature. The inputs from outdoor air temperature (u_1), solar gains (u_2), radiator system inputs (u_6, u_7), VAV system inputs (u_4, u_5), and occupancy (u_8) were all tested individually. For each model, internal gains were included and can be considered the unexplained portion of the model. Next, combinations of each input type were combined in order of best predictors. The results are shown in Figure 5.9. The grey lines represent the maximum and minimum MAE for each room, while the black line represents the averages for 20 of the 25 rooms. This process was done for 30, 60, and 120-minute prediction horizons; however, the trend was the same for all horizons, so only the results from the 60-minute predictions are shown in Figure 5.9.

Unsurprisingly occupancy and outdoor conditions alone are poor predictors of time-to-temperature. As individual parameters, radiator and VAV operational data are the best performing predictors, with the combination of the two being the best performing model. Interestingly adding other parameters to the model increased, rather than decreased MAE of the time-to-setpoint predictions. As a result of this analysis, only VAV and RAD inputs were included in the final implementation of the room models.

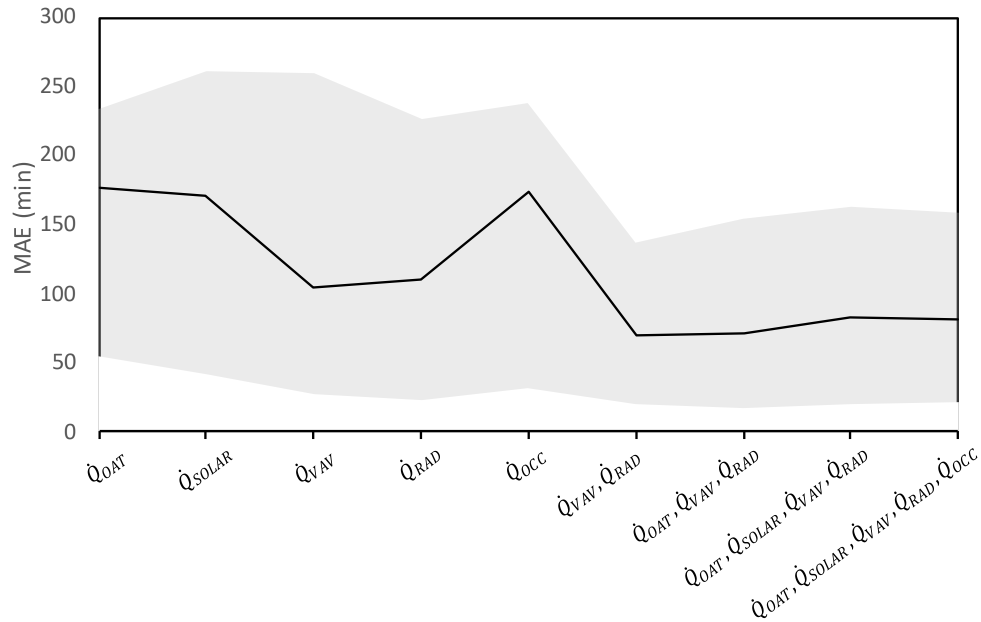


Figure 5.9 Room level model performance for the forward selection of parameters in 20 of the 25 rooms. The average MAE of all the rooms is shown in black and maximum and minimum MAE is shown in grey for 60-minute predictions

5.2.3.6 Room models

As discussed in the literature review, one of the major advantages of grey-box models is that they are interpretable by humans. Figure 5.10 shows the impact of each input on room temperature, assuming an indoor air temperature of 21°C. The figure represents the estimated maximum and minimum effect of each input parameter on room temperature over the next hour. These maximum and minimum influence are based on the inputs ($\mathbf{u}$) measured during the pre-implementation period, and the trained parameters ($\boldsymbol{x}$). The model is trained based on the full model as in equation (5.7) and the best performing model, which includes only the VAV and radiator inputs. The effects of each parameter based on the full model can be seen in Figure 5.10a, while the effects of each parameter based on the radiator VAV only model can be observed in Figure 5.10b. These graphs were made for each room, with only a representative room shown here. While it is difficult to know if these models are representative of the room, they can be at least inspected to ensure there are no significant deviations from what would be expected. For example, if higher solar gains decreased the temperature of the room, that would not be representative of reality.

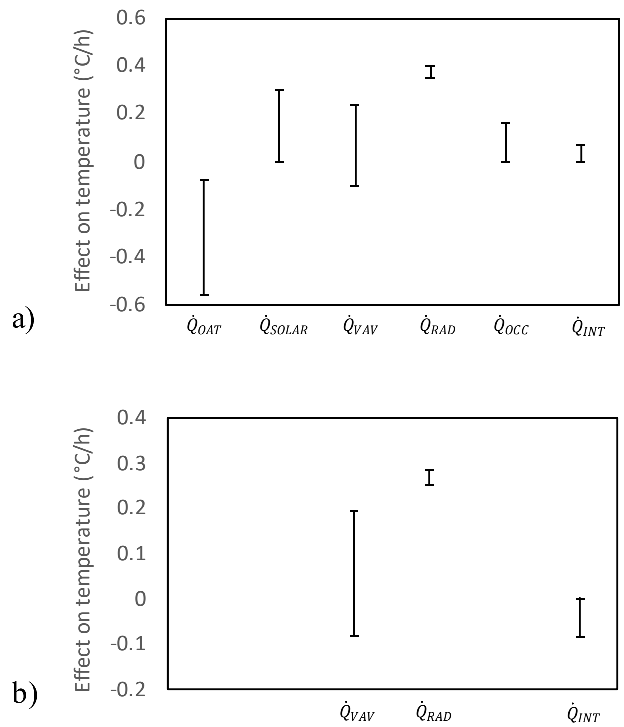


Figure 5.10 Impact of inputs on room temperature in the next hour, assuming an indoor air temperature of 21°C . The effects of each parameter are based on the observed operation during the pre-implementation period. One representative office is shown here. (a) is the model trained with all inputs, while (b) is only including RAD and VAV inputs.

5.2.3.7 Initial inspection of estimations

The initial results from using only the VAV and radiator inputs were inspected on a room by room basis. A key observation is that the predictions were highly sensitive to VAV supply air temperature. In the example shown in Figure 5.11, the heating system is switched on in the morning to recover from the setback temperature; however, the VAV takes about 10 minutes to reach its operating temperature. As a result, the prediction for the first 10 minutes predicts nearly twice the time actually required for the room to warm up. Similarly, changes to the state of the radiator valve, and fluctuations of the radiator flow caused large fluctuations in temperature predictions.

To address these concerns the radiator and VAV input variables were held constant to represent typical heating operation. The chosen constant numbers were based on average operating conditions during heating. Shown in Figure 5.11 is an example of the operational input prediction compared to the constant heating input model performance.

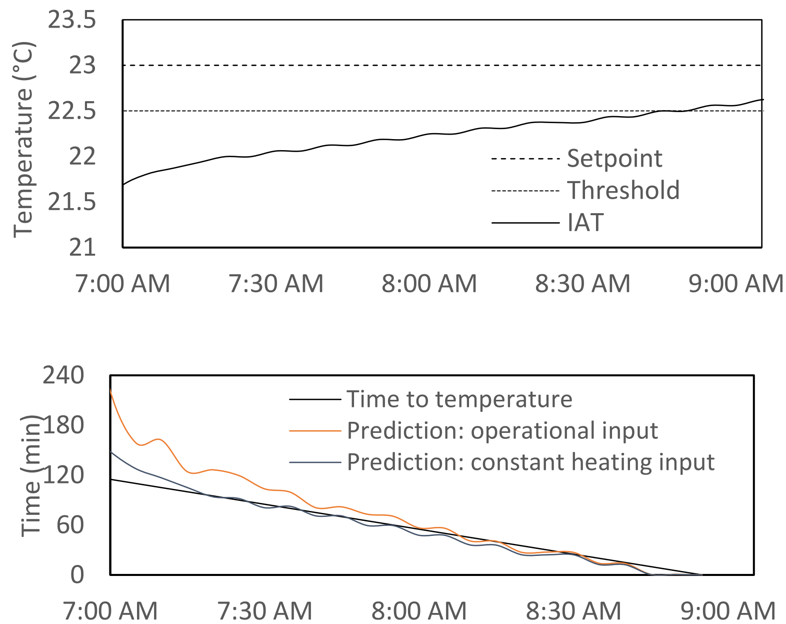


Figure 5.11 Example of time-to-temperature predictions comparing operational heating inputs, constant heating inputs, and measured data.

5.2.3.8 Input parameter tuning

The assumed constant heating and cooling were further tuned to improve performance. Combinations of increasing and decreasing the VAV supply air temperature and radiator temperatures were systematically compared to reduce the MAE, and the best overall values were selected. The best performance assumed VAV temperature was 3°C higher than typical operating conditions, and the radiator water temperature was 15°C higher than typical operating conditions.

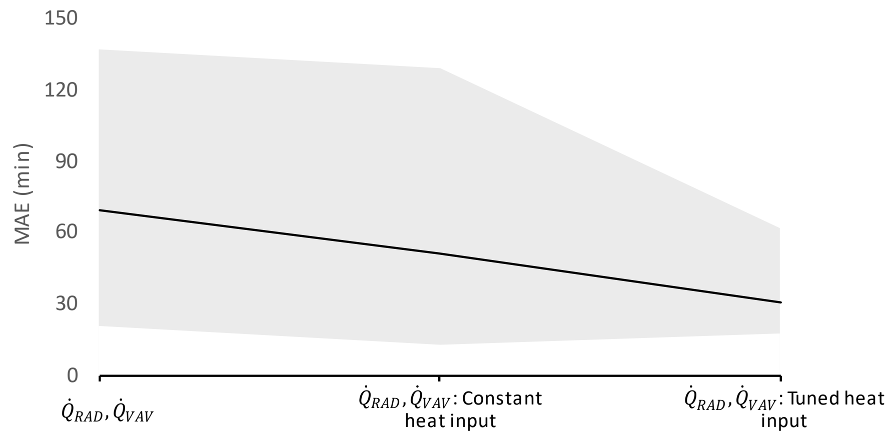


Figure 5.12 Comparison of MAE of 3 models, using operational data, constant heating inputs, and manually tuned heating inputs.

To further reduce the remaining performance variance between rooms, individual parameters were manually adjusted for the lowest-performing rooms. Since on the room level, validation data was limited, this process was done using a combination of considering the room level MAE and inspecting a visualization of the estimates. This manual selection of parameters was also performed based on rooms that were excluded from the validation set. The MAE of the VAV and radiator model, constant heat input, and tuned heat input is shown in Figure 5.12. Prior to this calibration, the lowest-performing room had a MAE of 130 minutes for a 60-minute time horizon. After the tuning process, the MAE was reduced to 62 minutes. In general, the tuned models produced time-to-temperature estimates with a MAE of 20, 42, and 65 minutes for 30, 60, 120 prediction horizons, respectively, when tested against the validation data set.

5.2.3.9 Final considerations

A linear model was chosen to model offices in this building for two reasons: (1) it could be easily coded into the building automation system with low computational power, and (2) it performs satisfactorily for the task at hand. This approach, however, had significant limitations in implementation, and the prediction accuracy was held back by the lack of linear behaviour of the indoor air temperature.

The room models showed that future temperature was heavily impacted by outdoor conditions. Despite this impact, including these parameters in the time-to-temperature estimation decreased overall performance. The likely cause of this is that these parameters change throughout the prediction horizon. Solar gains would vary significantly throughout the morning warmup period. In future work, predictions of the outdoor air temperature and light intensity measurements will be added into the model to test if this improves time-to-temperature estimates.

In the final step of this process, the VAV supply air temperature and the radiator water temperature input was adjusted to improve the model performance. Both inputs were increased above the typical operating conditions were selected, as this improved model performance. Finally, visualizations of the predictions where then inspected and further manual adjustments of the parameters were done when required. This step was performed to ensure estimates were behaving in a way that would be satisfactory to occupants; however, it is time-consuming and acts as a barrier to large scale implementation of this method.

Working from real building data presented several key challenges. First, this building has a slow response time to respond to a user setpoint and as a result, the prediction horizon for this model was quite long, often extending beyond four hours. The heating response was frequently non-linear, posing an issue for using a linear model to predict. This is likely a result of both non-linearity in the relation between the measured variables and room temperature, and as well as unmeasured inputs into the room. Occupant behaviour likely plays a key role. While occupancy is measured as a binary variable, heat generation due to occupancy is unknown. As an extreme case, some occupants may be using space heaters to adjust their thermal comfort.

An observed advantage of data-driven modelling is that unexpected or faulty equipment can be captured in the model. For example, one of the generated room models deviated from the rest, as the modelled internal gain deviated significantly from the other rooms. Upon further investigation, it was discovered that the radiator valve was allowing flow through the radiator even when the radiator valve was switch off by the BAS. This was automatically compensated for by the model by increasing the internal gain trained parameters.

5.3 Implementation and testing

The developed features were implemented into the existing thermostats in the 25 studied offices of the building. Due to the nature of the BAS, this change could be implemented remotely, without the need for access to the offices. The updates were made on Sunday, February 9th, 2020, making the official start date of the testing period Monday, February 10th, 2020. The instruction manual was emailed out just prior to the implementation. The features were monitored to ensure expected operation, and the time-to-temperature estimations were logged for later analysis. Due to a work at home policy administered by the university in response to COVID-19, which came into effect on

Monday, March 16th, 2020, the test period officially ended on Sunday, March 15th, 2020. The features were removed May 1st, 2020, as the heating season was ending. During the testing period, no observed errors occurred in the building automation system, and no complaints were made to facilities management regarding the interface functionality. The implementation on a technical level was therefore considered a success.

5.4 Phase 2 Discussion

In phase 2, features were developed which were aimed at addressing the specific usability issues found in Phase 1. The developed interface features were designed with limitations based on the existing office setup, including the existing design of the thermostat. Since the occupants had been using these devices for some time, they had already gained familiarity with the thermostats. Most of those surveyed reported ease of use when adjusting thermostats; therefore, the design favoured maintaining the existing thermostat operation. With these limitations, the thermostat features were designed to support the evaluation bridge (based on Norman's framework covered in Section 2.2.2) aimed at better-supporting people's understanding of the system.

Using colours, and the flame on the digital display, individuals were told when their heating system was active. The colours described the context for heating, red for heating to the occupant's setpoint selection, yellow for heating to another occupant's setpoint selection in another room located in the same zone with the shared VAV system. The flame symbol and numbers above described which heating systems were working to further encourage discoverability for interested occupants. The coloured backlight remained on, at a lower brightness, even when users were not interacting with their thermostats. Scheduled setbacks were communicated to individuals by switching off the backlight when users were not interacting with the thermostat and displaying the text "OFF".

The time-to-temperature feature aimed to address the issue of highly variant and slow response times. Since the control system only actively heats in the heating season, only heating time estimates were given. The training, tuning, and implementation of a grey-box model, which estimates time-to-temperature, was described in this section.

These features were implemented and tested with the occupants in the building for just under one month before work from home policies were implemented. While this work from home policy limited the timeframe of testing, the occupants still had time to interact with and gain an impression of the updated thermostat interfaces.

Chapter 6: Phase 3 – Post-implementation

The post-implementation phase aimed to assess the performance and obtain feedback about the implemented thermostat features. During this phase, the control system was analyzed and compared to the performance in the pre-implementation period (Section 6.1). Next, the performance of the new thermostat features was investigated (Section 6.2). Finally, a survey was used to gather feedback and understand how participants perceived the new features (Section 6.3).

6.1 Analysis of the control system

The primary purpose of the analysis of the control system in the post-implementation phase is to compare the building's operational performance during the testing of the implemented features with the pre-implementation period. For each metric, three time periods were used. The 2018-2019 heating season was compared to the 2019-2020 heating season from October 25th to March 25th to ensure the overall system conditions were the same. The specific period in which the new thermostat features were implemented (February10th, 2019 to March 15th, 2020) was also assessed to ensure there were no significant performance differences during this period.

6.1.1 Comparison of the heating season

The heating degree day method was used to compare seasons in relation to the heating system operation. Heating degree days measures the number of degrees the average daily temperature is below 18°C. This daily calculation is typically summed to represent a particular time period (e.x. over a month or a year) [57]. Figure 6.1 shows the summed monthly heating degree days over the analysis periods of the two heating seasons. The results show that more heating would be expected during the 2018-2019 heating season. The likely effects this has on building performance and perceived control is discussed throughout this section.

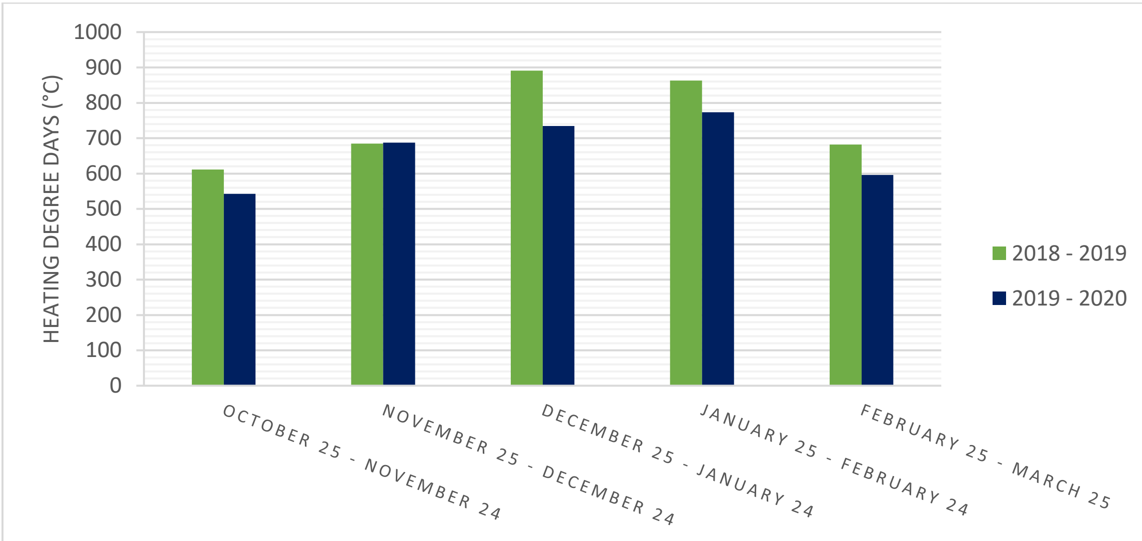


Figure 6.1 Monthly Heating degree days for Ottawa during the 2018-2019 and the 2019-2020 heating season. This graph was generated based on historical weather data collected by the Government of Canada [57].

6.1.2 Setpoint control

In the pre-implementation (Phase 1), the setpoint control was quantified to develop an understanding of the level or type of control people had over their offices. During the assessment, it was determined that the level of control was notably reduced if the setpoints differed within a given zone. Figure 6.2 shows the performance in the three time periods, as well as the performance when there is more than 2°C difference between two rooms within the same zone.

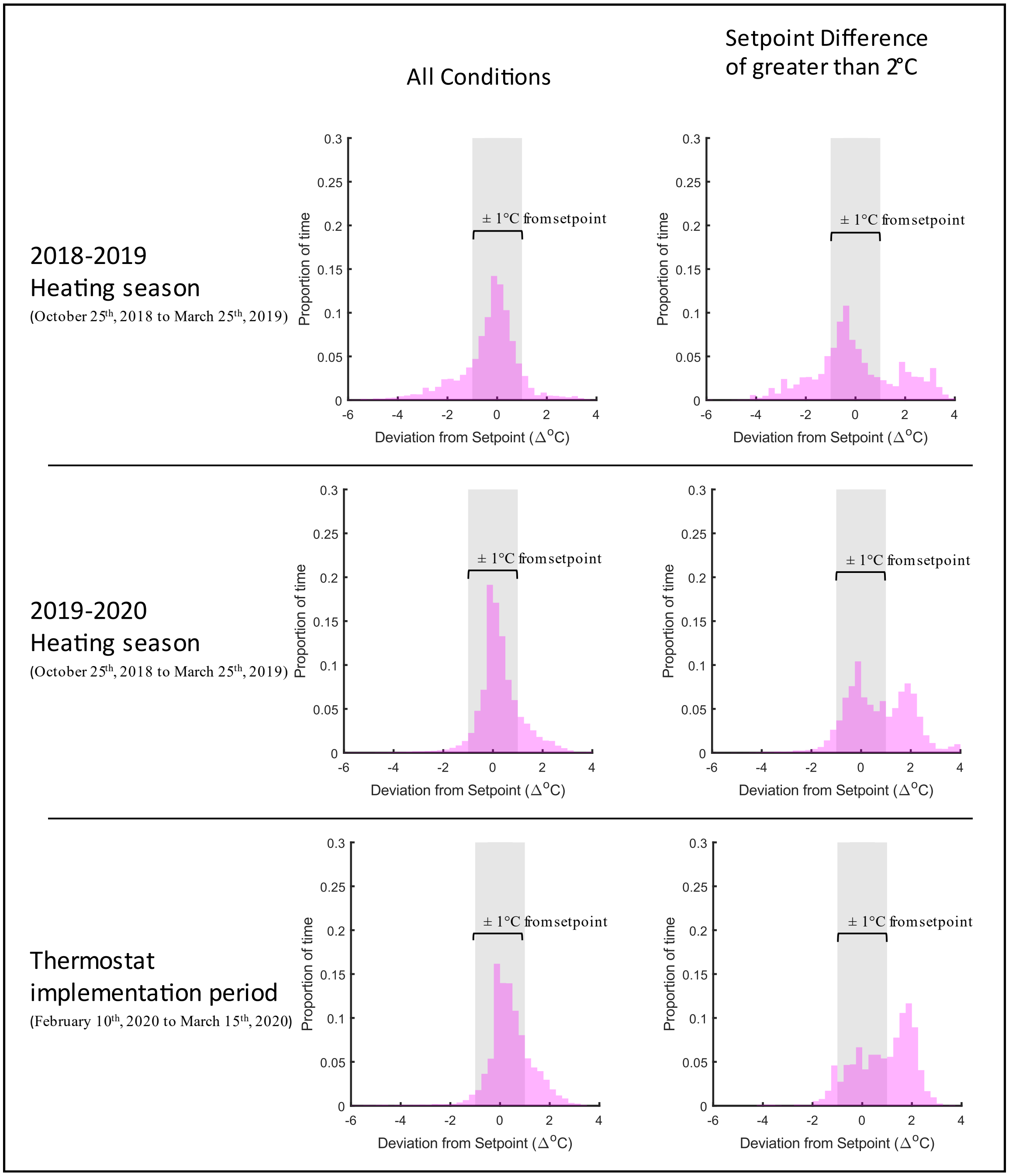


Figure 6.2 Comparison of setpoint control for the heating systems in different analysis periods.

Overall, the performance of the rooms between the two heating seasons and during the testing period are quite similar. Likely due to the slightly warmer winter in the 2019-2020 heating season, the distribution has shifted, leading to more time spent above the setpoint rather than below. Despite this, the setpoint was controlled within ±1°C a similar percentage of the time, of between 72% and 77% of the time under normal conditions, and 49% and 48% of the time when rooms within the same zone are requesting greater than 2.5°C, for the 2018-2019 and 2019-2020 heating seasons respectively. Similar performance was also observed while the thermostat features were in operation. Based on these results, it was concluded the rooms were operating within an acceptable level of consistency such that perceived effects of control are likely not due to changes in building operation.

6.1.3 Setpoint response

The second metric investigated during the pre-implementation phase (Phase 1) was the setpoint response time. The pre-implementation study found that response times were slow and highly variant, which likely influenced perceived control. Another conclusion from this study is that response times depended heavily on contextual factors such as temperature settings in neighbouring offices and outdoor weather conditions. Despite the importance of these contextual factors, there is significant value to studying the response time to reach a setpoint from the perspective of the difference between current indoor air temperature at the time of a setpoint change and the new setpoint. This is because the indoor air temperature and setpoint are the only thermal-based information presented to occupants through the thermostat. Figure 6.3 shows the results for all the measured rooms across the three analysis time periods.

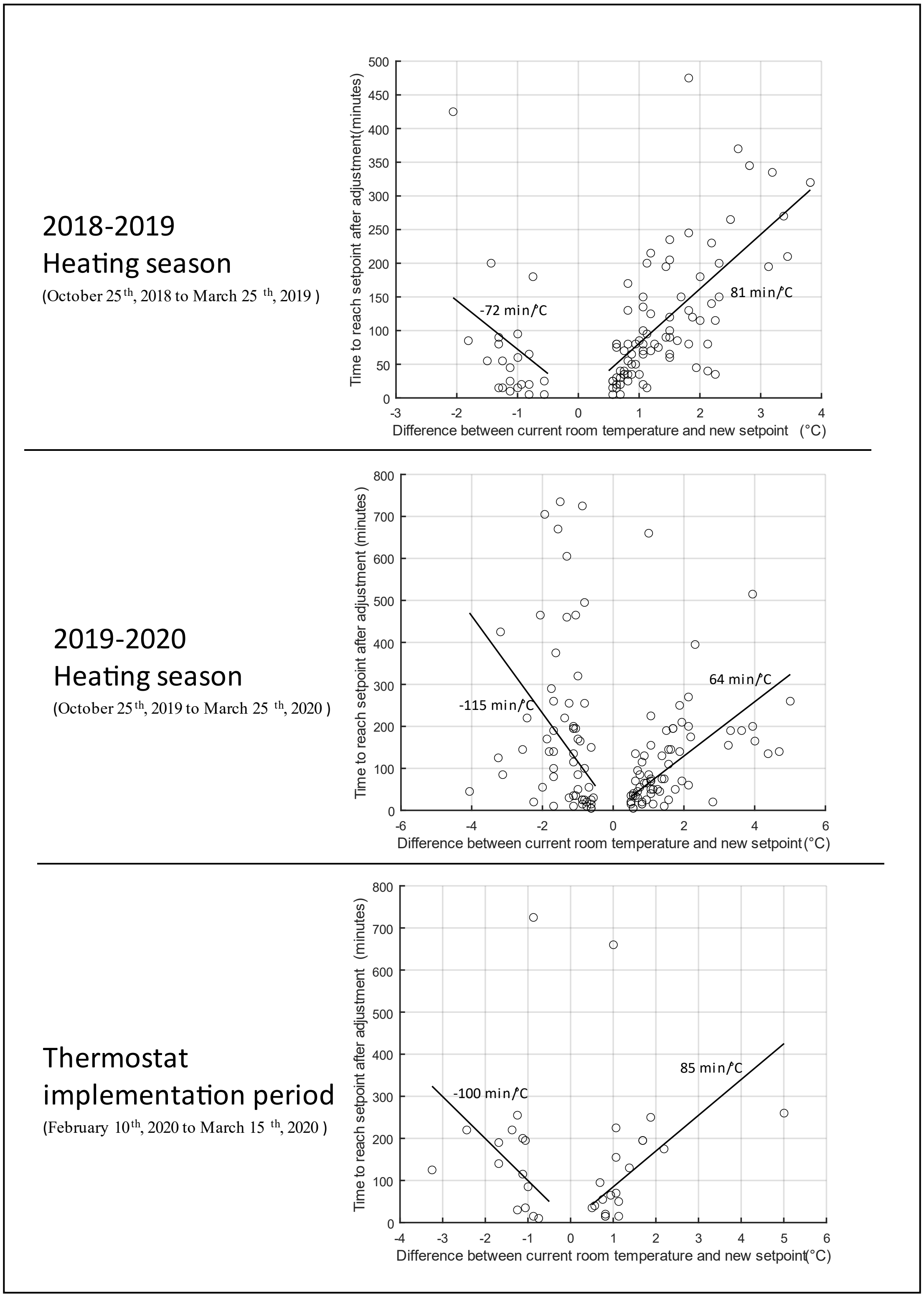


Figure 6.3 Comparison of setpoint response time for the heating systems in different analysis periods.

For setpoint increases, the overall response time based on the setpoint difference was, on average, faster in the 2019-2020 heating season by approximately 16 min/°C; however, a high variance exists in both heating seasons. A higher difference is observed for decreasing of setpoints. This difference does not necessarily represent a difference in room performance, since the setpoint decrease response was found to be heavily dependent on outdoor air temperatures, which were slightly warmer during the 2019-2020 year, as well as the setpoint in other rooms, and was therefore highly variant. Similar to the findings related to setpoint control, it was determined the rooms were acting within an acceptable level of consistency between the two seasons.

6.1.4 Schedules and occupancy

The occupancy distributions and how they relate to the scheduled setbacks were also investigated during the pre-implementation phase. While no changes were expected regarding the occupancy distribution, based on the request of the office users, facilities management expanded the HVAC schedule to operate later in the evening and during the weekend. In the initial assessment period during the winter of 2018-2019 the occupied schedule was between 6:30 am and 5:30 pm Monday to Friday. Prior to the winter season of 2019-2020 the HVAC schedule was changed to 7 am to 10:30 pm, seven days a week. As shown in Figure 6.4, 97% of the occupied hours now fall within the schedule during the 2019-2020 heating season. It is likely that it will increase the perceived control felt by individuals. It is also likely that this may reduce the value of the thermostat feature, which was designed to inform occupants of the setback schedules. Nevertheless, the feature may still be valuable for other buildings with shorter operating schedules.

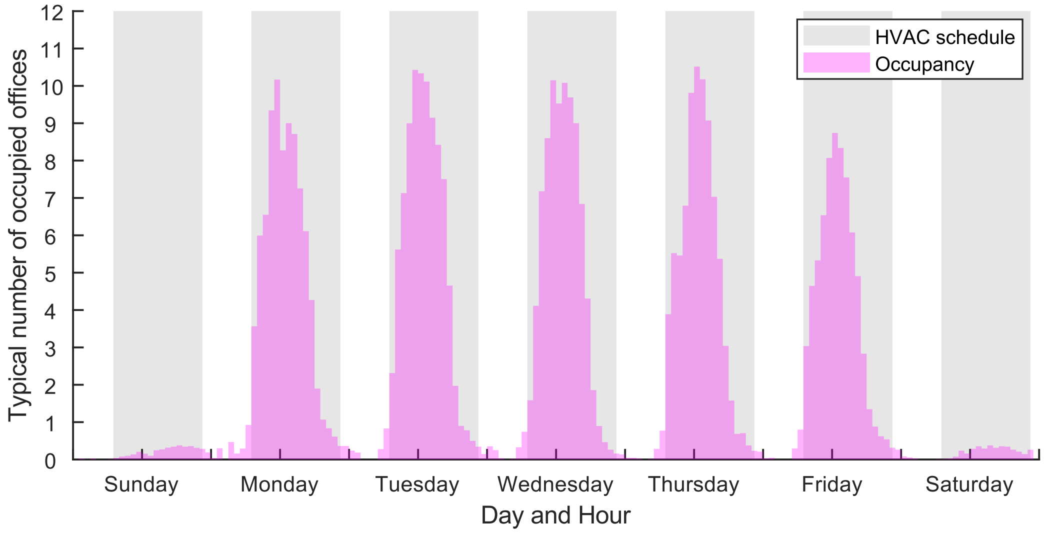
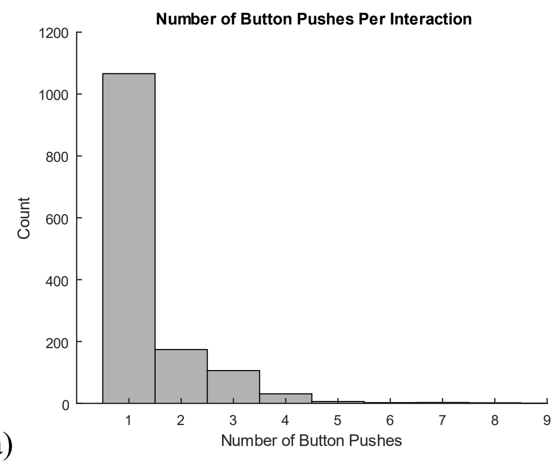


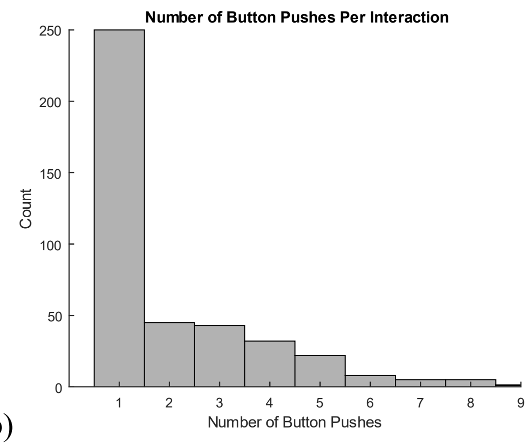
Figure 6.4 Distribution of occupancy for the 2019-2020 heating season compared to the HVAC occupancy schedule. October 25th, 2019 – March 25th, 2020

6.1.5 Thermostat use, button presses

Thermostat button presses with the upgraded thermostats were monitored in the same way as the pre-implementation phases. Consistent with the pre-implementation phase, an interaction in this context was defined as a cluster of button presses within a two-minute period from when the first button is pressed. When averaged for daily interactions to account for the differing periods, the aggregated number of interactions in all the offices during the test period was approximately 13 per day (approximately 0.5 per office), compared to 15 per day in the pre-implementation testing period. An increase in interactions involving more than two button presses was observed in the testing period. During the pre-implementation phase of the study, 97% of the interactions were three or fewer button presses occurring within two minutes, whereas 97% of the interactions occurring in the post-implementation phase involved six or fewer button presses within the same time interval. Since the office users had time to get used to their pre-implementation design, it is hard to assess whether the increased button presses were caused by confusion, interest with the new features, learning the new features, or another factor. A longer testing period would be required to give individuals time to adjust to the new features to further analyze the meaning of these interactions.



a)



b)

Figure 6.5 Comparison of button presses per interactions during (a) pre-implementation period and (b) the implementation period, while the thermostat features were in effect.

In the pre-implementation period, feedback via changes to the indoor air temperature was assessed and found to take up to 35 minutes. This delayed feedback was addressed through the heating system status thermostat feature by providing real-time information about the heating system status to occupants. The performance of the feedback provided by this feature is covered in Section 6.2.1.

6.2 Technical performance of thermostat features

6.2.1 Heating system status

The heating system status feature provided people real-time information about their heating system operation. One of the primary goals of this feature was to passively communicate HVAC operation to occupants by changing the colour between white, red and orange. In addition to this, further detail about which heating system was operating was communicated by changing the symbol of the flame to show either no flame, a flame with a one, and a flame with a two (based on which heating system was active). One aspect of the feature discussed in the technical implementation was that people may be annoyed if the thermostat changes colour numerous times within a short time period. The frequency in which the heating system status was updated was limited to 15 minutes unless people were actively engaging with their setpoint. The daily frequency per office within which the heating system status changed is shown in Figure 6.6. A box plot which compares the daily heating system status changes per office if no filter was applied (top), and the daily heating system status changes filtered by 15 minutes (bottom), as viewed by the occupants. When no filter is applied, some days would have exceeded 200 status changes in a single office. Once filtered, most rooms changed their status between 0 and 20 times per day. How frequently the heating system status, and therefore backlight colour, should be updated changed is difficult to know, and likely requires iterative user testing.

Another primary motive for communicating the heating system status was to provide immediate feedback to occupants after a setpoint adjustment. Previously, after a setpoint adjustment was made, the only form of feedback that the system is working to achieve the setpoint was viewing the system's effect on the indoor air temperature. The thermostat now provides feedback through the heating system status feature. The performance of this feature was monitored, and the results are presented in Figure 6.7. In approximately 60% of setpoint changes, no feedback would have been expected based on the current heating system status already displayed by the thermostat. For example, if a room was already in its maximum heating (due to the room temperature already being below the setpoint) and the user increased the setpoint, the room would remain in maximum heating, and no heating system status change would be expected. In the cases where feedback was expected, 58% of the time feedback was given within 1 second, and 80% of the time feedback was given within 5 seconds or less.

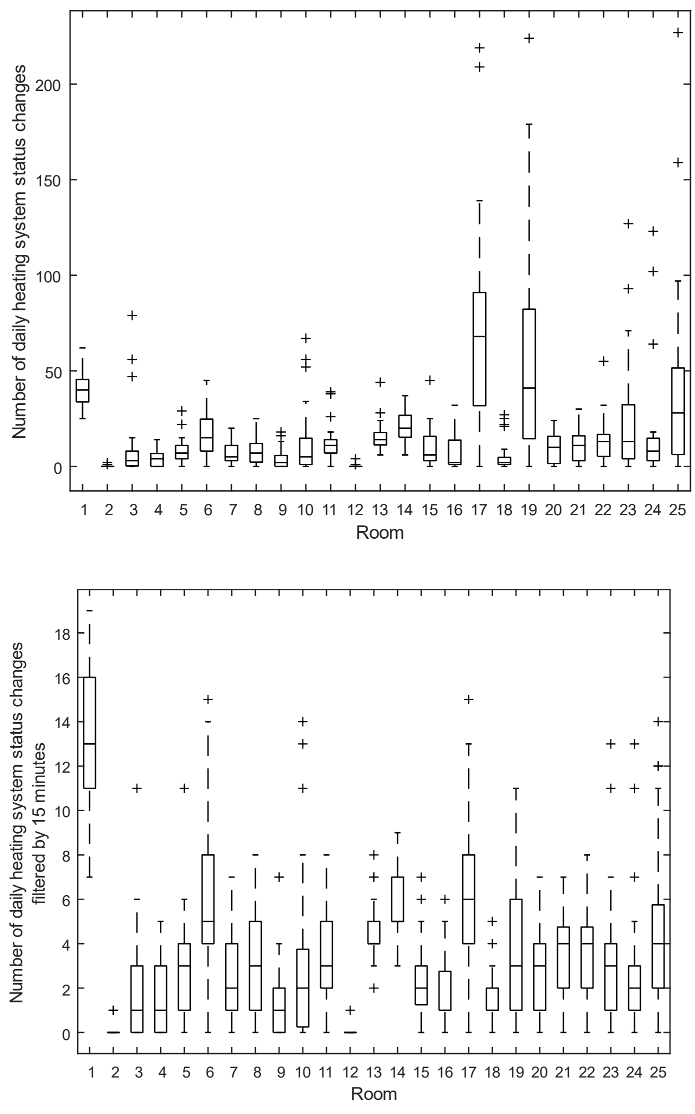


Figure 6.6 Box plots depicting the daily heating system status changes per office. (top) daily status changes per office if no filter was applied and (bottom) the daily status changes with the 15-minute filter applied, as seen by the office occupants. October 25th, 2019 – March 25th, 2020

Since the status was connected to the control variables in the room controllers, the times where it took more than 5 minutes was related to a slow or incorrect response from the control system. This finding points to a need to include control system design into the process when adding transparency to the system. The control system should be operating predictably for the occupants for this feature to work consistently.

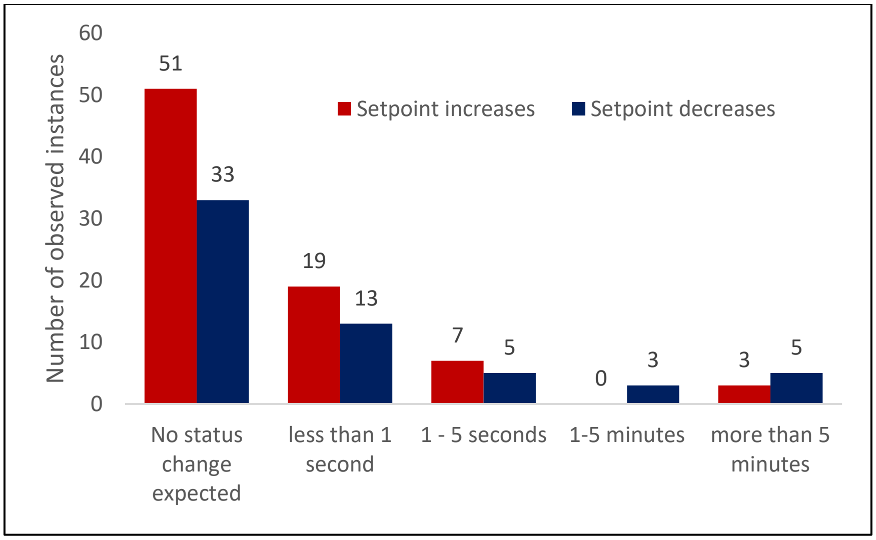


Figure 6.7 Time between when a user adjusts the setpoint and when a heating system status change could be observed on the thermostat. February 10th, 2019 – March 15th, 2020

6.2.2 Time-to-temperature data-driven model deployment

In the design and implementation of the time-to-temperature grey-box model, a model was developed, trained on three months of training data, and evaluated on three months of validation data. An average MAE of 30 min was observed for a 60 min estimating horizon during validation. Figure 6.8 shows the comparison between the validated model accuracy and the measured model accuracy during the period where the thermostat features were in effect for a 60-minute time horizon. These results show only a deviation increase from the expected model accuracy, with the average MAE of 37 minutes for a 60-minute time horizon. This increase could be due to several factors.

Firstly, the training and validation data where over the same months of October to January; however, the thermostat was implemented in the months of February and March. Additionally, the short time frame leads the MAE to be calculated from only a few estimates in some rooms. Since this is one of the first implementations of displaying time-to-temperature to office users, the acceptability of this accuracy is unknown. The survey asked participants if they were satisfied with the accuracy of this estimation, which is discussed in Section 6.3.1.

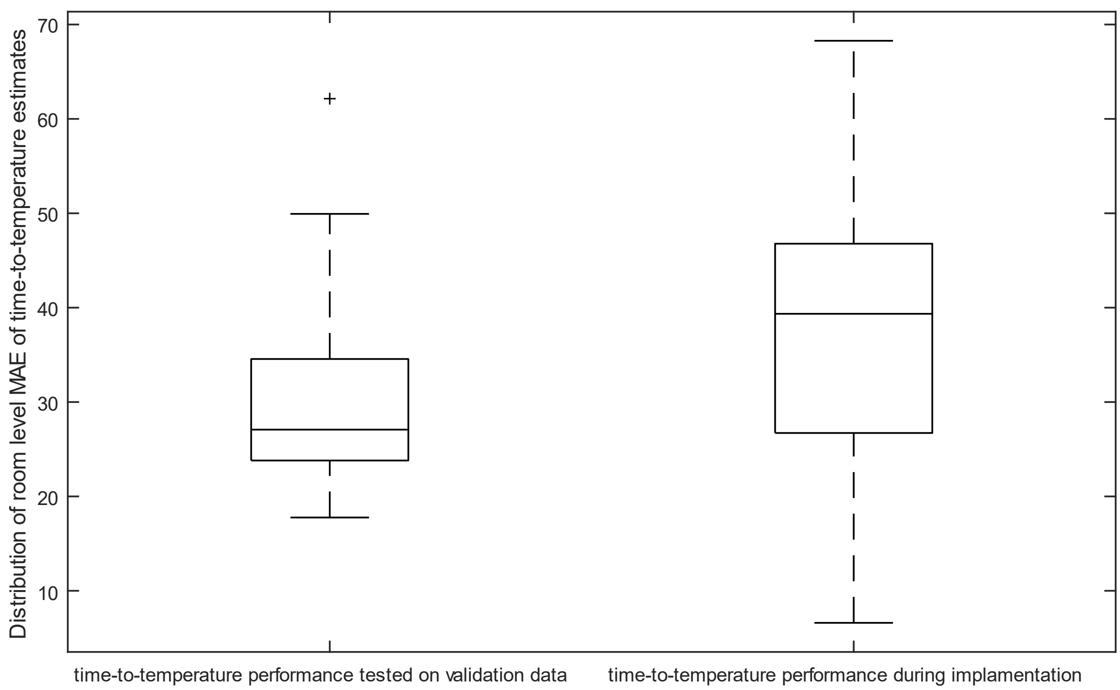


Figure 6.8 Box plot showing the time-to-temperature prediction accuracy when tested on the validation data compared to the prediction accuracy during the implementation period. The range indicates the difference in room level performance.

6.3 Post-implementation survey

The post-implementation survey was distributed immediately prior to the thermostat field testing to receive feedback on people's overall comfort, perceived control, understanding of the new features, and to assess the value of the new features.

This survey was administered on April 17th, approximately one month after the evaluation of the thermostat redesign, and during the time that the COVID-19 work from home policy was in effect. Surveys were emailed to participants' work email addresses, and participants who completed the survey likely did so from home.

The rationale and descriptions of the survey questions are described below. The full survey, as administered, is located in Appendix A.

1. Due to the limitations of the existing thermostat interface, the meanings of the features developed were not necessarily intuitive or immediately apparent to the users. To help support the implementation, an instruction manual was distributed to support comprehension if needed. Several questions in the survey were designed to evaluate whether the new features were understood by participants.
    a. Questions 5 to 7 showed different examples of the display of the thermostat, in various modes. Participants were asked to indicate what the display was telling them.
    b. Question 11 asked participants to rate how much they agreed that the instruction manual helped them understand all the new features. One of the answers allowed them to select if they did not read the manual.
2. The survey participants were also asked questions about their opinions about the various features. These questions were designed to inform future design iterations.

   a. Question 9 asked participants to rate the value of each of the new features between low, moderate, and high. An option was also provided if they were not aware of the feature added.
   b. Question 10 asked directly about their satisfaction with the accuracy of the time-to-temperature estimates that were displayed on their thermostats.
3. The improvements to thermal comfort are expected to come through the framework proposed in the literature review. Under this framework, the new features were intended to improve the feedback given to the user (i.e. what Norman and Draper refer to as the evaluation bridge) which allows for a better mental model or a better understanding of the system. To evaluate this, two questions were asked to assess if the features improved the participants' understanding of the system.
   a. Question 12, which was also asked in the pre-implementation phase to create a baseline of comparison, asked people to rate the impact of several factors of their office temperature. These parameters included setpoint temperatures, radiator operation, VAV operation, occupancy, time of day, and the conditions in neighbouring offices.
   b. Question 13 directly asked participants if they felt that the features improved their understanding of the heating system.
4. While the developed features primarily focused on usability, understanding, and feedback of the control system, the thermal comfort literature review (Section 2.1) established that improving the usability of thermostats may improve

perceived control and thermal comfort. To test the implemented feature's effect on perceived control and comfort, the same questions posed in the pre-implementation survey were restated in the post-implementation to examine potential changes in response. In cases where the participants did not fill out the previous survey, a question directly asked if these comfort factors improved, stayed the same, or got worse since the new thermostat features were implemented.

   a. Question 1 asked about the participants' overall comfort in the building, since the thermostat features were implemented.
   b. Question 2 asked how effective they felt their thermostat was at controlling their comfort preferences.
   c. Question 3 asked how satisfied participants were with the speed the temperature in the office changed after making a setpoint adjustment.

5. Finally, two additional open-ended questions were added to gather further feedback on the office comfort and usability of the thermostats.
   a. Question 14 asked if the participants had any more comments about the new features added to their thermostats.
   b. Question 15 asked if the participants had any additional feedback regarding the comfort in their offices.

For this post-implementation survey, facilities management did not request any additional questions to be added for their purposes.

6.3.1 Survey results

Likely due to the survey being administered during the work from home policy, only four respondents answered the survey. Each of the respondents answered in a notably different way such that even with these limited responses, the survey results may provide some preliminary insight about the changes made to the thermostat.

Participant 1 reported that their sense of comfort and perceived control improved due to the changes that were made. They rated all the new features as providing ‘high value,’ except for the feature which displayed the text “OFF” during scheduled setbacks, which the participant reported they were not aware of. This participant agreed that the user manual helped them understand the new features and, importantly, said that the thermostat improved their understanding and control of the heating system. Participant 1 reported that they were neither satisfied nor dissatisfied with the comfort of the thermal environment and satisfied with both the level of control and response time to setpoint changes. This participant also reported that these factors improved since the new thermostat features were installed. This is consistent with their responses in the pre-implementation survey, where they stated that they were dissatisfied with their thermal comfort, very dissatisfied with their level of control, and rated the response to setpoint changes as very poor.

Participant 2 had a positive rating to their thermal environment and level of control, reporting that they were satisfied with the thermal environment, found the control effective, and were satisfied with the response time to setpoint changes. Unlike Participant 1, however, they reported that this did not improve or get worse after the new features were implemented. Interestingly, in their pre-implementation survey, while they reported satisfaction with the thermal environment, they were dissatisfied with their level of control and rated the response times as poor. It is possible that this perception changes throughout the year or depending on other contextual factors and the change of opinion happened prior to the new features being added to the thermostat. This participant rated the red colour to indicate heating and the time to temperature estimate as having moderate value. They also reported that they were unaware of the orange light and the flame icon/number and rated the “OFF” text to indicate scheduled setbacks as low value. They had no opinion on the time to temperature accuracy and did not read the instruction manual. While they did not report any improved perceived control over the environment due to the new features, they did report that the new features helped them improve their understanding of how their heating system works.

Participant 3 was satisfied overall with their thermal environment, both in this survey and the pre-implementation survey. They were neither satisfied nor dissatisfied with their level of control and had never adjusted the thermostat. This participant was completely unaware of any of the new features added to the thermostat and had not read the manual. As a result, this occupant reported no increase or decrease of both their understanding of the system or their perceived control as a result of these new features.

Participant 4 responded very negatively to the new features. They reported dissatisfaction with their thermal environment, rated their control as poor, and were dissatisfied with the response time. The respondent reported all of these factors got worse after the new thermostat features were installed. This occupant was unaware of the red or orange light to indicate heating, was unaware of the “OFF” text to indicate scheduled setbacks, found moderate value in the number to indicate which heating system was active, and found high value in the time to temperature estimation. This participant had stated they were neither satisfied nor dissatisfied with the accuracy of time to temperature estimate. They agreed the instruction manual helped them understand all of the features; however, they disagreed that it helped them better understand the heating system, and strongly disagreed that it helped their perceived control. This participant left a comment, which perhaps identifies a reason for this negative response. The comment expressed a strong dislike for the zoning, stating the shared air-based system between offices is undesirable. The following quote is from their response.

> *"This is actually an equity issue, as people with health problems that affect their need for cooler/warmer conditions cannot self-regulate their environments."*

In three of the survey questions, participants were given a picture of the thermostat display, as shown in Figure 6.9, and were asked to identify what the displays indicated. All the participants were able to identify that the "OFF" text in example (a) indicated that their heating system was switched off. For example (b) of Figure 6.9, all of the participants identified that the system was heating, and all but participant 3 (who was unaware of the implemented feature prior to this survey) was able to identify that the room was predicted to reach their setpoint temperature in an hour and a half. None of the participants, however, identified that the thermostat was indicating that both the radiator and VAV were being used to heat the room. All the participants were able to understand that (c) was indicating that the room was being heated, even though the setpoint temperature was lower than the indoor air temperature.

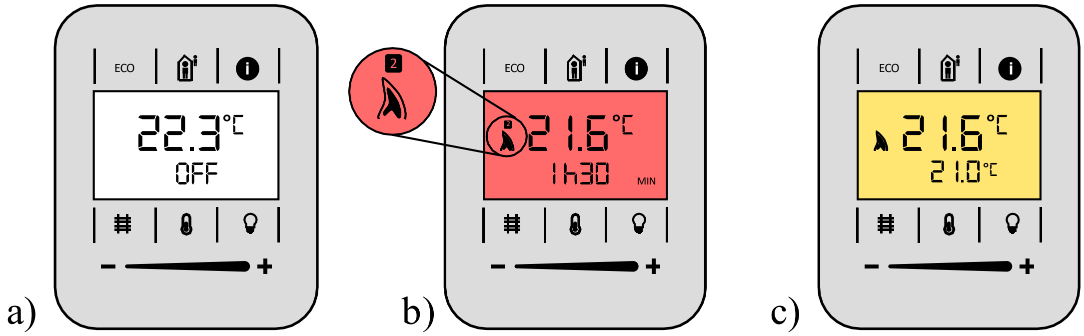


Figure 6.9 Displays as presented to survey participants in the post-implementation survey to test their understanding of the new features

Finally, the way in which survey participants rated the impact of various factors between one and five (one-no impact, five-high impact) on their room temperature was compared to the previous findings in the pre-implementation survey. When comparing the results of this question to those who completed the previous survey, there appear to be no patterns in these ratings, even for those participants stating that the thermostat improved their understanding of the system. Participant 4, who reported negatively to the features, did not fill out the pre-implementation survey, so a comparison is not possible. Participant 1, who found the features useful, rated the impact of the thermostat setpoint as three in the post-implementation survey vs two in the pre-implementation survey. They also increased the rating of the effect of other offices from three to four. Participants 2 and 3, both changed the effect of the thermostat from two in the pre-implementation survey to one in the post-implementation survey.

6.4 Phase 3 Discussion

The control systems operated similarly between the two heating seasons when assessing both setpoint control and the response to setpoint changes. It is therefore expected that changes in participant's experience towards comfort and perceived control are likely affected by the thermostat features, rather than the control system building performance. The one exception to this is the scheduled setbacks, where the time the system is operating based on the user setpoints were significantly expanded by facilities management. It is expected this may have increased the overall perception of people's perceived control.

Overall, the heating status features performed as expected. The thermostat provided near-instant feedback when expected for a majority of interactions, with only eight examples where the heating system took longer than 5 seconds to display feedback. The performance of the time to temperature model performed similarly to expected, with an average MAE of 37 minutes for a 60-minute time horizon. In the survey, two of the participants stated that they were neither satisfied nor dissatisfied with the accuracy of this estimate, while the other two participants had no opinion.

As there were only four participants in the post-implementation survey, it is not possible to generalize the results. Despite this, each respondent had a very different response to the updated thermostat, which provides interesting feedback to future design iterations and implementations. One participant reported that the updated features made to the thermostat were valuable and reported a significant increase in their level of control and satisfaction with the thermal environment. Providing additional support and transparency to the control system seems to have successfully improved this person’s perceived control, even though no changes were made to the control system.

On the contrary, another participant found a significant decrease in comfort and perceived control with the new features. Given the control issues identified in the pre-implementation assessment of the control system, this negative case shows how offering more transparency about the real personal control people have over their environment may have adverse effects if that real personal control is low. While this participant disagreed with the statement that the new features improved their understanding of the system, their comment displayed a high understanding of the building zoning, which appeared to be a major cause of dislike of the system and the real ability to exercise personal control.

Of the two neutral participants, one reported some value in the features, while the other reported that they were not aware of the new features. With only two participants in this category, it is difficult to draw conclusions; however, it is likely notable that both participants were overall satisfied with their thermal environment. It is likely that satisfaction with the thermal environment reduces the need for interactions with personal control devices and, therefore, would reduce frustration with a lack of control.

Chapter 7: Conclusion

This thesis aimed to identify, develop solutions, and obtain feedback with regards to usability issues related to HVAC control systems and thermostat interfaces in office buildings. The project was carried out on 25 offices in an institutional building located in Ottawa, Canada, during the heating season. There were three phases, the pre-implementation phase (Phase 1), the design and implementation phase (Phase 2), and the post-implementation phase (Phase 3).

The pre-implementation phase provided a solid foundation on which to design and implement new features to the thermostat. The analysis suggested that in the case of this building, low perceived control may be caused by control systems that are not designed for usability. Individual thermostat interfaces were provided in all the offices; however, the current implementation did not reflect the complexity of the HVAC control system. Setpoint control was highly contextual, the system was slow to respond to adjustments, and scheduled setbacks was in no way communicated to individuals in their offices. A pre-implementation survey was administered, and the results revealed that participants showed a high self-assessed proficiency with the ability to select setpoints and were able to understand the display of the current implementation of the thermostat. Despite this, participants reported low perceived control and were unhappy with their ability to control their thermal comfort system.

In the design and implementation phase, modifications were developed to the thermostat interface to address the usability issues identified in the pre-implementation phase. Features were developed which aimed to increase the visibility of the HVAC system by improving feedback provided through the interface, and by doing so, improve people's mental models of how the system works. Three forms of feedback were communicated through the thermostat interface; the status of the heating system, when scheduled setbacks were in effect, and a time-to-temperature estimate. To provide time-to-temperature estimates, a reverse modelling approach was used to develop grey-box room models. All of these features were implemented while retaining current operation such that people are not frustrated with the changes made. The process for the interface design was described in detail and involved establishing the requirements, designing alternatives, prototyping, and evaluating.

In the post-implementation phase, the building performance was analyzed to ensure consistent operation between seasons. The operating conditions during the implementation period remained relatively similar, allowing the impact of the thermostat interface on user experience and thermal comfort to be tested independently. Surveys were administered to gather feedback, and while final survey participation was low and did not present generalizable findings, valuable feedback was provided regarding the developed prototype. While one participant found the new features did as intended and improved perceived control and thermal comfort, another was dissatisfied and appeared frustrated by what the increased transparency told them about their limited control. This result may create hesitancy to provide this level of feedback; however, an important take away is that usability of the control system is related to the whole system design, and future considerations regarding the zone level design should be considered in the usability and control of the office.

The recommendation is to perform this interface development process with iterative loops, rather than linearly, using techniques such as paper prototyping. Due to time constraints, limited access to the users, and limitations of the existing interface in this project, the design process was performed without involving users, and a relatively advanced prototype was used for testing. The results from this process represent one of the first real-world implementations in an office building of a thermostat with the features developed, and the survey results provided relevant feedback for future designs. While the analysis only involved one building in the heating season, many of the learnings are applicable to other types of office buildings in both heating and cooling.

7.1 Contributions

The first significant contribution to the field is the combination of a long-term control system measurement and analysis of 25 offices in an institutional building in Ottawa, Canada, combined with survey results of the office users. This analysis quantified the building control characteristics by measuring setpoint control, setpoint response time, and occupancy during scheduled setbacks. Thermostat interactions and feedback through the display was measured, and a survey was used to understand participants' level of comfort, perceived control, and proficiency with the existing interface. The three primary suspected usability issues were identified (1) setpoint control was contextual based on a user prescribed setpoints in an occupants room, and the other rooms in that same zone, (2) response times to user prescribed setpoints changes were slow and unpredictable, and no immediate feedback was provided through the interface, and (3) setpoint control was significantly reduced during scheduled setbacks, which were not communicated to individuals in the room.

The second major contribution is the documented design process of a thermostat interface, which aimed to address usability issues in this building. The developed features were (1) providing detail about how the system was operating through the thermostat display and backlight colouring, (2) indicating when setback schedules were in effect, and (3) providing time-to-temperature estimates when the system was heating to meet a setpoint.

The third major contribution is the implementation of the proposed thermostat features in 25 offices of an institutional building, representing one iteration of this design process. The building performance was monitored, and a survey was administered to gather feedback about the implemented features. The results of each participant were documented and described in detail and provided relevant feedback for future designs.

7.2 Future work

While the work in this thesis focuses specifically on a single institutional building in Ottawa, Canada, during the heating season, it is suspected that the fundamental problems this building suffers from are likely widespread. The literature in human factors recommends that human-computer interaction be considered beyond the user technology and be implemented early in the design process. Further research should be performed to help characterize the complexity of HVAC control systems, how thermostat interfaces are designed, and how these affect perceived control. Further consideration should also be put towards understanding how much control should be provided to people. In the case of this research, individual thermostats were provided to each office; however, due to zoning, office-level control was not always available. Slow thermal response times also meant that if people were uncomfortable, they could not quickly alleviate their discomfort. Currently, guidance on acceptable response times and setpoint regulation is limited and requires further research and standardization.

In the building studied for this research, many fundamental human factors principles related to these types of devices were not followed. Clear feedback after an adjustment and communicating system status are seen as basic design principles in the human factors literature; however, they were not features of these thermostats. It is expected that this also applies more broadly, and more research is required to understand the true implications of thermostat design on perceived control. Aspects of the thermostat features developed in this thesis should be further iterated and implemented in other buildings to provide these fundamental human factor design elements.

The complex control system design was identified as one of the barriers to usability in this building; however, in many cases, there are advantages to advanced control schemes for purposes of energy savings and comfort. Modern building automation systems and IoT connected sensors provided exciting prospects for advanced control schemes. Some examples of emerging controls which aim to reduce energy are optimum start scheduling, model predictive control, and occupancy detection-based space conditioning. Designers of these systems should study and employ human factors research to understand the implications of these systems. Since thermal comfort is recognized as a state of mind, which is affected by both physiological and phycological factors, it is not enough to simply maintain environmental conditions. The psychological effects associated with these systems, and how they remove or add perceived control should also be considered.

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Appendix A – Survey questions

The two surveys were emailed to the individuals using the 25 offices studied for this thesis. These surveys were emailed out via google forms. Based on the ethics clearance, consent was collected to use the survey responses for research purposes. For both surveys, participants could opt out of the research portion and send their responses directly to the facilities managers of the building.

A.1 Pre-implementation survey questions

Please enter your primary office number in the Health Sciences Building: ______________

1. Rate your overall satisfaction with the temperature in your office during the summer months (cooling season).

❑	❑	❑	❑	❑
Very dissatisfied	Dissatisfied	Neither	Satisfied	Very satisfied

2. In the summer months, my office feels: (select all that apply)

	Most of the time	Mornings	Afternoons	Evenings	Weekends
Comfortable	❑	❑	❑	❑	❑
Too Hot	❑	❑	❑	❑	❑
Too Cold	❑	❑	❑	❑	❑
Too much air movement	❑	❑	❑	❑	❑
Not enough air movement	❑	❑	❑	❑	❑

3. Rate your overall satisfaction with the temperature in your office during the winter months (heating season).

❑	❑	❑	❑	❑
Very dissatisfied	Dissatisfied	Neither	Satisfied	Very satisfied

4. In the winter months, my office feels: (Select all that apply)

	Most of the time	Mornings	Afternoons	Evenings	Weekends
Comfortable	❑	❑	❑	❑	❑
Too Hot	❑	❑	❑	❑	❑
Too Cold	❑	❑	❑	❑	❑
Too much air movement	❑	❑	❑	❑	❑
Not enough air movement	❑	❑	❑	❑	❑

5. How effective is your wall-mounted thermostat at controlling the temperature to your comfort preferences?

❑	❑	❑	❑	❑
Very Poor	Below Average	Average	Above Average	Excellent

6. How satisfied are you with the speed that the temperature of your office changes after you change the temperature setting on your thermostat?

❑	❑	❑	❑	❑
Very dissatisfied	Dissatisfied	Neither	Satisfied	Very satisfied

7. Rate your satisfaction with the humidity in your office.

❑	❑	❑	❑	❑
Very dissatisfied	Dissatisfied	Neither	Satisfied	Very satisfied

8. With regards to humidity, my office generally feels:

In the summer:	❑ Too humid	❑ Too dry	❑ Acceptable
In the winter:	❑ Too humid	❑ Too dry	❑ Acceptable

9. Rate your satisfaction with the light levels in your office.

❑	❑	❑	❑	❑
Very dissatisfied	Dissatisfied	Neither	Satisfied	Very satisfied

10. Do you have any other comments regarding comfort in your office?

11. Based on your experience, indicate anywhere on this scale the impact the following factors have on your office air temperature.

	1 (No impact)	2	3	4	5 (High impact)
The temperature setting of your thermostat	❏	❏	❏	❏	❏
Increasing/decreasing the requested temperature setting significantly above/below the current air temperature	❏	❏	❏	❏	❏
The temperature of air coming through the vent in your ceiling	❏	❏	❏	❏	❏
The temperature of the radiator under your window	❏	❏	❏	❏	❏
Whether or not I am in my office	❏	❏	❏	❏	❏
The temperature settings of neighboring offices	❏	❏	❏	❏	❏

12. When do you typically adjust the temperature on your thermostat? (select all that apply)

❏ I don't typically adjust the temperature
❏ When I feel uncomfortable with my office temperature
❏ I know what temperature I prefer, and I adjust when I notice my thermostat is not at that setting
❏ I have given up on adjusting my thermostat as it does not seem to work
❏ Other ___________________________

13. How easy it is to adjust the following settings on your wall-mounted thermostat?

	Never attempted to adjust this	Not sure how	Difficult	Moderate	Easy
The temperature setting	❏	❏	❏	❏	❏
The light level	❏	❏	❏	❏	❏
Blind position	❏	❏	❏	❏	❏

14. Based on what is displayed on the wall thermostat below, please indicate which of the following statements are/is true. (Select all that apply)

❑ The temperature setting is greater than the current indoor air temperature

❑ The temperature setting is less than the current indoor air temperature

❑ The office is being cooled

❑ The office is being heated

❑ No information about whether the office is being heated or cooled is shown

15. Are there any suggestions or complaints you have regarding the operation or interface of your wall-mounted thermostat?

A.2 Post-implementation survey questions

Please enter your primary office number in the Health Sciences Building.

____

On February 9th, 2020, software changes were made to your wall mounted thermostat. Please answer all these questions based on your experience since the new thermostat features were installed.

1. A) Since the update to the thermostat was installed, rate your overall satisfaction with the temperature in your office during the most recent winter months (heating season).

   ❑ Very dissatisfied ❑ Dissatisfied ❑ Neither ❑ Satisfied ❑ Very satisfied

   B) Did this improve, stay the same, or get worse since the new thermostat features were added?

   ❑ Improved ❑ Stayed the Same ❑ Got worse

2. A) How effective did you find your wall-mounted thermostat at controlling the temperature to your comfort preferences?

   ❑ Very Poor ❑ Below Average ❑ Average ❑ Above Average ❑ Excellent

   B) Did this improve, stay the same, or get worse since the new thermostat features were added?

   ❑ Improved ❑ Stayed the Same ❑ Got worse

3. A) How satisfied were you with the speed that the temperature of your office changed after you changed the temperature setting on your thermostat?

   ❑ Very dissatisfied ❑ Dissatisfied ❑ Neither ❑ Satisfied ❑ Very satisfied ❑ I did not adjust my thermostat since the new features were installed

   B) Did this improve, stay the same, or get worse since the new thermostat features were added?

   ❑ Improved ❑ Stayed the Same ❑ Got worse ❑ I did not adjust my thermostat since the new features were installed

4. A) How satisfied were you with the with time it takes for your office to warm up in the morning?

   ❑ Very dissatisfied ❑ Dissatisfied ❑ Neither ❑ Satisfied ❑ Very satisfied

   B) Did this improve, stay the same, or get worse since the new thermostat features were added?

   ❑ Improved ❑ Stayed the Same ❑ Got worse

Please answer these questions based on what you remember. Please do not refer to your wall mounted thermostat, the user manual, or other sections of this survey.

5. Based on what is displayed on the wall thermostat below, please indicate which of the following statements are/is true. (Select all that apply)

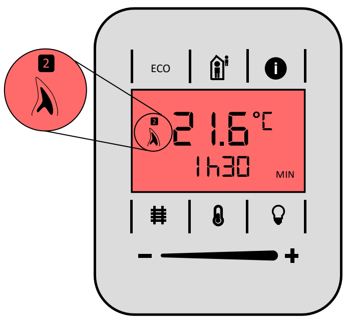
❑ The light is currently switched off

❑ The thermostat backlight has been turned off

❑ The office heating system has been turned off

❑ The office is being heated

6. Based on what is displayed on the wall thermostat below, please indicate which of the following statements are/is true. (Select all that apply)



❑ The office is being heated

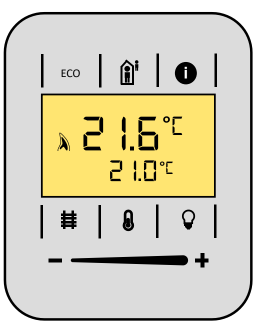
❑ The radiator is currently being used to heat the room

❑ The air-based system is currently being used to heat the room

❑ It is estimated that it will take 1.5 hours for the room to heat up to your temperature setting

❑ There is no information on whether the room is currently heating

7. Based on what is displayed on the wall thermostat below, please indicate which of the following statements are/is true. (Select all that apply)



❑ The office is being heated

❑ The radiator is currently being used to heat the room

❑ The air-based system is currently being used to heat the room

❑ It is estimated that it will take 1.5 hours for the room to heat up to your temperature setting

❑ There is no information on whether the room is currently heating

8. Based on your experience, indicate on this scale the impact the following factors have on your office air temperature.

	1 (No impact)	2	3	4	5 (High impact)
The temperature setting of your thermostat	❑	❑	❑	❑	❑
Increasing/decreasing the requested temperature setting significantly above/below the current air temperature	❑	❑	❑	❑	❑
The temperature of air coming through the vent in your ceiling	❑	❑	❑	❑	❑
The temperature of the radiator under your window	❑	❑	❑	❑	❑
Whether or not I am in my office	❑	❑	❑	❑	❑
The temperature settings of neighboring offices	❑	❑	❑	❑	❑

9. How do you rate the value of the following features which were added to your thermostat display?

	High Value	Moderate Value	Low Value	I was not aware of this feature
The screen turns red when your room is being heated based on your room's settings.	❑	❑	❑	❑
The screen turns orange when your room is heating due to the settings in a neighbouring office.	❑	❑	❑	❑
The flame appears with a number (1 or 2) depending on which heating system is active	❑	❑	❑	❑
The time that displays the estimate for how long it will take your room to reach your setpoint	❑	❑	❑	❑
The OFF display, which indicates when the heating system is off, and the room is no longer being controlled to your setpoint.	❑	❑	❑	❑

10. How satisfied were you with the accuracy of the time-temperature estimate which now displays on the thermostat?

❑	❑	❑	❑	❑	❑
Very dissatisfied	Dissatisfied	Neither	Satisfied	Very satisfied	No opinion

11. The thermostat instruction manual that was emailed to me helped me understand all the new features.

❑	❑	❑	❑	❑	❑
Strongly Agree	Agree	Neither	Disagree	Strongly Disagree	I did not read the user manual

12. The changes to the thermostat helped me better understand the heating system.

❑	❑	❑	❑	❑
Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

13. The changes to the thermostat improved my sense of control over the office temperature.

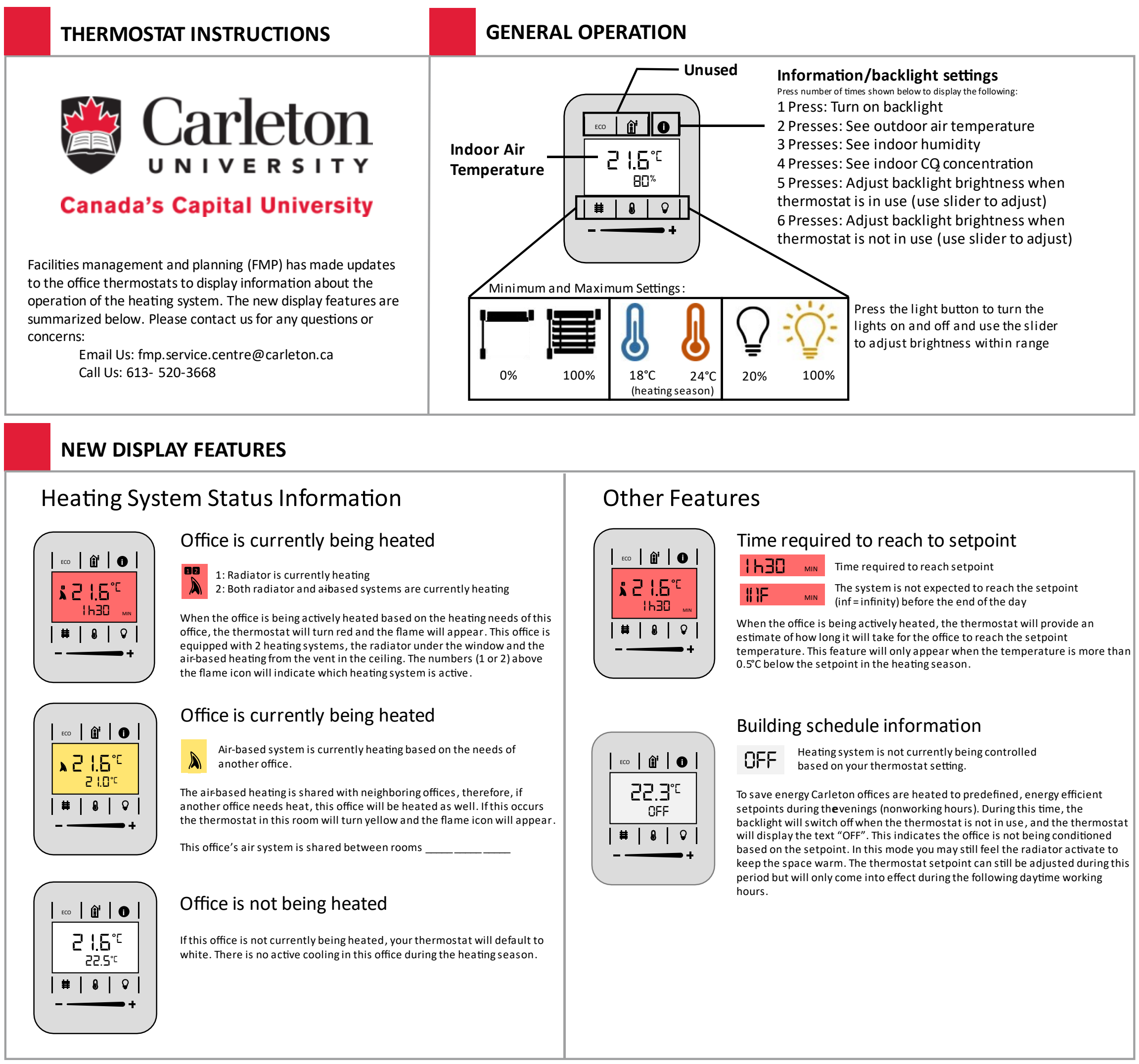
❑	❑	❑	❑	❑
Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

14. Do you have any more comments about the new features on your thermostats?

15. Do you have an additional feedback regarding comfort in your office?

Appendix B – Thermostat instruction manual

The thermostat instruction manual was distributed via email to the individuals which use the 25 offices where the modified thermostats were implemented. Distribution occurred prior to implementation.


THERMOSTAT INSTRUCTIONS

Carleton UNIVERSITY

Canada's Capital University

Facilities management and planning (FMP) has made updates to the office thermostats to display information about the operation of the heating system. The new display features are summarized below. Please contact us for any questions or concerns:

Email Us: fmp.service.centre@carleton.ca

Call Us: 613- 520-3668

GENERAL OPERATION

Unused

Indoor Air Temperature

Information/backlight settings

Press number of times shown below to display the following:

1 Press: Turn on backlight

2 Presses: See outdoor air temperature

3 Presses: See indoor humidity

4 Presses: See indoor CO_2 concentration

5 Presses: Adjust backlight brightness when thermostat is in use (use slider to adjust)

6 Presses: Adjust backlight brightness when thermostat is not in use (use slider to adjust)

Minimum and Maximum Settings:

0% 100%

18°C 24°C (heating season)

20% 100%

Press the light button to turn the lights on and off and use the slider to adjust brightness within range

NEW DISPLAY FEATURES

Heating System Status Information

Office is currently being heated

1: Radiator is currently heating

2: Both radiator and air-based systems are currently heating

When the office is being actively heated based on the heating needs of this office, the thermostat will turn red and the flame will appear. This office is equipped with 2 heating systems, the radiator under the window and the air-based heating from the vent in the ceiling. The numbers (1 or 2) above the flame icon will indicate which heating system is active.

Office is currently being heated

Air-based system is currently heating based on the needs of another office.

The air-based heating is shared with neighboring offices, therefore, if another office needs heat, this office will be heated as well. If this occurs the thermostat in this room will turn yellow and the flame icon will appear.

This office's air system is shared between rooms ____ ____ ____

Office is not being heated

If this office is not currently being heated, your thermostat will default to white. There is no active cooling in this office during the heating season.

Other Features

Time required to reach to setpoint

1h30 MIN Time required to reach setpoint

INF MIN The system is not expected to reach the setpoint (inf = infinity) before the end of the day

When the office is being actively heated, the thermostat will provide an estimate of how long it will take for the office to reach the setpoint temperature. This feature will only appear when the temperature is more than 0.5°C below the setpoint in the heating season.

Building schedule information

OFF Heating system is not currently being controlled based on your thermostat setting.

To save energy Carleton offices are heated to predefined, energy efficient setpoints during the evenings (nonworking hours). During this time, the backlight will switch off when the thermostat is not in use, and the thermostat will display the text "OFF". This indicates the office is not being conditioned based on the setpoint. In this mode you may still feel the radiator activate to keep the space warm. The thermostat setpoint can still be adjusted during this period but will only come into effect during the following daytime working hours.