Towards a Human-Centered Thermostat
An Open-Source Approach

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ABSTRACT
August 21, 2024. Traditional thermostats are often unintuitive, difficult to use and lack specific control features. Users commonly struggle with complex interfaces, poorly labelled buttons and the necessity of consulting lengthy manuals to understand all the modes and settings on top of accessibility issues. These challenges hinder the efficient and comfortable management of home heating systems. We apply a human-centered-design process to the evaluation and creation of thermostats and a working prototype to provide an open source solution to thermostats.

Author Keywords
Smart Thermostat, Human-Centered Design, Accessible Thermostat, Smart Technology, Open Source

INTRODUCTION
As a response to the common usability issues plaguing traditional wall-mounted thermostats, our project aims to develop an accessible, open-source 'smart' thermostat. Our motivation is driven by the recognition of the needs for intuitive solutions that would empower users and allows for community collaboration through an open-source approach. By making our thermostat open-source, we allow users to individually adapt and customise the solution to fit their specific needs. This ensures that the device remains relevant and useful across a wide range user preferences as well as environments and areas of installation.

We understand that technical solutions can seem overwhelming and that diving into this kind of area of *creating* technology can be daunting for many people. However, our design prioritises simplicity, ensuring that rebuilding and modifying the thermostat does not require extensive technical knowledge.

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We believe that a well-crafted step-by-step guide can allow most people to engage with the technology, thereby making it accessible to a broader audience and encouraging innovation and improvement from the community. With this, we try to create an approach that democratises technology.

After briefly describing the main goals and motivation behind our project, as well as its scope, we detail the methodology we followed, including our human-centered design process and project plan. Following, we describe related work and the literature and research that informed our design choices and plans. Then we describe our actual implementation of our prototype and lastly conclude with implications and outlines for future work.

Objectives
Our project aims to have:

- *Affordance:* Intuitive interface with clearly labeled buttons and a high-resolution display. Operable without extensive manual consultation.
- *Advanced control features:* Specific, fine-grained control over temperature settings. Easy-to-understand modes such as eco, comfort and vacation. Mobile app for control and monitoring.
- *Ensuring simple installation and compatibility:* Easily installable hardware with clear instructions. Compatibility with standard heating systems.
- *Accessibility:* Incorporating a simplified mode in the app for easy use. Offering an advanced mode with more features for users who want greater control.
- *Open-source approach:* Detailed documentation and source code available for the community. Encouragement of user contributions and modifications.

This project focuses on creating a thermostat that is not only functional and efficient but also accessible and adaptable. By publishing all resources that are needed to recreate our solution, as well as documuent our design-choices, we allow for community engagement and continuous improvement.

Motivation

Based on a review of our own thermostat installations and existing systems as well as more background research, we identified a few issues:

- *Complexity and Lack of Intuitiveness:* A lack of affordance in the design choices of traditional thermostats limits the usability.
- *Limited Specific Control:* Precise control and more advanced control is often either unavailable or hidden deep in menus.
- *Dependency on Manuals:* Reliability of long manuals that aim to describe complicated use processes can further exacerbate existing usability issues.
- *Accessibility:* Several concerns regarding the usability and accessibility, especially allowing a usage for *all* people, such as height or visual clarity, were identified.

A more concrete description and how we identified issues is outlined in Section *Background & Related Work*. One notable observation from our literature review is also that many papers exist that identify flaws in thermostat design but offer few actual solutions or implementation strategies. Therefore, our project aims to address this gap by not only identifying issues but also by building a solution from the ground up and hence potentially identifying other solutions that could come up during design processes.

Scope and Frame

This project is part of a university course at the Technical University of Vienna (TU Wien), specifically under the Human-Computer Interaction (HCI) group[1]. The HCI group at TU Wien is dedicated to advancing a human-centered approach to technology and emphasising the importance of designing digital technologies thoughtfully to benefit people in meaningful ways. They are committed to ensuring that their work, whether in research or teaching, reflects this principle of digital technologies making a difference, but needing to be designed with care and fairness.

As master's students within the 'Media and Human-Centered Computing' program, we bring a diverse range of expertise in design, engineering and user experience to the project. Our experiences span across various projects and classes focused on accessible design, reflecting our commitment to creating technology that is inclusive and user-friendly. Our master's program is not solely about software development or engineering; it emphasises the importance of designing technology that meets the needs of users effectively and ethically and includes classes that dive into social sciences to provide development approaches that actually create usable technology.

Despite the limited timeframe of a single semester, we aim to deliver a functional prototype and open-source documentation that demonstrates our commitment to accessibility, usability and openness. This project represents a foundational step, with the potential to be expanded into a larger project, which could possibly be concluded in a master's thesis. This will be further discussed in the section 'Future Work.'

[1]http://igw.tuwien.ac.at/hci/

Additionally, our project scope is limited to how wall-mounted thermostats that are commonly operated in Vienna, Austria, since this is the location of our residences and where we have access to. We want to clarify that here, thermostats are primarily connected to heaters, unlike other places where thermostats may also control cooling systems or air conditioning units. While we aim to create a comprehensive solution, the geographical and functional limitations mean that this project cannot be generalised globally. Additionally, we focus on thermostats that are mounted to the wall and connected to it to the heating of an apartment. Thermostats that are directly mounted onto heaters also exist but work differently and our approach is not applicable to them. Nonetheless, the principles and methodologies we employ can serve as a foundation for broader applications.

DESIGN APPROACH

In our project we integrate two fundamental approaches to ensure our solution to a thermostat is both effective and inclusive: Human-Centered Design (HCD) and Open-Sourced Development. They guide our design and development process and make sure that the solutions we create are not only technically sound but also highly usable and freely accessible for further innovation.

Human-Centered Design

We acknoledge that fully-fledged human-centered design (HCD) approaches require more time than is available in the context of a single semester course. They often involve extensive user research, iterative design cycles and prolonged testing phases to deeply understand and address user needs. Despite these time constraints, we place a high value on the principles of HCD and remain committed to integrating them into our project as much as possible. HCD is an approach to interactive systems development that focuses on users, their needs and requirements[2]. This approach not only aims to make systems usable and useful but also enhances their effectiveness, efficiency and overall user satisfaction by incorporating human factors and usability knowledge and techniques. This interdisciplinary approach has its origins at the intersection of various disciplines. The idea was initially proposed in 1958 at Stanford University's design program by Prof. John E. Arnold, who advocated for engineering design to be human-centered [12].

In our commitment to Human-Centered Design, we rigorously follow Stanford's five phases of Design Thinking: Empathise, Define, Ideate, Prototype and Test [9]. Each of these phase is critical and feeding into the next.
In the **Empathise** phase, we conduct focused research to understand users' needs, behaviors and challenges. We conduct thorough research to understand user needs and existing thermostat shortcomings, encompassing a literature review of current approaches in thermostat design and human-computer interaction. This informs our design decisions.
During the **Define** and **Ideate** phase, we try to articulate and tackle these needs and challenges. We aim to challenge traditional assumptions and generate a broad spectrum of creative

[2]https://www.iso.org/standard/77520.html

solutions. Outline in the planning section, we include the roadmap that iss defining objectives, tasks and timelines to guide project implementation.
The **Prototype** phase involves creating a solution, essential for visualising and initial testing of design concepts. Section *Implementation* will describe this approach of putting the research into an actual prototype that is prioritising accessibility, usability and adaptability where we aim to focus on implementing innovative features like intuitive interfaces and remote monitoring.
Finally, in the **Test** phase, we evaluate these prototypes. Understanding the limitations of our testing scope we try to gather some crucial insights to refine our designs and give suggestions for further research of this approach.

Therefore we have also structured the following sections according to the design thinking stages. In studying the background, we conduct thorough research to understand user needs and existing thermostat shortcomings, encompassing a literature review of current approaches in thermostat design and human-computer interaction. This informs our design decisions. The Plan stage involves developing a detailed roadmap, defining objectives, tasks and timelines to guide project implementation. Project Implementation will describe our approach of putting the research into actual prototypes, prioritising accessibility, usability and openness. In Functionality we focus on implementing innovative features like intuitive interfaces and remote monitoring. Lastly, the Outlook phase reflects on outcomes, evaluating effectiveness and identifying future directions for refinement and collaboration, allowing continued innovation in thermostat design.

Open-Source

Open-source development represents a philosophy of transparency, collaboration and freedom in software and hardware design. It allows developers to access, modify and redistribute the source material of a project for a community-driven approach to innovation and is a philosophy that is rooted in the belief that collective input and accessibility can lead to more robust, innovative and adaptable technologies.
For our project, adopting this philosophy was fundamental. It not only enhances the accessibility of our design by allowing others to adapt and modify it according to their specific needs but also aligns with our commitment to creating a solution that is inherently adaptable. We understand that open-sourced projects require users to build the prototype themselves, which may not be feasible for everyone. This on the one hand suggests a limit to accessibility, as not all potential users have the capability to assemble the device from scratch. A pre-built solution, while immediately more accessible, would inherently involve making certain design choices that might not meet every user's needs. In contrast, an open-source approach still empowers individuals by putting the power of customisation and improvement directly into their hands and give them personal agency. We acknowledge the trade-offs involved but believe in the benefits of user empowerment, community engagement and the democratisation of technology. Open-source practices enable individuals and communities to create solutions that are precisely tailored to their needs and circumstances. [4, 10, 8]

Publishing

Since our solution includes hardware as well as software, multiple web pages will be used to publish our findings. Firstly, a Github repository compromising of all of our data, including for example the files for the 3D-printing and the PCB as well as the structure of all folders needed for the setup of the software part of the solution are provided. Additionally, our project will be published on *Intractables* [3] with a guide on recreating the casing of the thermostat. Concrete links to each part are presented in Section *Implementation*.

BACKGROUND & RELATED WORK

In general, effective design requires not only a deep understanding of the technical workings of thermostats but also the human aspects of their use. In developing our thermostat solution, we recognise that our experiences with technology cannot be generalised. Therefore, we complement our technical research with literature reviews on thermal comfort and how people use thermostats as well as direct conversations, for example with people with disabilities, to ensure our solution is comprehensive and inclusive.

Thermostats

In our research we examined the thermostats installed in our home apartments in Vienna, Austria. By checking the manuals and physically inspecting the devices, we discovered that these thermostats operate on a simple mechanism involving two wires coming out of the wall that control the power supply of the heating system, represented in Figure 3.1 of a *Vaillant calorMATIC 330*.
When the thermostat detects that the temperature has dropped below a threshold of a set temperature, it closes the circuit between these wires, signaling the heating system to turn on. The heating continues until the thermostat opens the circuit once the desired temperature is reached. This straightforward on-off control method means that if the thermostat's initial power source (e.g., batteries) fails while the heating is on, the heating system could remain activated indefinitely until manually switched off or until power is restored to the thermostat. Finding and understanding this functionality was critical for our project because it shows a potential failure that our design must address. Specifically, our solution needs to ensure that in the event of a power failure or battery depletion, the system does not leave the heating permanently on, which could lead to excessive energy consumption and unsafe temperature levels.

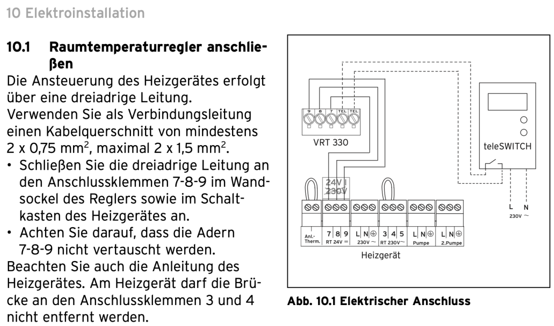
Additionally, during our evaluation, we noticed several usability issues with the existing thermostats. Many of the icons did not have any particular meaning and were rather descriptive or ambiguous, making it difficult to understand their function without thorouhgly consulting the manual, seen in Figure 3.1. While some icons were more understandable, as shown in Figure 3.1, they still likely required users to read about them once to fully grasp their meaning.

Literature Findings

Interfaces

Our findings align with those discussed in the paper "Thermostat Interface and Usability: A Survey" by Meier et al.,

[3] https://www.instructables.com/workshop/3d-printing/projects/


10 Elektroinstallation

10.1 Raumtemperaturregler anschließen

Die Ansteuerung des Heizgerätes erfolgt über eine dreiadrige Leitung.
Verwenden Sie als Verbindungsleitung einen Kabelquerschnitt von mindestens 2 x 0,75 mm², maximal 2 x 1,5 mm².

- Schließen Sie die dreiadrige Leitung an den Anschlussklemmen 7-8-9 im Wandsockel des Reglers sowie im Schaltkasten des Heizgerätes an.
- Achten Sie darauf, dass die Adern 7-8-9 nicht vertauscht werden.

Beachten Sie auch die Anleitung des Heizgerätes. Am Heizgerät darf die Brücke an den Anschlussklemmen 3 und 4 nicht entfernt werden.

Abb. 10.1 Elektrischer Anschluss

Figure 1. Description of the control in the manual of a Vaillant calorMATIC 330 thermostat.

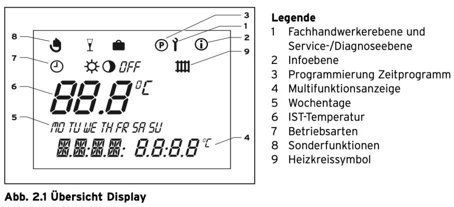


Figure 2. Possibly unclear symbols and numbers of a Homematic IP WTH-2 thermostat.

which provides a comprehensive overview of thermostat functionality and design [7]. The authors describe thermostats as devices that regulate and maintain the temperature of a system near a desired setpoint by automatically switching heating or cooling devices on until the target temperature is reached. Programmable thermostats can adjust the temperature based on a series of programmed settings that take effect at different times of the day, offering feedback on temperature setpoints, current temperature and schedules. Our approach only targets devices that enable the heating of apartments since AC units are (still) uncommon in Vienna, Austria.

Meier et al. also outline the essential components of a thermostat, which are expanded by us to serve as a valuable framework for our implementation:

- *User Interface (UI):* The input/output system for controlling the thermostat. It can be mechanical, digital with buttons, or digital with a touchscreen. Newer interfaces can also include web, mobile, TV, audio and remote controls. In our design, we focused on creating an intuitive UI on an app which could also allow for different modes for different kinds of users (simple / advanced mode). Either way, it is important that it is easy to use and accessible to all users. Existing UI designs often fail at this, oulined in more detail in Section Identified Issues.

- *Sensors:* Most thermostats include primarily room temperature sensors, with possible additions like humidity, outside temperature, or occupancy sensors. These sensors are crucial for accurately monitoring environmental conditions and adjusting the system accordingly. Some thermostats could also feature CO_2 sensors.

- *Data and Settings Storage:* Permanent or volatile memory storing essential data like time of day or the target temperature. This data storage must be reliable to maintain user settings and schedules.

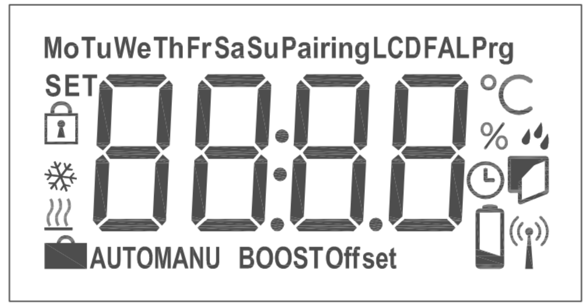


Figure 3. Descriptive symbols of a Vaillant calorMATIC thermostat that might be understandable.

- *Clock:* Provides the ability to set and keep track of time. This is crucial for programmable thermostats to operate according to user-defined schedules.

- *Communication Interface:* Enables communication with the HVAC system and other devices using various protocols. Direct communication to the heating as well as connection to a for example server for data storage and evaluation for smart controls.

- *Control Logic:* Algorithms that determine when the system switches on and off based on data from storage / server as well as the sensors. The logic should be optimise energy use and fail safe.

- *Power Supply:* Provided through batteries or mains power, with batteries often used to preserve settings during power outages.

Their paper highlights that the design of thermostats play a vital role user comfort and points out common usability issues, such as complexity, small buttons and confusing symbols, which can hinder an effective use.

Thermal Comfort

Thermal comfort is a critical factor in creating environments that promote well-being and productivity. Comfort, defined as "that condition of the mind that expresses satisfaction with the thermal environment," is considered a subjective state rather than a physiological condition. Thermal comfort specifically refers to this state of mind in relation to the thermal environment, impacting people's ability to work, relax and live comfortably. Ensuring thermal comfort is essential not only for individual satisfaction but also for overall energy efficiency and environmental sustainability [13]. When trying to understand Thermal Comfort, the Predicted Mean Vote (PMV) model is a standard method used to define and measure thermal comfort. However, adaptive models have emerged that consider variables such as clothing and window adjustments and that offer a more dynamic approach to gauging comfort. Despite their utility, both PMV and adaptive models face significant criticisms. The PMV model, for instance, is critiqued in *The adaptive approach to thermal comfort: A critical overview* by its authors for its reliance on hypothetical averages which do not account for individual variations in thermal perception [3]. These models predict an 'average' response, ignoring significant inter- and intra-individual differences that can be as large as one scale value on a seven-point thermal sensation scale. This variance, approximately 3°C, highlights the challenge of precisely predicting individual comfort. Adaptive models, while innovative, are criticised for not adequately addressing the cultural, climatic and social contexts of comfort [1]. Additionally, the heavy reliance on mechanical ventilation systems in these models contradicts environmental concerns and energy conservation efforts [3].

User Interaction

Making sure that thermal comfort is given is closely linked to the usability of thermostat interfaces, which control indoor climates. Recent studies have identified numerous design flaws that impede user interaction [6]. Thermostat interfaces often use unclear terms and symbols or confusing abbreviations such a "'tmp', 'prg', 'hld', etc. - to conserve space" and user-unfriendly interface elements such as unclear buttons and displays. Additionally, shown by Sanquist et al. in Figure 3.2.3, the physical placement of them matter highly and can create issues, such as thermostats being located in poorly lit or hard-to-reach areas, further exacerbate usability problems [11]. Gender differences in thermal comfort perceptions and thermostat usage have also been documented: women are generally less satisfied with room temperatures than males, yet men more frequently adjust the thermostats in households [5].

In Fussenegger's paper evaluation *Depending on Independence An Autoethnographic Account of Daily Use of Assistive Technologies*, several assistive technologies are discussed, including smart thermostats, which are used to manage the temperature at home due to a high spinal cord injury. The importance of a reliable temperature control for his well-being is reported. It is stated that smart thermostats allowed precise temperature adjustments via smartphone, however, he experienced a critical failure when the thermostats malfunctioned, leading to excessive heating and an inability to reset them without specific tools. This incident underscored the need for accessible and reliable assistive technologies and the importance of having fail-safes and backup plans [2]. Especially in assistive contexts, it should be considered that users are still able to manage these devices independently, especially with potential malfunctions happening.

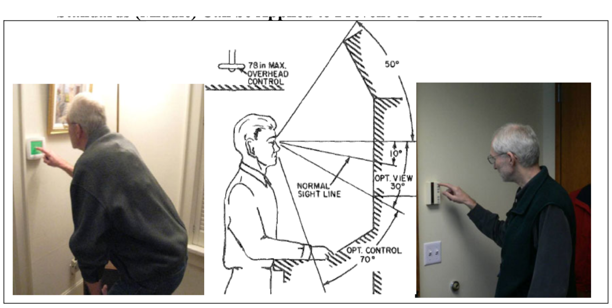


Figure 4. Authors Sanquist et al. showcase that poor positioning impacts Users stance.

One key observation from our literature review is the large number of papers that identify flaws in thermostat design but offer few actual solutions or implementation strategies. Therefore, our project aims to address this gap by not only identifying issues but also by building a solution from the ground up. Through it we contribute to the existing literature by documenting our process and potentially uncovering new challenges in the implementation of thermostat design solutions. The insights gained should additionally underscore the general need for more open source and also user-centered design approaches that consider individual variability and practical usability and by focusing on developing an accessible and intuitive thermostat, we are trying to to bring the gap between theoretical research and practical application in this field a little closer.

Lived Experiences

To ensure human-centered design, it is crucial to consult and also genuinely understand a diverse range of people. It is never sufficient to base a usability on the experiences of a narrow demographic, usually in research that being a 180cm tall white male. Instead, a broad spectrum of users must be considered and ideally engaged in discussions about their needs and challenges. Recognising the importance of this approach, we reached out to Fussenegger for further insights from his perspective and were able to have a valuable conversation with him.

Fussenegger shared that his disability and resulting implications of fine motor skills made it impossible to use the manufacturer's intended reset method, which required a needle or pin. This highlighted that often times manufacturers do consider fail safes or reset methods, but just not think about the actual people using their technologies. It was emphasised by him that assistive technologies must be designed with all functionalities being accessible and that fallback plans must be thought out actually thoroughly in advance. He highlighted the principle of "first-fault safety" seen in medical contexts, stressing that common failure modes, such as battery depletion, should be anticipated and addressed in the design. More importantly, he pointed out that components might fail unexpectedly and designers must plan for these scenarios to ensure user safety and system reliability.

Furthermore, it was stated that our adaptable design approach inherently supports accessibility, but it was noted that clear communication on how to handle these adaptable features is important. He recommended that all potential issues and their solutions be documented thoroughly. This includes considering fallback mechanisms and why they were chosen, ensuring that users actually understand how to manage potential failures.

Using Failure Mode and Effects Analysis (FMEA) was also suggested to iteratively consider and address potential failures, user groups and usability issues. This method helps clarify who the actual users are and what their needs might be, ensuring that the design process remains user-focused. The importance of including the perspectives of marginalised groups early in the design process was stressed many times to capture a wide range of needs and ensure inclusivity.

Although our project aimed to include perspectives from people with various lived experiences, such as deaf or visually impaired individuals, we were unable to do so within the extend of this project. Some steps like an extensive FMEA was also beyond the scope, however, these insights are vital for more comprehensive human-centered design. Already, Fussenegger's contributions show the importance of this inclusive approach and provide valuable guidance for future research on user-friendly technologies.

PROJECT PLAN

We structured our project in two main phases, each comprised of two components. The first phase focused on research and prototyping to align with our 'empathise' step, while the second phase concentrated on developing the controlling mechanisms and preparing for publication.

This phase was crucial for understanding the technical and user requirements of the thermostat. at the same time the prototyping component focused on designing and building the physical thermostat, including testing basic functions, designing the circuit board and creating a suitable 3D printed housing.

Phase 1 - Research and Prototyping:

- **Research:**
  - *Analysing Existing Solutions:* Comprehensive review of existing thermostat solutions to identify strengths and weaknesses.
  - *Risk Assessment:* Evaluation of potential risks associated with our design. Considering various failure modes and their impacts.
  - *Understanding User Groups:* Examining how different user groups might interact with existing thermostats - helps identify specific needs and challenges.
  - *Designing Better Controls:* Understand how to design more effective and accessible control systems for diverse user groups.
- **Prototyping the Thermostat:**
  - *Building the Thermostat Prototype:* A physical prototype of the thermostat to make sure that the basic structure and components were in place.
  - *Testing Basic Functions:* Ensuring that temperature and humidity control are working correctly.
  - *Designing the Circuit Board:* Creating, ordering and then and soldering on it the necessary circuit board components to ensure proper functionality.
  - *Creating the Housing:* Suitable housing to encase the thermostat components - should be both protecting and also allow for mounting on wall.

Phase 2 - Controlling Mechanisms and Publication:

After having a working prototype that records temperature data and can control the heating, the second phase of our project focused on developing a controlling mechanism that is user friendly. Therefore, it involved creating an app that would be the user interface for the thermostat. It is important for us to aim to account for accessibility features, but unfortunately were not able to include this step in our prototype project. An inclusion would be a possible and certainly necessary extension for this project and could also support different user profiles with different kinds of levels of interaction. These points are discussed in Section Outlook and Future Work.

- **Controlling - App Development:**
  - *Visualisation:* An app with temperature data visualisation (e.g. graphs and statistics over the past months.)
  - *Control:* Controlling mechanisms to set desired temperatures or heating settings.
- **Publication:**
  - *Open Source:* Release as an open-source project - and figure out which platforms best suitable.
  - *Documentation:* Comprehensive, to support the understanding and replication of our project.
  - *Publication of Documentation:* Published the documentation.

Timeline

We initially planned the project to follow a structured timeline, with **Phase 1** occurring in **March** and **April** of 2024 and **Phase 2** taking place in **May** and **June** and ending with the end of the semester at the start of July. Despite our initial plans, the timeline experienced some delays due to various complications, which will be discussed in detail in Section Discussion. These required adjustments to our schedule and allowed us to finish the project at the end of **July 2024**, a month later than originally planned.

Identified Issues

To help us structure our projoect and the goals defined in Section 1.1, we indentified and clarified several issues, some of which already mentioned as motivations in Section Introduction.

- **Complex User Interfaces Lack of Intuitiveness:** Many existing thermostats feature complex user interfaces with unclear icons and confusing abbreviations.
- **Lack of Intuitiveness:** Displays are hard to read or don't provide much understandable information and a lack of affordance exists.
- **Insufficient Control:** A Lack of precise control over temperature settings.
- **Inaccessibility for Users with Disabilities:** Current thermostat designs often do not consider the needs of users with disabilities.
- **Height and Placement:** Thermostats are often installed at heights that are not accessible to all users or cannot be customised.
- **Visual Dependency:** Current thermostats typically rely on visual displays and controls, making them unusable for visually impaired individuals. An absence of tactile buttons and feedback can also create more complexity.

- **Lack of Robust Fail-Safe Mechanisms:** The failure of power sources, such as batteries, can leave heating systems permanently on, leading to excessive energy consumption and unsafe temperature levels.

- **Limited Adaptability and Customisation:** Many thermostats do not offer sufficient customisation options to cater to diverse user needs and preferences. Expert users and users that might only want the most basic features are presented with the same control.

- **Insufficient Feedback Mechanisms:** Existing thermostats often provide inadequate feedback, making it difficult for users to understand the status of the device or the changes they have made.

- **Confusing System:** Advanced settings buried under multiple menu layers.

- **Dependency on Manuals:** Need to read through lengthy manuals to fully understand and use all features.

- **Documentation and Support:** Many thermostats come with poorly written or incomplete documentation, making it difficult for users to troubleshoot issues or fully use all features.

IMPLEMENTATION

The following sections describes steps of our protoype. The design choices we decided on are also discussed at each step. The steps that guided the actual implementation of this project are motivated by the issues outlined above and were ultimately structured by project plan. Some identified issues are not tackled in our objectives, constrained by the scope of this project. The main resources and materials that are mentioned below are found on our Github repository[4] as well as an Instructuables page[5] with step by step guides to rebuild our solution.

Hardware

Our hardware implementation involved the selection and integration of various sensors, the design and manufacturing of a custom printed circuit board (PCB) and the assembly of these components into a functional thermostat prototype. Below, we detail the components used and the steps taken to achieve this.

It must be noted that working with electrical components, especially those involved in controlling heating systems, requires careful handling and adherence to safety guidelines. Therefore it is important to make sure that the power supply is disconnected before making any adjustments to the wiring or components. Despite this project is aiming to empower everyone, people not experienced or at least comfortable working with electrical systems, should advisably seek assistance from a qualified professional or aim to gather the necessary competences beforehand.

[4]https://github.com/lolokraus/Open-Source-Smart-Thermostat/tree/main/Custom_KiCad_PCB

[5]https://www.instructables.com/Build-Your-Own-Smart-Thermostat-Open-Source/

Sensors

To ensure an accurate monitoring and control of environmental conditions, we integrated sensors into our thermostat. The following were selected based on their reliability and compatibility with our system:

- **Temperature and Humidity Sensor (SHT31-D):** This sensor was chosen for its ability to measure both temperature and humidity. While we do measure both values, our project focuses mainly on thermal comfort and temperature control, but the inclusion of this sensor also allows for an extension to also include more detailed information and possible recommendations for ideal humidity in ones home.

- **CO_2 Sensor (MH-Z19C) (Optional):** Similarly to the humidity, we used a CO_2 sensor to collect additional data on air quality. This provides additional insights into indoor environmental conditions and could for example allow for an implementaion of ventilation recommendations.

- **OLED Display (SSD1306):** This small display module provides a visual interface. We sensed it important that there is no interaction necessary with the actual thermostat on the wall once set up correctly. Therefore, a display was only used in our project during the development of the thermostat for real-time monitoring of sensor data and system status.

- **Real-Time Clock (RTC) Module (DS3231):** It ensures precise timekeeping for scheduling and logging purposes.

- **Relay Module (5V, SRD-05VDC-SL-C):** This module controls the heating system by acting as a switch, opening and closing the circuit to activate or deactivate the heater.

Printed Circuit Board (PCB)

Our first protoype only consisted of Breadboard and Jumper Wires. Afterwards, the design and creation of the PCB were essential for integrating the various sensors and components into a cohesive system. We used KiCad, an open-source software for electronic design automation, to design our custom PCB. This custom PCB allowed us to integrate all the sensors and control modules more efficiently.

After ensuring that our basic prototype works, we created a schematic diagram of the circuit, detailing all components and their connections. This step involved careful planning to ensure that all necessary functions were included and correctly integrated. Custom footprints and symbols were created for each component in the schematic. Footprints represent the physical layout of components on the PCB, while symbols represent the components in the schematic diagram. The schematic was then converted into a PCB layout, positioning the components and routing the electrical connections to ensure efficient and compact design.

A list of important files for the creation of this PCB are included in our *Instructables* guide and Github repository. They include a layout file containing the design of the board, a directory containing custom footprints used in the project, the custom symbol file for the pinholes and the schematic file containing the circuit diagram.

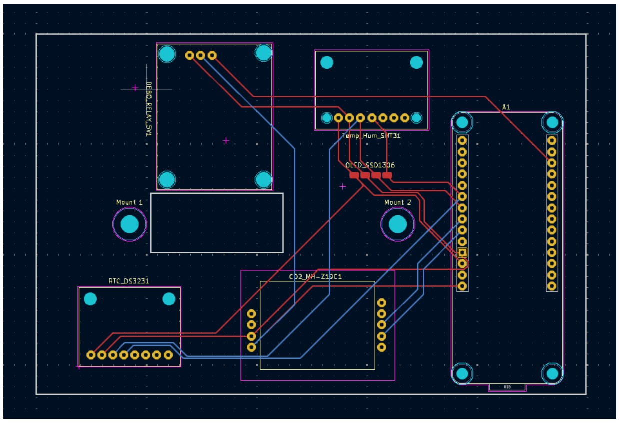


Figure 5. KiCad Design for our PCB Board.

Once the design was completed, we utilised *Eurocircuits*[6] to manufacture the PCB. After receiving the manufactured PCBs, we soldered the components onto the board, ensuring secure and reliable connections.

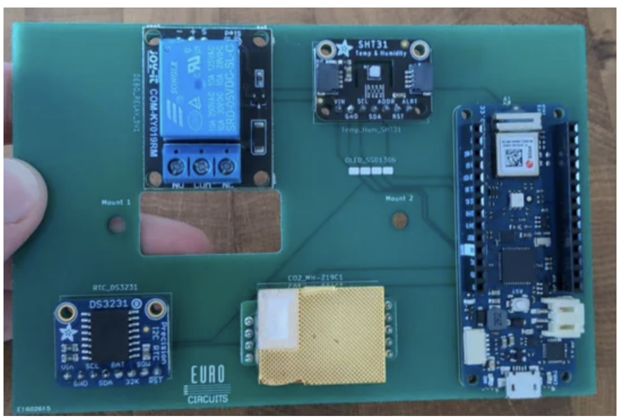


Figure 6. Final Circuit Board with components.

Microcontroller

For processing sensor data and controlling the heating system, we selected the Arduino MKR WiFi 1010 microcontroller. This choice was driven by its features, including WiFi and Bluetooth capabilities, although we primarily utilised WiFi for this project. The Arduino MKR WiFi 1010 provided a robust platform for implementing our control logic and integrating with our monitoring and control systems.

Power Supply

A 5V/2A power adapter was used to power the thermostat, ensuring sufficient power for all components, including the microcontroller, sensors and display.

Case

To make sure that our thermostat prototype not only functions effectively but also has a godo looking and functional appearance we designed a 3D printable case. The design process involved creating a basic structure that could easily be modified and improved. Starting out by integrating the PCB layout from KiCad as an SVG file into the 3D modeling software to ensure precise fitting allowed for a basic design. The case was printed using a RAISE3D-Pro2 printer with standard settings on a raft to print, though high-quality settings can be used for a cleaner finish. We used standard PLA filament for the printing. The case was printed with a layer height of 0.10mm and an infill density of 10% to ensure durability while keeping the print time reasonable. Our mechanism for closing the case was initially by having a latch secured with a pin through a long hole in both the lid and the main case, but printing the hole was not possible since they were to small. The latching mechanism still worked by just pushing the latch of the lid into the designated spot.
After printing, minor post-processing steps such as sanding and fitting checks were performed to ensure all parts fit together smoothly. We used a Lasercutter to cut a draft of the PCB on a thin piece of wood to check for the fit with the 3D printed case before ordering the PCB online. The final assembly involved placing the PCB into the case.

Software

Our software implementation includes both the Arduino setup and the development of a monitoring website. These components work together to operate the data monitoring and user control over the thermostat system.

Ardunio

The Arduino MKR WiFi 1010 serves as the central processing unit of the thermostat. It handles sensor data and hence controlls the heating system by also communicating with the server. The Arduino is programmed using the Arduino IDE with code that connects to WiFi, uploads data to the server, sends heartbeats and manages the heating based on server settings or the fallback temperature. The primary libraries used include *WiFiNINA*, *Adafruit GFX Library*, *Adafruit SSD1306*, *RTClib*, *MHZ19* and *Adafruit SHT31*. The code includes configurations for WiFi credentials, server details and authentication via JWT tokens. The main loop in the code performs tasks such as sending heartbeats, processing sensor data requests, managing fallback mode and updating the display.
The setup of it requires configuring the Arduino IDE, uploading the sketch to the board and monitoring the serial output for debugging and validation. Adjustments to the WiFi and server configurations are necessary to match the user's setup. Additional variables manage operational states, such as connection status, heating status and task intervals. The complete code[7] and detailed instructions for setting up and uploading to the Arduino can be found in our GitHub repository.

Monitoring Website

The monitoring website acts as a central hub for users to track and manage their thermostat settings remotely. Developed using Angular 17 for the frontend, it allows users to view real-time data from sensors, configure temperature settings and monitor system status. The backend, created using Node.js and Express, provides APIs for sensor data, authentication and heating control. The server setup includes a database to store sensor data and user configurations. The databasesetup, for

[6] https://www.eurocircuits.com

[7] https://github.com/lolokraus/Open-Source-Smart-Thermostat/blob/main/Arduino_MKR_WiFi_1010/thermostat.ino

which we used MariaDB, involves creating a new database, setting up a user with the necessary privileges and using provided SQL scripts to create tables and insert default data. The frontend setup involves installing Node.js and Angular CLI, cloning the repository, installing dependencies and running the development server. For production, the Angular application is built and deployed and Caddy is used as a reverse proxy for SSL termination. The backend setup includes configuring environment variables, installing dependencies and using PM2 for process management in a production environment. Once again, detailed setup instructions for the database, frontend and backend, including configuration files and deployment steps, are all available in our GitHub repository[8].

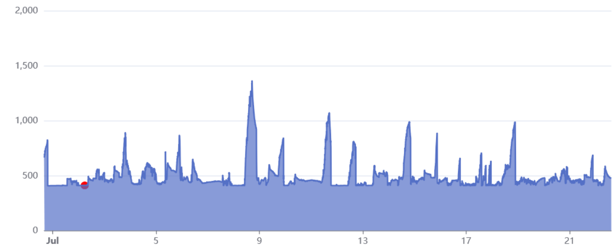


Figure 8. CO_2 data during June 2024.

DISCUSSION

This final section reflects on the implications of our design, the outlook for future work and the learnings from our project. By examining the challenges and limitations we encountered transparently, we aim to provide insights that can guide future iterations and similar projects.

Objectives

Some of initial objectives defined in Section 1.1 turned out to be too ambitious and sadly were not fully integrated into our prototype. An extensive mobile application turned to be beyond the scope of this project. Nonetheless, we not only used this opportunity to learn a lot for our personal future work, but were also able to provide a comprehensive starting point for an open source solution to a human-centered thermostat.

Real World Application

With only a few weeks running we were able to gather over 100,000 data entries for each of our recorded categories. The temperature data provided interesting insights into this summers heat waves. Clearly visible over the last months was the beginning of the summer as well as days where it cooled off. Although these are typical findings for temperature data recordings, we were also able to find specific days where a poor job was done in ventilating the flat. One day, the windows were kept open during a particularly hot day, resulting in a flat with a temperature of 31 degrees.

Figure 7. Temperature data during August 2024.

Additionally, the humidity and CO_2 sensor data displays days that were spent at home, as seen in Figure 8. This sensor was already used in supporting us in figuring out when it is time to air out the apartment. Manually checking the values already turned out to be a nuisance. An automatic reminder whenever the CO_2 values are too high would be a valuable addition.

[8]https://github.com/lolokraus/Open-Source-Smart-Thermostat/tree/main/Custom_KiCad_PCB

Learnings

The project planning phase revealed several critical insights. Ordering of parts often took longer than anticipated, delaying the overall timeline. The integration of components also required more time than initially planned. Additionally, the development of the software, including both the Arduino programming and the server setup, was more lengthy than anticipated. This is once more highlighting the need for more flexible timelines and ultimately extended the projects duration and resulted in us sadly not being able to achieve some goals within the timeframe.

Another very important realisation was that the consultation with users and the gathering of lived experiences takes significant time. This emphasises on the importance of early and continuous engagement with these stakeholders.

Effective communication within the team and regular milestone reviews, although sometimes hindered by other commitments and unforeseen challenges, were very critical in keeping the project on track. Future projects would benefit from a more detailed risk management plan and allocating additional time for testing and refinement stages. Learning from these limitations, we will better structure future projects to accommodate obstacles and ensure even more robust outcomes.

Creating such a detailed documentation of how to replicate our results, especially to people that might be not as technically educated, but who should still understand our results, is something that was new to all of us.
The open-source approach, and within it not only publishing whatever a projects results were, but actively thinking about how to communicate our findings, allowed us to really think about the end user and additional demographics who might be using our product. It was also very interesting to us to not only think about the end product and a functioning interaction with it, but also to consider what and how findings during our process could be of importance to other people. This led to somewhat of a realisation: that not only results that are 100% perfect are of value, but the way to get there, and the challenges that might have come up along the way, can be beneficial both to others and ourselves. And all of these points are of course also valuable if one not gets all the way to the *finish line*. Lastly, we also believe we finally truly understood that this is what science and research is all about and where even small efforts, when taken with integrity hold a significant worth.

Limitations

The development of our smart thermostat prototype highlighted limitations encountered during the project:
We were challenged by creating a user interface that is both simple and comprehensive in the scope of this project. While we aimed for an intuitive design, the necessity to include multiple features and settings made it difficult to avoid complexity. Although our design allows for customisation, the scope of adaptability was limited by our timeframe and resources. We could not implement all possible customisation features for a more advanced version, such as designated user profiles or even the possibility for voice control.
Ensuring robust fail-safe mechanisms proved to be a complex task. Our solution includes basic fallback features, but more sophisticated error-handling and redundancy systems, for example in the case of hardware failure, are needed to address all potential failure scenarios comprehensively.
Providing thorough documentation and adopting an open-source approach was integral to our project. However, we faced challenges in ensuring that the documentation was comprehensive and easily understandable by a diverse audience, for example by people with little or no technical expertise.

Outlook and Future Work

Future work should address the identified limitations by expanding the scope of such a project to include additional environmental controls, enhancing accessibility features and integrating more advanced sensors. Comprehensive testing and user feedback are crucial to refining the design and ensuring it meets the needs of a broader user base.

Future iterations could also challenge our current solution, testing it through various research methods such as user observations and real-world usability studies. This project could be expanded into a master's thesis. This would allow for more rigorous testing and the incorporation of advanced features suggested by more users, experts or other researchers.

Some imaginary future work could include developing more sophisticated control algorithms, integrating renewable energy sources or creating a more interactive and intelligent-user-interface (IUI). Regarding IUI, further exploration of energy-saving algorithms and machine learning techniques could optimise the heating schedules and improve user comfort. Collaboration with experts in various fields and gathering insights from diverse user groups will be essential in these efforts.

We are pleased to have laid some groundwork for this project but still acknowledge that our solution is not complete. However, our preparation provides a solid foundation for the next iteration, focusing even more on ensuring true Human-Centered Design. This next phase should have the goal to validate and expand our approach, ensuring that a possibly final product, although probably never perfect solution, is genuinely centered around the needs and experiences of its users.

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