Tailored family adaptation to living in a zero-energy house

Occupant's crises and conflicts with
a heat pump-based system

Master Thesis

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PREFACE

This thesis represents a significant milestone in my academic journey. Over the past six months, I have dedicated myself to exploring interaction and experience design. As an IPD student, it is a pursuit that has been filled with challenges, but also immense growth. Despite moments of pressure and uncertainty, I have been rewarded with new insights and a broader perspective on design. I hope you can enjoy the reading.

I believe my role as a designer is to promote comfortable and joyful living so that people can live authentically in line with their personal aspirations. I am particularly interested in the domestic experience and interaction, seeing homes as places of rest, self-expression and true relaxation. This interest has led me to focus on adaptation to zero energy houses - a topic I have been working on for the past year and a half. From the ACD course to research projects and now this thesis, my deep dive in the subject has been both enlightening and rewarding.

My aim in this project is to facilitate the co-performance between household and the complex indoor climate system. I hope to encourage active exploration of the inevitable conflicts that arise between occupants and the systems. Rather than prescribing a 'one size fits all' solution, my design aims to guide individuals in discovering their unique responses.

I would like to express my gratitude to my supervisors - Stella, Samuel and Evert - for their invaluable support and guidance, particularly in the areas of research and analysis. I would also like to thank my friends for their constant encouragement and companionship throughout this special journey.

Yichen Jin

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GLOSSARY

Zero-energy house:

A well-insulated home with a heat pump at its core, coupled with a heat recovery system that can automatically regulate the indoor climate. This advanced system uses solar panels as a renewable energy source to produce an equivalent or surplus amount of energy required for heating, cooling, domestic hot water and ventilation specific to this dwelling on an annual basis (D'Agostino, 2015).

"Crisis in routine":

The conflicts between the system and the households that occur in everyday life due to the misjudgement of the system in the background and the misunderstanding of the residents about the appropriate actions (Reckwitz, 2002).

Productive "crises":

Productive "crises" encompasses a series of contextual touchpoints that can spark the curiosity and interest of households. These touchpoints not only engage residents, but also provide them with relevant information and foster their motivation to generate ideas and hypotheses for further exploration of 'crises'. The ultimate goal is to make it easier for households to adapt and establish a mutually satisfying relationship with the system, particularly in the context of zero energy housing.

"Enacted interface":

Different from common graphical user interface, "enacted interface" refers to the new matching of residents to buildings, which is not designed in advance but enacted in everyday practice. It exists between the occupant and the automated home system, acting as a new link between people and the system in everyday use. The occurrence of enacted interface can facilitate the adaptation process, which mainly concerns heating, but also ventilation and hot water boiling in this project (van Beek et al., forthcoming in Human Computer Interaction).

SUMMARY

Background

This project, belong to the IEBB project, contributes to the goal of reducing this energy consumption by encouraging more people to live in "zero energy houses" (ZEH), a well-insulated and airtight house in combination with heat pumps (Integrale Energietransitie Bestaande Bouw, n.d.). The effective energy saving impact of heat pump systems depends largely on how occupants use it. From a systems perspective, inappropriate human interactions are often interpreted as barriers to ideal energy savings targets. Conversely, occupying a smart building can experience several conflicts from an occupant perspective, as system performance may not always match their preferences (Hargreaves et al., 2017). This study therefore focuses on the conflicts between households and the system and aims to streamline the post-occupancy adaptation.

The early research found that these conflicts have different implications for different households within their routines due to individual differences in cognition of the role of the system, perception of the indoor climate, and response to system performance. This makes the adaptation process inherently different for each household. In addition, family living scenarios may amplify these conflicts due to the different distribution of family roles and potential communication gaps. Therefore, this project aims to facilitate co-performance (Kuijer & Giaccardi, 2018) between the heat pump-based indoor climate system and multiple actors within a family.

Research

The core of the research is an ethnographic study in the form of semi-structured interviews, which aims to find out how residents currently respond to 'crisis in routine' and adapt to the new system through the existing touch points in the family scenario. Thematic analysis was used to identify the elements of 'routine crisis' that facilitate the occupant's discovery of a satisfactory response to the system, and to investigate the impact of diversity within the family on individuals' understanding and response to ' crisis in routine. The main findings of the research part are a framework of common stages in all "crises" and a framework of three themes indicating the effect and relationship of different elements. I also explored the interrelation between these two frameworks by mapping the themes to the stages to define the design space.

Design

In an effort to stimulate the curiosity of households to explore the 'crises' and the 'enacted interface', and to encourage the discovery of their individual adaptations, I conceived two concepts: the 'Clock' thermostat and the Feeling Message Board. The former acts as a long-term functional control, allowing users to interact with it to regulate temperature, while the latter acts as a supporting device, capable of offering lifestyle advice based on user-reported feelings and changing contexts. The latter device is more suitable for short-term use and can be returned afterwards. Both seek to enhance the system's ability to express contextual status and real-time heat pump status, thereby encouraging occupants to proactively learn about the system's functions. In addition, these devices aim to encourage family discussion and communication about indoor climate and system settings, thereby promoting innovative responses to 'crises'. It is my aspiration that adaptation can be realised through the active expression of the system and the family's engaged learning and discussion of the system's features and use.

Future Recommendations

Based on the evaluation, the final design, including the 'clock' thermostat and the Feeling Message Board, plays a roughly successful role in arousing the interest of households to start exploring the 'crises' and the staged 'interface' to find out tailored adaptations to ZEH. There is still room for further iteration. For the 'clock' thermostat, I recommend improving the label design and the flashing light design for a clearer system expression. Also, considering the real-world scenario, I suggest integrating the modes related to domestic hot water supply into the thermostat. For the Feeling Message Board, more iteration should be done in the future, especially in the playful bubble design, to attract residents to continuously interact with it and to convey the information in a more straightforward and understandable way. The detailed dialogue design is not the focus of this project and deserves further development. In addition, I have well discussed the feasibility, manufacturability and cost effectiveness in chapter 9.3.

CONTENTS

01

PROJECT INTRODUCTION

1.1 Initial Assignment

Dutch households use a lot of energy. A large part of this energy comes from fossil fuels, such as natural gas. This energy is used to maintain a good indoor climate (heating, ventilation) and to heat hot water. This project, as part of the IEBB project (Integrale Energietransitie Bestaande Bouw, n.d.), contributes to the goal of reducing this energy consumption by renovating existing houses into well insulated and airtight houses in combination with heat pumps for heating, which can be considered as "zero energy houses" (ZEH). This project aims to support the Dutch goal of renovating 200,000 homes per year in a way that reduces greenhouse gas emissions and achieves a climate-neutral built environment.

Heat pumps should be very efficient, but they require adaptation. The actual effect of heat pump systems on energy saving fundamentally relies on how they are used by occupants (Linden et al., 2006). To maintain an optimal indoor climate and minimise energy consumption, it is recommended to keep the windows and other openings of the house closed when the temperature outside differs significantly from the indoor temperature (Behar & Chiu, 2013). This is what residents are not used to and residents need to adapt their living practices to suit the capabilities of heat pumps. Living in a smart building can be full of conflict from a household perspective, and the performance of the building services system does not always match what the occupants feel is appropriate (Hargreaves et al., 2017). From a system perspective, inappropriate human interactions are often seen as an obstacle to achieving the ideal energy savings target.

Therefore, this project will focus on the adaptation phase and the conflicts between households and the indoor climate system based on heat pumps and aims to optimise the matching process between households and the new technology. It is believed that if households and the system live together in a satisfying way with more mutual understanding, it could help to achieve the sustainability goal as much as possible in the end. If people do not find their own relationship with the system, they are also likely to struggle with living with the new technology.

1.2 Problem Statement

In order to explore why conflicts between households and their indoor climate systems happen during the post-occupancy phase, this section analyses the problems and misfits behind them from both a household perspective and a technology perspective.

key problems behind the conflicts

The first problem behind conflicts is that the automated indoor climate system operates based on design assumptions that refer to the average behaviour in the calculation of the Energy Performance Coefficient (EPC), which was based on standardised occupancy and the characteristics of the building envelope and installations (Guerra-Santin et al., 2022). The technology considers that the standard operation is designed for the optimal living environment and should satisfy most occupants, while individuals have different needs and preferences for a comfortable indoor environment, so the system does not always meet the user's intentions without friction (Guerra-Santin et al., 2022). Gender, age, BMI and experience of living in different climatic zones all influence people's expectations of ideal indoor climate settings. However, people's perception of a good indoor climate may not match the actual healthy or sustainable indoor climate. It has also been found that people are more likely to act on perceived experiences than on factual or advisory data (Semenza et al., 2008). In summary, the first problem is the lack of alignment between households' intention and system performance, typically excluding human diversity for simplicity, leading to conflict.

The second problem behind conflicts is that the automated, intelligent technologies work in the background to deliberately reduce the required interactions of residents with their homes (Harper-Slaboszewicz et al., 2012). Such systems operate on the assumption that they will perform optimally in the background, seamlessly adapting to residents' intentions and obviating the need for complicated control options. This can be seen as a refusal to collaborate with occupants. However, reality often contradicts this assumption. As a result, occupants cannot maintain control over complex and interactive systems through limited touch points if they are unfamiliar with relevant technologies and ZEH. Additionally, Luo et al. (2014), conclude that occupants with personal control accepted wider ranges of temperatures and expressed lower expectations to change their current thermal conditions. Therefore, a lack of communication and collaboration between the system and occupants will cause and even increase the occurrence of conflicts.

The third problem is that the role and characteristics of the heat pump are not in line with households' previous perceptions, which increases learning barriers and causes conflicts in daily life. Historically, the evolution of home heating systems has meant a shifting role between human and artificial performers. While humans once played a precise role in controlling these systems, such as adding fuel to a fire, recent advances, such as smart thermostats, have seen automated systems increasingly take over this role (Kuijer & Giaccardi, 2018). However, occupant' cognition of the role shapes idea of appropriate behaviour and the expectation on system control and performance. Chasing for higher standard of living, the demand of separating the space and functions appeared and increased in the past century, leading to role of heaters shifting from multi-functional units, including heating and cooking, to specialised systems focused solely on efficient domestic heating (Kuijer & Watson, 2017). All these makes it now difficult for occupants to understand the role of the heat pump as it is responsible for both room temperature control and domestic hot water supply.

Family living scenario

Designated "expert"

Bedir & van Dam (2013) found that family dynamics also influence the way occupants interact with the system, thus affecting energy consumption. A designated "expert" is chosen for a specific complex system within a family and is responsible for understanding the operation of the specific system and utilizing properly. The interviews indicate that designating an expert was a way for families to pursue efficiency. When an advanced function of the system is required, other members can just advise the expert to adjust for them. In this way, not all members have to waste time and energy learning the specifics of a system. However, it was found from the interviews that, despite having less knowledge, it is inevitable for other members to interact with the system due to diverse personal indoor activities. Thus, the discrepancy in knowledge and understanding of a system between family members may lead to more inefficient behaviour by members with inadequate knowledge, causing more conflicts with the system Bedir & van Dam (2013).

From the interviews, it was found that the designated "expert" may not be the one who interacts with the system most in the family. Shrestha et al. (2021) also discovered that usually, women have a higher responsibility for the household's energy use, which means they are more likely to frequently interact with the system. Surprisingly, their participation and impact have been less prioritized or even ignored in energy-related decisions (Strengers, 2014). This discrepancy between the operator and expert can lead to adaptation problems and conflicts between the system and occupants (Figure 1).

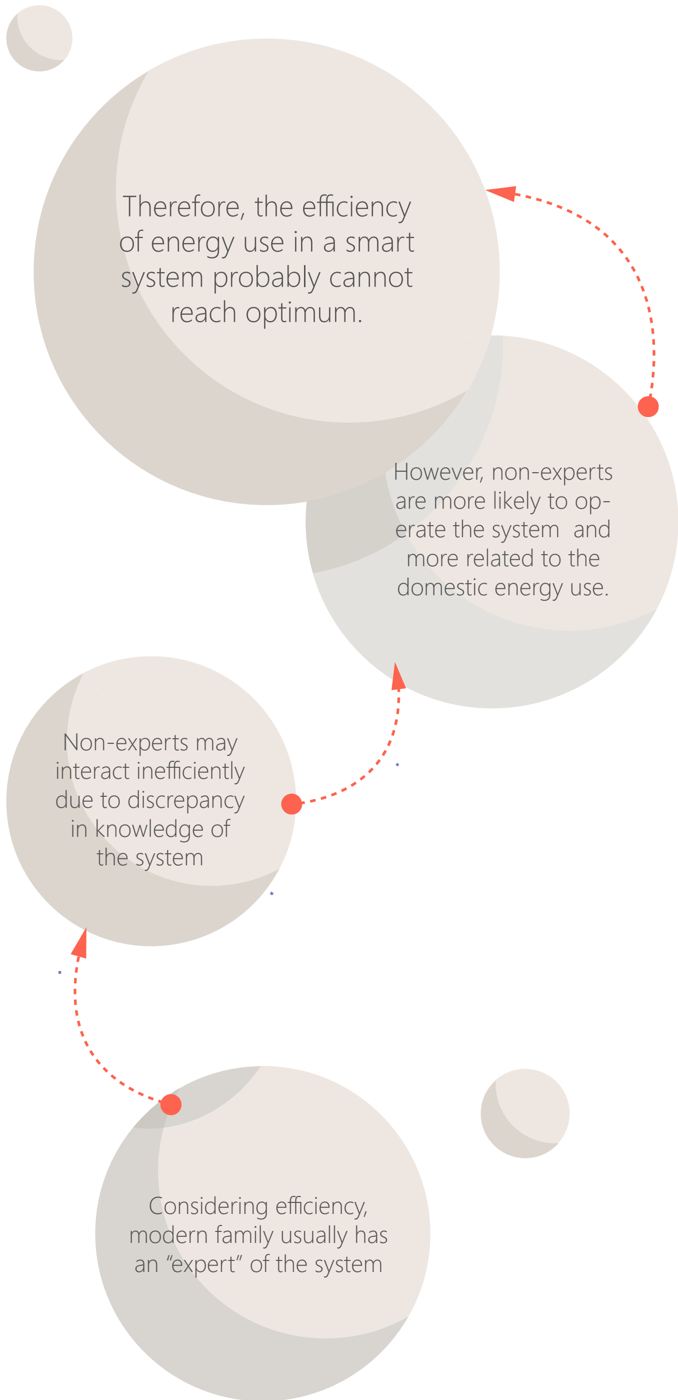


Figure 1: Occurrence of "expert" in smart home

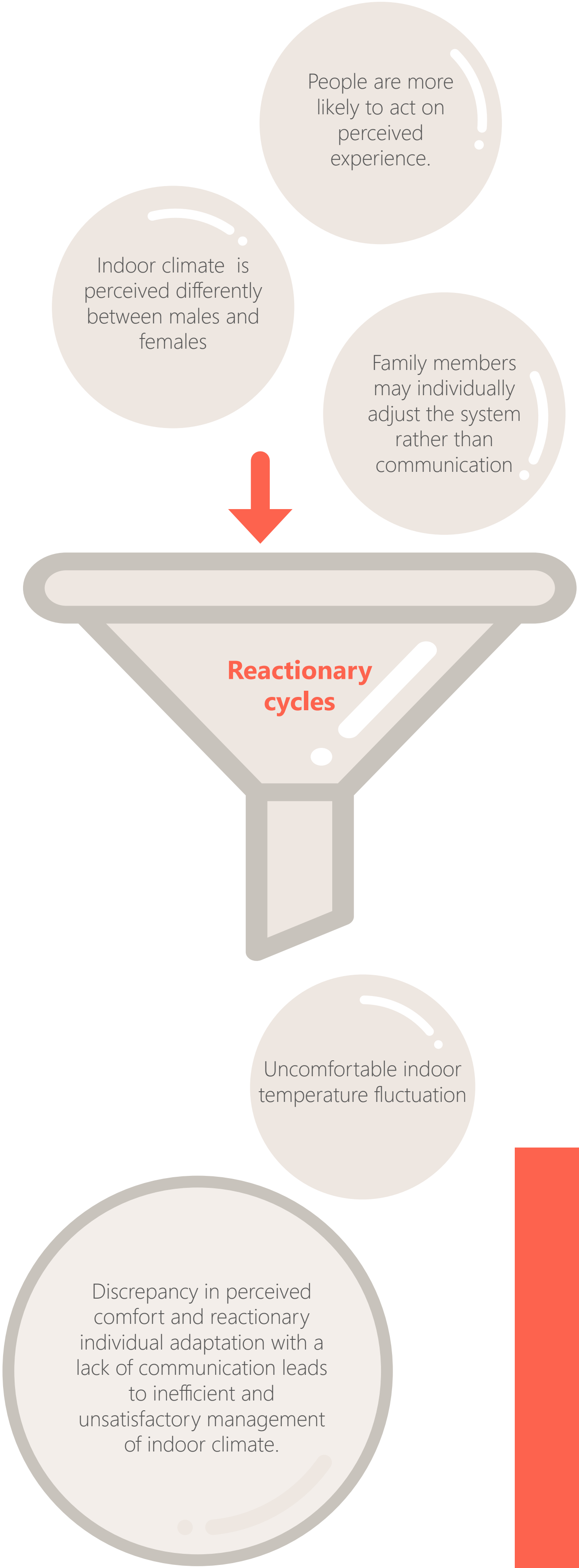


Figure 2: Appearance of reactionary cycle

Reactionary Cycle

As mentioned before, it was found that the perception of a comfortable climate is influenced by many factors such as sex, age, weight, and cultural background. Within a family household, these covariates may differ significantly between members of the family, resulting in diverse and possibly contradicting definitions of a comfortable climate. In the interview observations, an interesting link was found that family members may make adjustments individually, compensating for reacting to each other's decisions rather than communicating. The discrepancy in perceived comfort and reactionary individual adaptation with a lack of communication leads to inefficient and unsatisfactory management of the indoor climate. Reactionary cycles may occur where family members keep reacting to one another's decisions, creating a feedback loop, leading to frequent and unexpected changes in the heat pump system setting. This results in the discomfort of all involved parties and also conflicts with the system, adding difficulty to adaptation (Figure 2).

Summary

The key problems behind the conflicts are 1) the misalignment between households' varying perceptions and system default performance; 2) the lack of collaboration between the system and occupants; 3) the misalignment between the role of the heat pump system and households' previous cognition on the indoor climate system. Additionally, more conflicts may happen under family living scenarios because of the existence of "expert" and the lack of family communication in indoor climate settings. The key takeaway is that conflicts hold different meanings for different households in their routines, thus it is hard to prevent conflicts due to human diversity. Correspondingly, the adaptation process will be unique.

1.3 Scope & Focus

The technical system scope refers to the indoor climate system with the core of an in-house heat pump which can automatically control the indoor temperature and warm domestic water supply, simultaneously reducing energy consumption on an annual basis. The system also includes a heat recovery system for ventilation which incorporates a heat exchanger to retain the warmth of the fresh air while exhausting the stale air. The key elements in the project encompass the indoor climate system predicated on heat pumps, alongside the individual family members cohabiting in a technologically advanced, energy-efficient house, each possessing different degrees of technological literacy. The conflict scope includes 1) conflict between each occupant and system; 2) conflicts between different occupants living in the same house.

In summary, the focus of this thesis is to optimise the matching process between multiple occupants and new technology in the post-occupancy phase. Instead of preventing conflicts and minimising interactions, an alternative approach, defined as co-performance, could be considered to redirect the design focus towards fostering embodied learning through everyday practices, both for the residents and the systems (Kuijer & Giaccardi, 2018). Co-performance involves considering artefacts as active learners and performers alongside humans, while acknowledging the dynamic differences in capabilities between the two (Kuijer & Giaccardi, 2018). Co-performance examines the appropriate interaction between human and artificial bodies/minds in terms of the evolving division of roles and responsibilities between human and artificial performers. This process is variable and unpredictable for different individuals. Co-performing behaviour has been found to be influenced by perceptions of the human/non-human relationship and iterative experience (Kim & Lim, 2019).

This project is expected to facilitate co-performing between the heat pump-based indoor climate system and multiple actors within a family. An expected outcome is a set of design insights, illustrated by a design case, that optimises co-performing adaptation.

1.4 Methodology

Research Methodology

The cornerstone of the research phase is the ethnographic research, which includes a generative semi-structured interview. The methodology employed in this phase incorporates the grounded theory method (GTM) (Tie et al. ,2019), which serves to systematise the analysis procedure of the semi-structured interview findings. In addition, the application of thematic analysis (Villegas, 2023) to the interview data aims to construct a framework to guide subsequent ideation phase.

Design Methodology

The design phase can be classified into two main parts: idea finding and solution developing. Idea finding session involves 1) the brainstorming based on analogy (van Boeijen et al., 2020), which aims to stimulate ideation through specific but similar case and transformation; 2) co-creation with end-users through the exhibition of various rapid prototypes, with the aim of tailoring the design to closely match the practical application. The solution developing mainly refers to the personal iteration on the solutions specific to the context of living with an indoor climate system based on air/water heat pumps. The evaluation of design proposals is influenced by storytelling (van Boeijen et al., 2020) and uses role-playing and scenario-based exercises as evaluation tools.

02

HUMAN-SYSTEM CONFLICT ANALYSIS

To explore how to intervene in the conflicts between occupants and the indoor climate system, this section begins with a detailed definition of the technical system scope, which is the non-human role in the conflicts. In the following research, I analysed the reasons for the occurrence of the conflicts, referring to the mismatches between the needs of the occupants and the functions of the system. The findings can serve as design opportunities for optimising the match between multiple occupants and the indoor climate system.

2.1 Technology Research

This section will briefly introduce the technical scope of the indoor climate system based on the heat pump focused on in this project. It contains 1) the air/water heat pump units, which are responsible for indoor temperature regulation and warm water supply system; 2) the thermostats; 3) the balanced ventilation system (D type), which refers to mechanical air exhaust and mechanical air supply; 4) windows; 5) smart meter.

Air/water heat pump system

The air-to-water heat pump, widely used in the Netherlands, is particularly suitable for retrofitting existing buildings with convectors or underfloor heating. These heat pumps serve two purposes: heating and cooling. The mechanism is to transfer heat from a cooler source to a warmer sink by compressing and expanding refrigerant, making efficient use of electrical energy. A characteristic feature of heat pumps is low-temperature heating, which involves the slow transfer of heat through water to indoor spaces, typically around 45°C. This low temperature mode allows for a more even distribution of heat and a more efficient way of energy use, making it well suited to underfloor heating as opposed to convectors (Information from Evert van Beek). In addition, heat pumps provide domestic hot water, but unlike gas boilers, they require a storage tank and cannot heat water instantaneously. Consequently, there is a limited capacity to supply hot water in a certain period, which if exceeded, results in the unavailability of hot water.

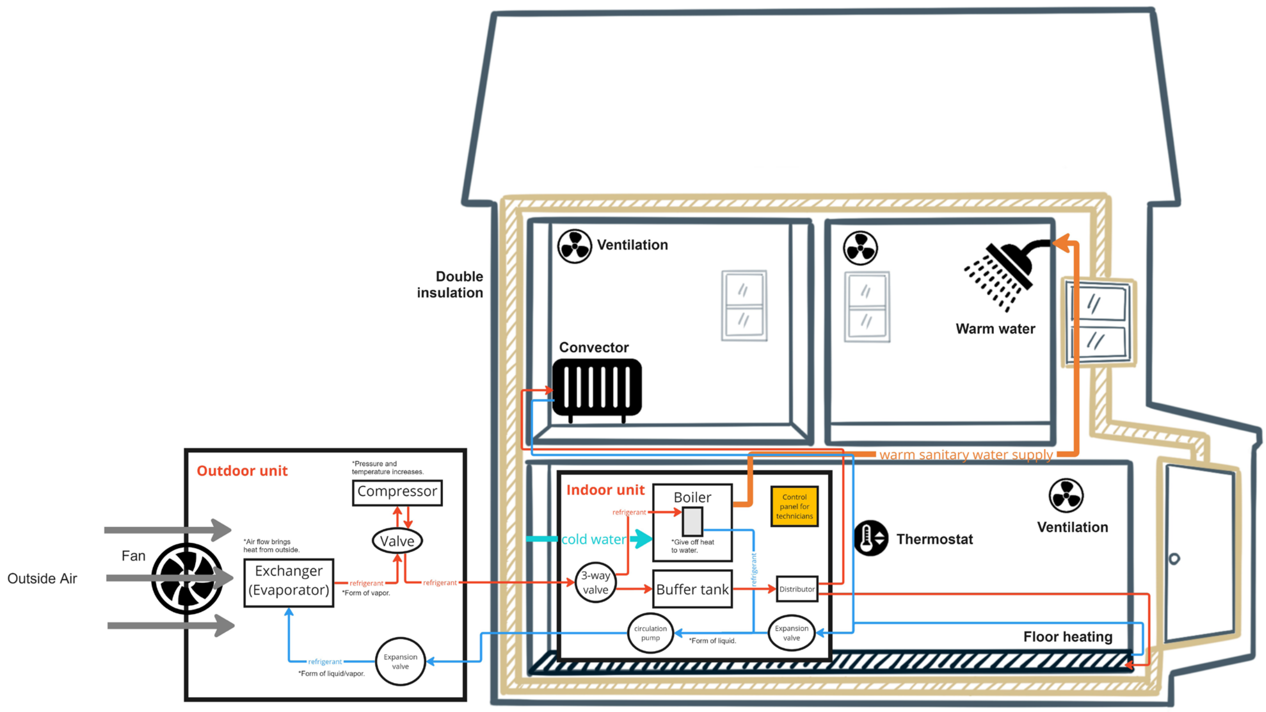


Figure 3: Air/water heat pump working mechanism


Figure 4: Main thermostat


Figure 5: Ventilation control in kitchen


Figure 6: Ventilation control in bathroom


Figure 7: Change the filter

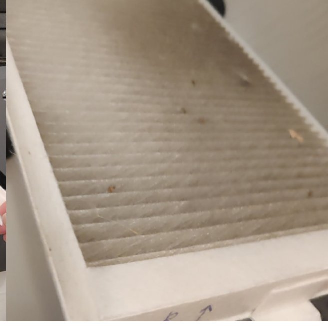


Figure 8: Used filter

Ventilation system (system D)

The Type D ventilation system (Figure 7) operates automatically, using two fans to draw in fresh air and extract stale air. The heat recovery ventilation system incorporates a heat exchanger to retain the warmth of the fresh air while exhausting the stale air (Which Ventilation Systems Exist?, n.d.). Ceiling diffusers deliver the heated fresh air into the rooms, and optional sensors can control ventilation levels, including humidity and CO2. This system offers benefits such as heat recovery, balanced airflow distribution and effective pollutant removal through filters, improving air quality. It offers flexibility in the position of supply and extract air for tailored configurations. However, drawbacks include fan energy consumption which affects overall efficiency, regular maintenance such as filter changes for optimum performance, and potential noise generation which affects occupant comfort.

Domestic smart meter

Smart meters have been widely installed in the Netherlands. These advanced devices empower residents by providing valuable information about their daily energy consumption, enabling better energy management and informed decision-making. In addition to real-time monitoring, smart meters give homeowners access to their daily energy bills, promoting transparency and accurate budgeting. In addition, these meters support integration with other devices and systems, enabling comprehensive energy analysis and optimisation. A dedicated website provides homeowners with an interface to conveniently access energy consumption data, enabling them to evaluate the energy consumption patterns of their homes.

Existing control options

In most cases, a main thermostat control (Figure 4) the indoor temperature and hot water supply, while additional thermostats may exist in different rooms, allowing users to control the temperature only in those specific rooms. Heat pump systems cannot heat and cool simultaneously. Therefore, the temperature settings on the room thermostats determine the level of heating or cooling compared to other rooms. Some renovated houses use convectors with physical knobs for manual temperature control.

Ventilation systems can be classified as automatic or manual, offering control options based on specific needs, such as extra ventilation in bathrooms or kitchens. However, all controls share common functionalities. Typically, ventilation systems provide three levels of ventilation: level 1 for absence, level 2 for regular activities and level 3 for increased ventilation during activities such as cooking or showering (Figure 5&6). Manual systems require adjustments to be made using dedicated controls, while automatic systems use CO2 and humidity detection to automatically ventilate. However, manual controls remain accessible for occupants who require additional ventilation beyond the system's requirements. With Type D ventilation, occupants are responsible for regular filter changes (Figure 7&8).

2.2 Conflicts between System and Residents

As I have explained the detialed definition of the system which this project focuses on, it is time to figure out the reasons behind the occurrence of conflicts between this system and residents. In this section, I investigated 1) the effect of specific system elements and features on residents' interactions; 2) what drives an individual to perform certain interactions or make decisions related to indoor climate setting. Additionally, a family is not a self-contained unit. It consists of members that perceive the environment and the system in a different way. Therefore, I also investigated factors that cause the diversity between individuals' perceptions of comfortable indoor climate and cognition of the role of the heat pump system.

Mismatch between residents' perception and system performance

Occupants' experience of the indoor climate is influenced by various external and internal factors. Research by Chinazzo et al. (2019), highlighted the significant impact of daylight on thermal comfort and acceptability, although it did not directly affect thermal sensation. In cold conditions, reduced daylight illuminance contributed to a less satisfactory thermal environment, while in warm conditions it contributed to a more favourable thermal experience. Seasonal adaptation was found to influence human temperature perception, even when the indoor temperature remained constant Rupp et al. (2015). The diverse indoor activities can also change people's perception of the temperature, for example occupants may feel warmer when they are busy with housework. Furthermore, Semenza et al. (2008) found that behavioural changes were primarily driven by individual perceptions of poor air quality, rather than explicit air quality advisories. This suggests that people are more likely to act based on their own experiences and perceptions, rather than objective data. As perceptions change, so do expectations of indoor comfort and system performance, leading to interactions with the system to adjust settings.

In the field of zero energy houses, a conventional heat pump works by transferring heat to the indoor environment via water at a comparatively modest temperature (around 45 °C) (information from Evert van Beek).This means that it takes a relatively long time to heat the house from, say, 18°C to 20°C. It is also difficult for the system to detect the change in perception under the same conditions, which means that the automation cannot prepare in advance. As a result, the system cannot react in time to rapid changes in occupant interactions and expectations, leading to the occurrence of the malfunction. In addition, adequately insulated homes can be significantly affected by solar radiation, resulting in overheating of south-facing rooms or heat loss through open windows. Due to the subtle nature of low-temperature heating, these effects may be more noticeable to individuals than the heat generated by the system itself. As a result, it is more difficult to understand how the heating system is actually working, making adaptation even more difficult (Guerra-Santin et al., 2021).

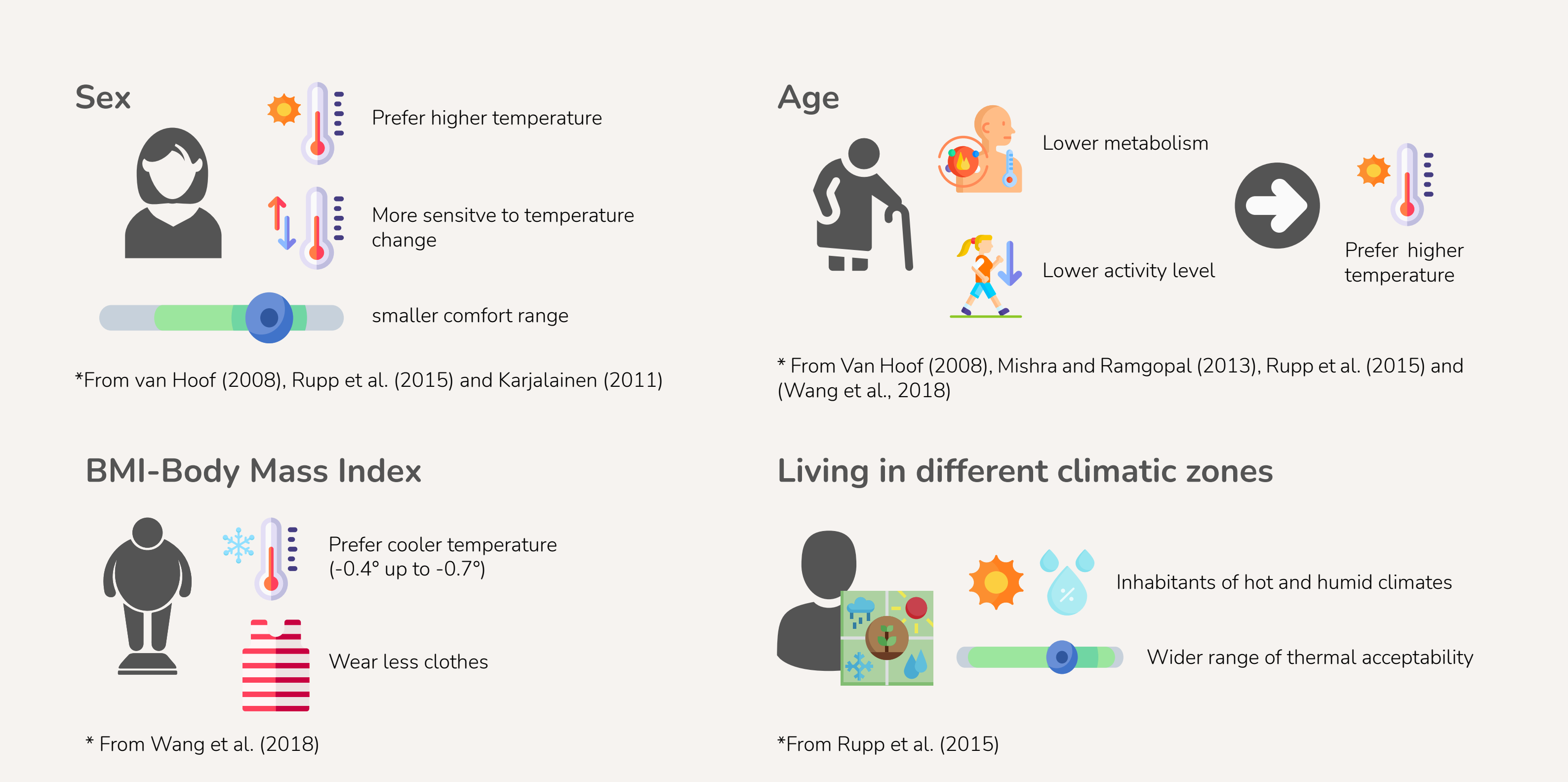


Figure 9: The illustration of individual difference on perceiving comfortable climate

Various internal factors, such as gender, age, BMI and life history, have been identified as influencing people's perception of indoor climate and their corresponding behaviour. Research by van Hoof (2008), Rupp et al. (2015) and Karjalainen (2011) indicates that females generally prefer higher temperatures and are more sensitive to temperature variations. Females also show more variation in clothing choices between seasons compared to males (Mishra & Ramgopal, 2013). Furthermore, Wang et al. (2018) found that older individuals with lower metabolism and activity levels tend to prefer higher temperatures, while those with higher BMI indexes prefer cooler temperatures (-0.4°C to -0.7°C). Rupp et al (2015) reported that residents of hot and humid climates show a wider range of thermal acceptability, even when moving to a different environment. Therefore, it is challenging to design systems based on average behaviour to accommodate the diverse preferences of individuals.

In the heat pump system, the slow heat-up combined with the good insulation allows the heat to be distributed more evenly throughout the house and prevents the house from cooling down quickly. This could also be seen as a disadvantage because the large temperature difference between different rooms, especially those on the same floor, is difficult to achieve compared to radiators or air conditioning. It will therefore be difficult to satisfy each individual perfectly in a family living scenario. There are also conflicts between different family members, which will affect the family's adaptation to the new technology.

In summary, the inevitable individual difference together with the immutable system design determine that the misfit varies for different households and is unpredictable, also indicating the complexity of the family living scenario.

Lack of collaboration between the system and occupants

The system is designed to operate automatically and seamlessly, fulfilling the user's intentions without the need for complex control options or system monitoring. However, occupants may notice certain indications of changes in system operation as they go about their daily lives. Without clear communication from the system, confusion and mistrust can arise, leading to conflict between the occupants and the indoor climate system.

One potential issue is the automatic transition of the heat pump between heating and cooling modes, which can be based on seasonal variations or measured temperature. The accessibility of this information to the occupants may not always be clear or readily available. As a result, occupants may experience sensations such as a cooler floor or cold water through convectors, leading to further confusion.

In extremely cold weather, air-to-water heat pumps require defrost cycles to remove frozen water from the coil. These cycles, which last 5-15 minutes and occur every few hours, or even every 30-45 minutes in Netherlands, are initiated based on a combination of time and sensor readings, which can create unpredictability for occupants. The defrost cycle is often accompanied by high-speed fan rotation, resulting in noticeable noise levels. In addition, the heat pump's outdoor unit produces noise during operation, particularly during start-up, with regulated sound levels. Anticipating when the heat pump will make noise becomes difficult for occupants due to several factors.

In terms of personal control and environmental perception, research by Luo et al. (2014) found that occupants with personal control experienced a comfortable temperature that was 2.6°C lower than those without control. They also showed greater acceptance of wider temperature ranges and had lower expectations of changing their thermal conditions. Another study by Brager et al. (2004) demonstrated the effect of different levels of window control on neutral temperature in warm seasons, with increased control leading to greater satisfaction at warmer temperatures. Furthermore, Luo et al. (2016) showed that the mere perception of having control can increase comfort.

Ultimately, promoting effective communication and collaboration between the system and occupants can improve the understanding of the heating system's functions and increase the range of occupants' acceptance. This can help reduce difficulties during the adaptation phase and minimise conflicts. Providing more real control options may not be necessary, but increasing the number of touch points and creating a sense of greater control can contribute to occupant satisfaction.

Mismatch between the role of the system and households' cognition

Research reveals a significant misfit between the current features of the system and the prior cognitions and habits of the occupants, which largely influence their operational behaviour. This mismatch increases learning barriers and contributes to human/non-human conflicts.

Early research found that when occupants lack confidence in the system, they prefer higher levels of control and independent systems to reduce perceived risk. In such cases, they view the heating, ventilation and tap water systems as separate 'soldiers' under their command, disregarding the interdependencies and simultaneous operation of these subsystems. Conversely, when users trust the system, they show less interest in understanding its inner workings and show greater acceptance of automation, perceiving the system as a reliable 'server'. When users trust the automation of the system, they refrain from unnecessary interactions. However, if they are dissatisfied with the performance of the systems, they may turn to familiar devices such as fans or radiators, just as they may seek service at another restaurant if they are dissatisfied, rather than trying to educate the staff. Thus, how occupants perceive the role of the system has a significant impact on their behaviour and expectations.

However, the role and operational features of this new system do not match the previous perceptions of the occupants. Historical research suggests that role of heaters shifting from multi-functional units, including heating and cooking, to specialised systems focused solely on efficient domestic heating (Kuijer & Watson, 2017). As a result, occupants are challenged to understand the multi-functional role of heat pumps, which include both room temperature control and domestic hot water supply. Unlike conventional high-temperature heating systems that frequently cycle on and off, heat pump systems prioritise extended heating periods at lower temperatures, particularly in well-insulated homes, so that they can operate at lower power levels but provide consistent comfort and warmth. This approach positions the heat pump system as a 'slow maintainer' rather than a ‘rapid changer’ in indoor climate regulation, which deviates from users' previous cognitive frameworks and leads to increased conflict and adaptation issues. In addition, the effect of heat pump is often less obvious to occupants. This is because low-temperature heat delivery requires expansive surfaces, such as underfloor heating, which challenges their previous belief that they can directly feel the heat sources to verify their operational status (Guerra-Santin et al., 2021). This difference makes it difficult to build trust between humans and automated systems.

2.3 Key Insights

01

Conflicts vary for different households due to diverse individual perceptions of comfortable indoor climate. Therefore, the adaptation process and potential conflicts are unpredictable and worth further exploring.

02

The situation gets more complex in the family living scenario because conflicts between different family members also exist and will affect the family’s adaptation to the new technology.

03

For occupants, the perceived access to collaboration with the system help expands the range of adaptability and lower the expectations for constantly modifying the indoor climate. With the communication from the system, confusion and distrust can be removed, benefiting solving conflicts between humans and non-humans.

04

Occupants’ understanding of the system’s role significantly influences their behaviour and expectations of system performance. Currently, there is a misalignment between system features and occupants’ previous cognition, where exists design opportunity.

03

EMPIRICAL DESIGN RESEARCH

Since the conflicts and adaptation process are unpredictable and diverse for different households, I am wondering whether the system can react differently according to the changing individual behaviour and routine. In this section, I conducted empirical research on the current occupants' experience in zero-energy houses, borrowing the dataset from Evert van Beek. It was outside of the graduation project but part of a research elective I have taken before. The main aim is to explore a new potential way of collaboration between the system and households to tailor the adaptation process. By investigating the effect of occupant action input on indoor climate change, the research attempts to answer the following question: Can the system learn about the occupants' routines and preferences through changes in sensor data, and then adapt accordingly to deal with the mismatches? Details can be found in Appendix B.

3.1 Approach

The analysis process is under the guidance of empirical research, which is grounded in observation and evidence (Bhat, 2023). This study investigated two ZEH in Delft, one inhabited by a single occupant (Case 1) and the other by a couple (Case 2), focusing on the impact of occupant's behaviour and routines on the system performance. All the data and evidence, collected by Evert van Beek in March and April 2022, comprised video-recorded home tours, semi-structured interviews, interaction records (through scanning QR code) and indoor climate data from an integrated sensor box measuring temperature, humidity, light, motion, CO_2 levels.

3.2 Findings

The system can notice unusual changes by detecting unusual fluctuations in sensor data, such as irregular activity or interruption.

Residents' regular routines can cause repetitive patterns in sensor data change, indicating that the system can notice some living habits. Via comparison, the system can detect unregular activities, such as guest visiting, since these will cause unusual fluctuations in sensor data. The intervention of the system automation, such as the opening of windows or the shutting down of the system, can be observed through sudden indoor climate fluctuations, in line with the external weather conditions.

However, there is no fixed relationship between the specific behaviour and the sensor data change.

The relationship between a single subsystem interaction and sensor data is not fixed, as indoor climate changes are influenced by multiple factors. Interactions with different subsystems, such as heating and ventilation, affect several indoor climate parameters simultaneously. As a result, it becomes difficult to attribute specific variations in sensor data to a particular interaction with a single subsystem. Secondly, differences in personal habits or intentions will also affect the change in indoor climate data under the same interaction with the same subsystem. In case 1, the activation of the heating leads to an increase in humidity, whereas in case 2 the opposite relationship is observed. This difference can be attributed to the habit of the occupant in case 1, who tends to hang wet clothes near the heater.

Additionally, the system and the house can build the intentions and living habits together with the residents.

Zero energy housing includes the ability to monitor occupants' activities and establish habits in relation to their preferences. The design of the house layout, including room orientation, pathways and layouts, influences the frequency and duration of residents' interactions with key elements. In Case 1, one resident expressed a preference for drawing the curtains in the afternoon, as the west-facing windows receive more sunlight at this time. The bedroom window emerged as the main point of interaction in both cases, probably due to its accessibility during morning routines. The occupants' expectations of the indoor climate varied according to the function of the room, leading to different patterns of interactive behaviour. For example, in Case 1, the resident desired a cooler environment and more fresh air during sleep, which resulted in frequent interactions with the bedroom window and the distant heater location. Emotional attachment to one's home also influences residents' intentions and behaviour. In Case 1, the resident believed that keeping all the windows closed restricted air circulation. For him, leaving the window open during the day was seen as preparation for a comfortable indoor climate when returning home. In Case 2, the occupant always leaves the radiator in the porch on in order to experience warmth on arrival.

3.3 Key Insights

01

The active involvement of occupants matters. Occupants' behaviour cannot always be detected or understood by the technical systems. Chasing for automation cannot solve the conflicts.

02

Adaptation is a collaborative process for the occupants and the technology. There is no standard or correct answer for all the people since the system and the house can build the intentions and living habits together with the residents.

03

The experience of conflicts with system in the daily life was more impressive for residents and worth further exploration to discover design opportunities.

04

"How to arise occupants' interest in active exploration of solutions to conflicts to adapt to the new tech in ZEH?" could be a potential direction for further research.

04

ETHNOGRAPHIC STUDY

Since I have already identified the importance of the involvement of occupants and the value of conflict experience, this section, from an ethnographic perspective, deeply investigates currently how the residents respond to the conflicts between them and indoor climate systems, which can be referred to as “crises in routine”. The key aim is to figure out how residents currently adapt to the new system through the existing touch points in the scenario of multiple households. The focused research questions are: 1) What elements enable "crisis in routine" to arise households’ interest in the discovery of satisfactory ways to live together with the indoor climate system peacefully? 2) How the diversity within the family and the family relationship affects households’ understanding and response to the “crisis in routines”? The whole study is under the guidance of grounded theory. Semi-structured interviews and small stimulus are used for collecting data. The thematic analysis is conducted for figuring out design space and a framework for the ideation.

4.1 Method

Participants

The target participants are the couple who now living together in the same house in Netherlands to take part in the interview together. This research recruited 4 couples, all of whom are between 20-30 years old. This key aim is to figure out what they will do when facing conflicts with a new system in family scenario while the touch points design is different in every single house. Therefore, couples not living in a zero-energy house now are still suitable and the findings should still be valuable for zero-energy house cases.

Data Collection

Data for this study was collected through semi-structured interviews conducted in the participants' homes. The interviews were in two parts. In the first part, participants were asked to provide an overview of their current indoor climate system and daily routines. In the second part, participants experienced simulated interventions designed to mimic the new indoor climate system in a zero-energy house. Following the interventions, participants answered a series of questions. During this process, participants independently wrote down their answers and a subsequent discussion was held to observe how diversity within families and family relationships influenced households' understanding and response to the identified 'crisis in routines'. All data were audio recorded and photographs taken for documentation purposes.

Stimuli

In the research, stimuli simulated features of new ventilation systems and contrasted old radiators with new heat pump heating systems. A distant fan simulated the sound and airflow of the new ventilation system. Hot water bottles, uncovered (Figure 10 left: representing old radiators with rapid heat emission) and covered (Figure 10 right: representing newer systems with slower room heating), simulated heating dynamics. Placing the bottles in specific enclosures emulated heating and cooling processes in normal homes (Figure 11) and in ZEH (Figure 12) respectively, effectively illustrating the differences between the systems.

Analysis Approach

I conducted the analysis of the interview findings using the grounded theory framework as outlined by Tie et al. (2019). The process began with the identification of 'crisis in routine' storylines within the interview transcripts on a case-by-case basis. Initial coding was used to mark significant information within these storylines, with the aim of identifying the factors influencing the productivity of the 'crises' in each case. The next stage involved the merging of similar codes into distinct clusters. To extract design direction, I identified relationships between the clusters, paving the way for the formulation of themes under the guidance of thematic analysis (Villegas, 2023). This resulted in the establishment of a framework for guiding the ideation phase.

Figure 10: The hot water bottle without/ with a cover

Figure 11: The empty box & the empty cushion cover simulate normal house. (No insulation)

Figure 12: The empty box and the cushion simulate the new house with good insulation.

4.2 “Crises” & Elements Identification: Initial Coding

This section attempts to outline the archetypal 'crisis' storylines and to identify the factors that influence the productivity of these 'crises' on a case-by-case basis. The storylines, presented as timelines, are derived from interview transcripts, and the use of different colours serves to distinguish the different residents involved. In storyline figures, dark yellow represents the actions and thoughts of male resident, while green represents those of female resident. Light yellow indicates it can be conducted by either occupant, while light blue reflects actions or information from external stakeholders. These graphs are generated using Figma.

Then I broke down the crises on a case-by-case basis, highlighting the different roles played by those involved and the evolving boundaries surrounding the crises. I illustrated factors contributing to the "crises" and their subsequent impact on the development and productivity of the "crises". During the analysis, I proposed explicit definitions of the roles within the 'crises' and categorises the different factors for clearer explanation (“my glossary” below). Within the graphical analysis of the 'crises', the colour-coded scheme includes orange boxes representing Actors, green boxes representing Supporters and blue boxes representing Professional Advisors. Beige here indicates collaborative actions or either one family member's action. The boundary of the 'crisis' is delineated by a grey frame within which beige squares indicate Elements within the Boundary and purple squares indicate Assumed Elements referred to by the participants. Same with the storyline diagrams, orange boxes represent Actors, green boxes represent Supporters, and blue boxes represent Professional Advisors. The Boundary may expand from version 1 to version 3 as the story evolves and time passes.

My Definition

Actor:

Refers to an individual who is actively engaged in the "crisis" and has the ability to dynamically expand the "crisis" boundary by proactive discovery.

Supporter:

Refers to a person who plays a role of bystander during a 'crisis', providing additional perspectives and inspiration to the actor, facilitating a broader understanding of the 'crisis' (e.g., neighbours or members of an online community).

Professional Advisor:

Characterises an entity that has no intrinsic link to the 'crisis', but provides credible references and expertise to actors, encouraging positive contributions in expanding boundaries and revealing hidden elements (e.g., technicians or instruction manuals).

Boundary of “crises”:

Refers to the aggregate that encompasses the context and all the human and non-human entities involved when the 'crises' occurred. It is imperative to note that the boundary is inherently dynamic and may expand over time as hidden elements are brought to light.

Element within Boundary:

Represents the factors that are perceptible at the onset of a "crisis." It varies through the boundary extension.

Hidden Element:

Refers to factors that are intrinsically present but not perceptible to the household. These elements have the potential to be revealed to become Element within Boundary as “crisis” evolve.

Assumed Element:

Indicates a hypothetical factor that is not inherently present but is assumed to be present by households. It indicates that the system expression is not aligned with user cognition, negatively affecting on productivity of “crisis”.

“Crisis” 1: Story of floor heating, technician, and energy bill APP

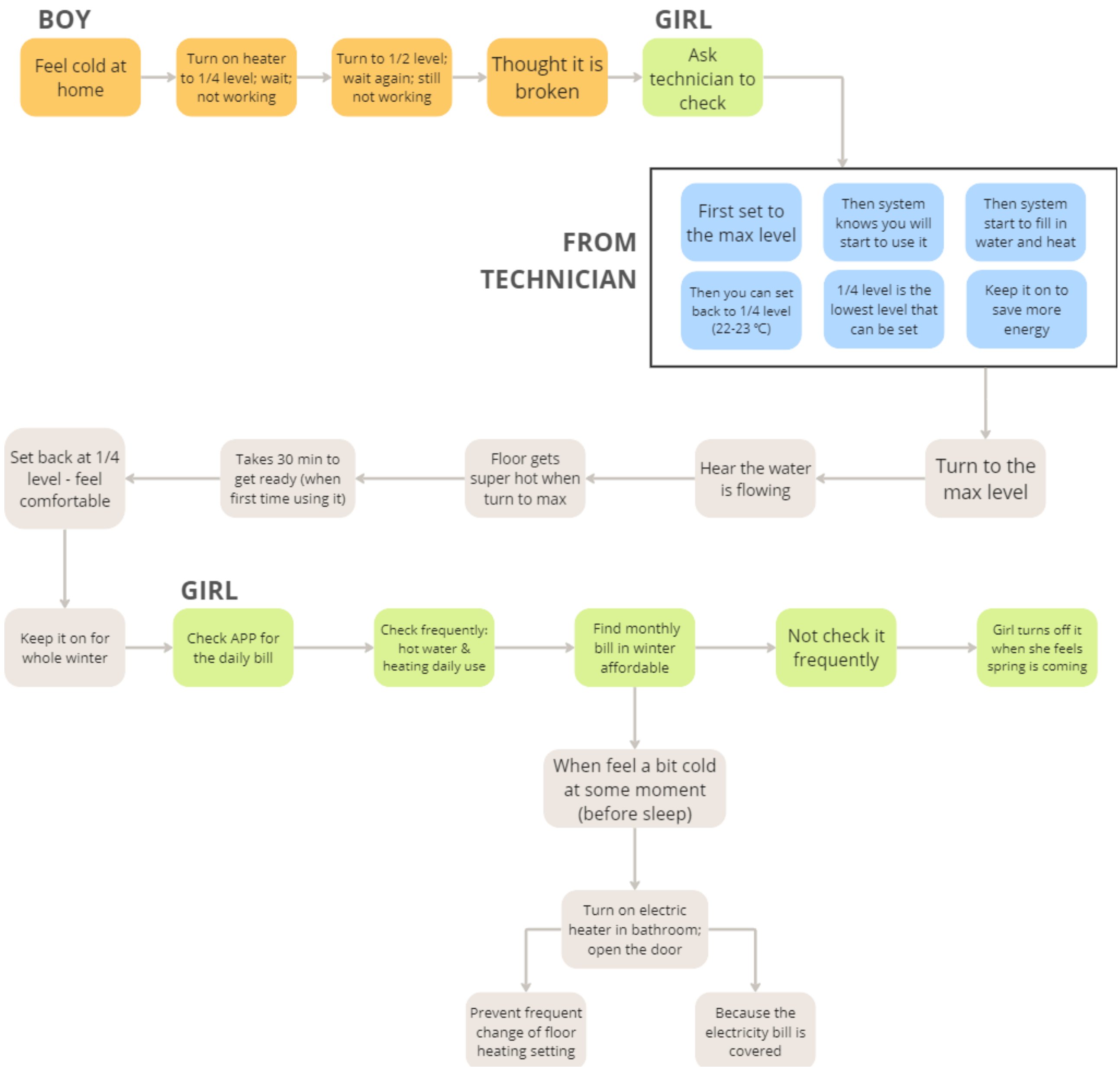


Figure 13: The storyline of “crisis” 1

The occurrence of the 'crisis' can be interpreted as a fundamental mismatch between the system's and the occupants' perceptions of appropriate practice. The system operates on the premise that users should initially turn on the floor heating at maximum levels for pre-heating, before adjusting to the desired temperatures. Conversely, the occupants assume that they are free to set the system to any desired temperature with the expectation of immediate heating. Consequently, occupants disregarded the recommended maximum setting during initial use, culminating in a perception of system failure. This discrepancy led to doubt and concern about the reliability of the system. The intervention of a technician and the female resident triggered the transformation of the 'crises' from an unproductive to a productive state, facilitating a shift in the occupants' perceptions and inspired new adaptation strategies, armed with a range of external resources. By considering the entire indoor heating system as an integrated entity, the bathroom door emerged as a new 'interface', serendipitously discovered by the occupants in their daily routines (Figure 13).

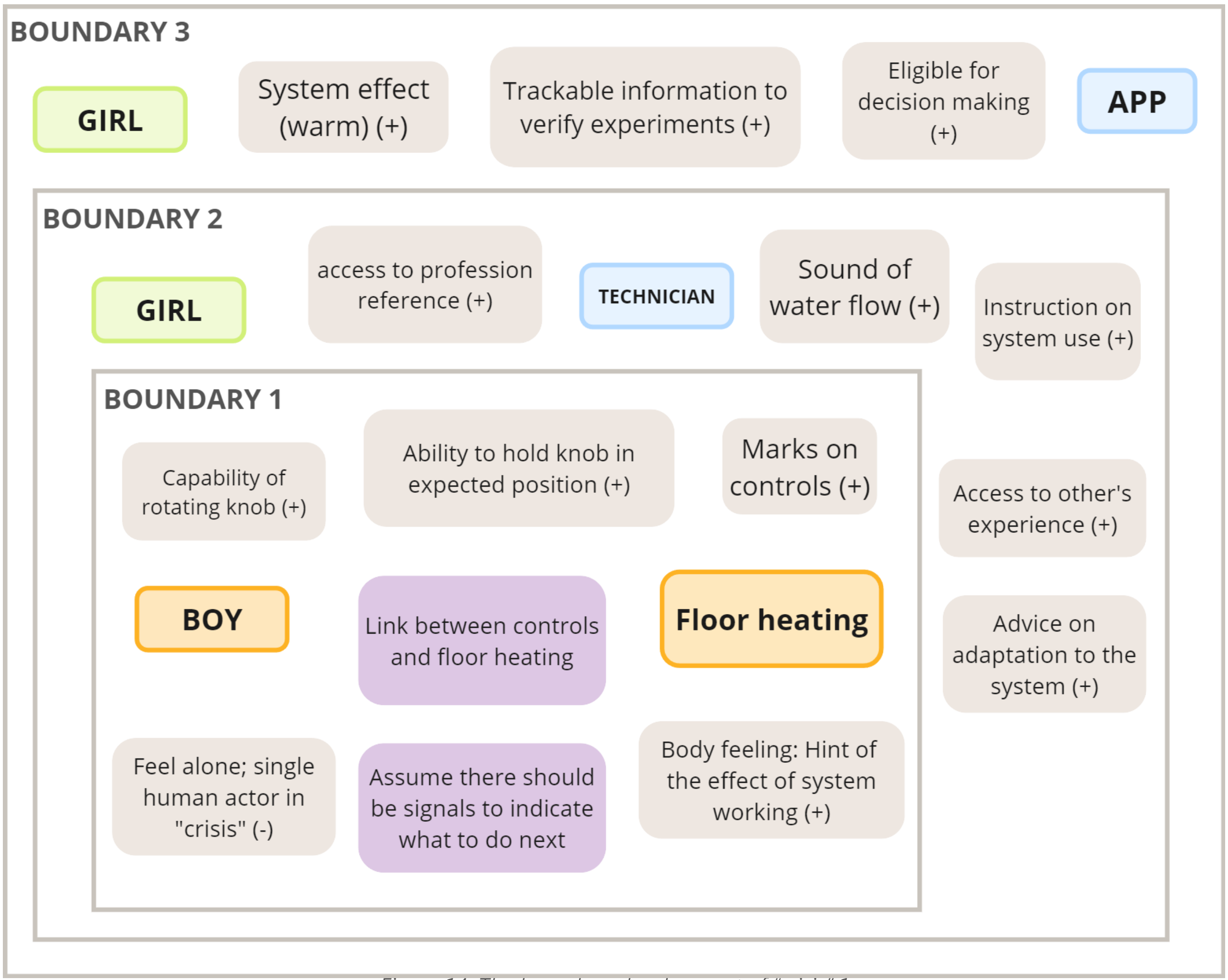


Figure 14: The boundary development of "crisis" 1

In Crisis 1, the male occupant and the floor heating system took on the roles of actor, while the female occupant and the technician took on the roles of supporter and professional advisor. The crisis boundary experienced two successive extensions. The first expansion was facilitated by the collaborative efforts of the resident and the technician, due to her exclusive access to the technician. Subsequently, the resident extended the boundary further through her engagement with the energy bill application, to which she had exclusive access (Figure 14).

Within the first boundary, the functionality of the heating system was signified by the capability of rotating and holding the knob at expected position and the marks on the controls, which provided the male resident with confirmatory feedback on his actions. Additionally, the absence of hints reflecting the effect of the system working fostered doubt and encouraged exploratory behaviour. Thus, I define these elements have a positive effect (with +) on the productivity of "crisis". Conversely, the absence of anticipated factors, referred to as assumed elements, had a negative impact (with -) on the productivity of the crisis, as they were expected to provide guidance but did not materialise.

Upon expansion to the second boundary, additional hidden elements were revealed through the engagement of the female resident and the technician who served as supporters. These newly discovered elements had a beneficial effect on the productivity of the crisis by expanding the actor's understanding of the system's features and providing instructions for its use.

Subsequently, the crisis boundary underwent a third expansion using the energy tracking APP by the resident. The elements revealed during this phase had a positive impact on the productivity of the crisis by providing trackable data that guide further experimentation and ultimately helped residents to develop their personalised solutions.

“Crisis” 2: Story of convectors, different sensitivity on heat between male and female, doubt and trial

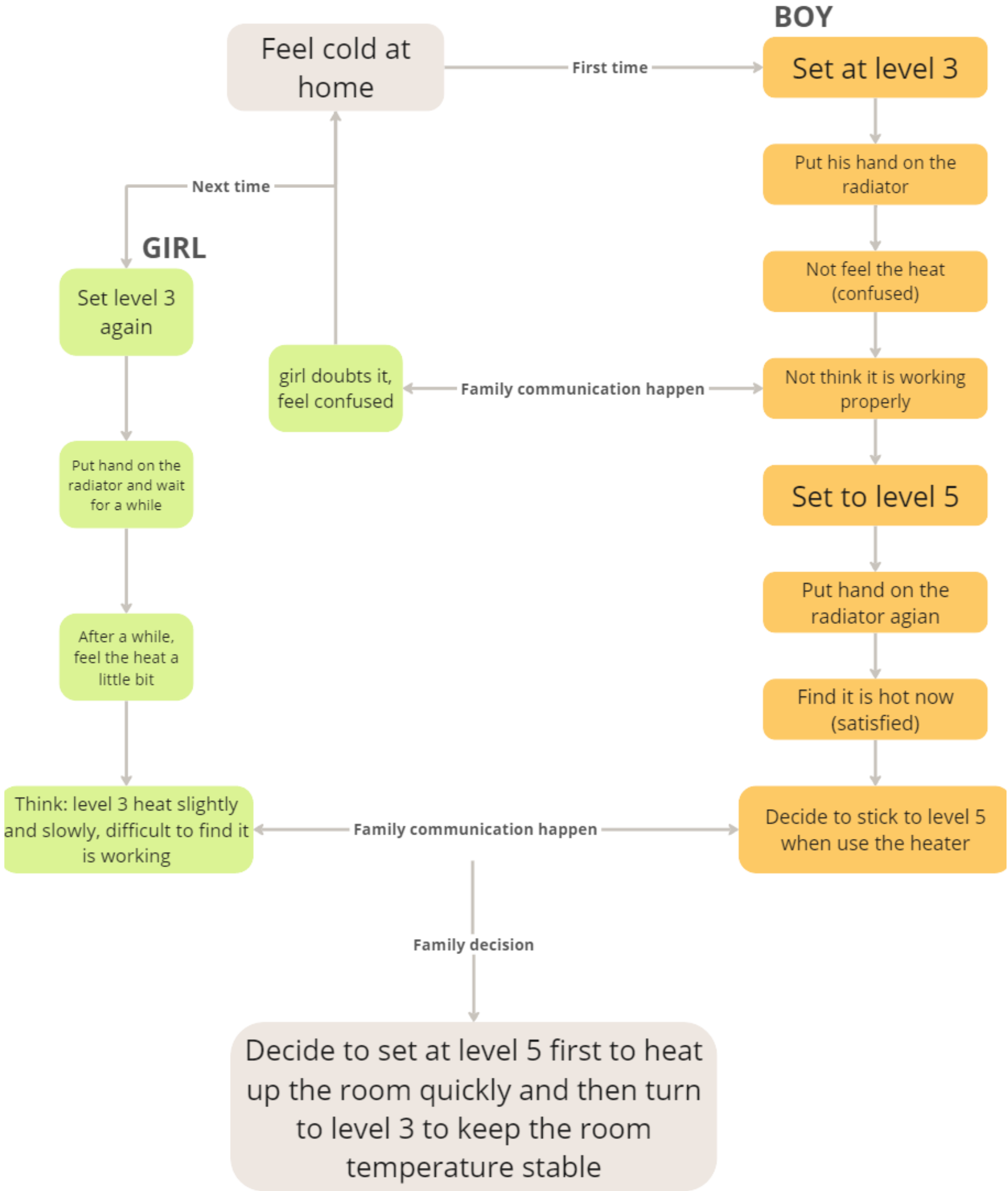


Figure 15: The storyline of “crisis” 2

In case 2, there is a mismatch between the operational assumptions of the system and the expectations of the residents. The system is based on the idea that users should set the unit to the desired setting and wait patiently for the room to warm up gradually. Conversely, the occupants expect the radiator to emit heat immediately as an indicator of its ability to heat the room quickly. The resulting mismatch is manifested when the radiator, set at level 3, maintains a relatively low temperature with a gentle heat-up. The occupants, unable to perceive immediate warmth, question the radiator's effectiveness and resort to maximising the setting, inadvertently resulting in energy inefficiency. The situation changed when another member of the household intervened in this 'crisis'. Differences in thermal sensitivity and decision-making authority prompted a collaborative effort. Working together, they devised a tailored approach to coexist harmoniously with the system. In this scenario, the 'crisis' proved productive as it facilitated collective problem-solving and adaptation strategies among the residents (Figure 15).

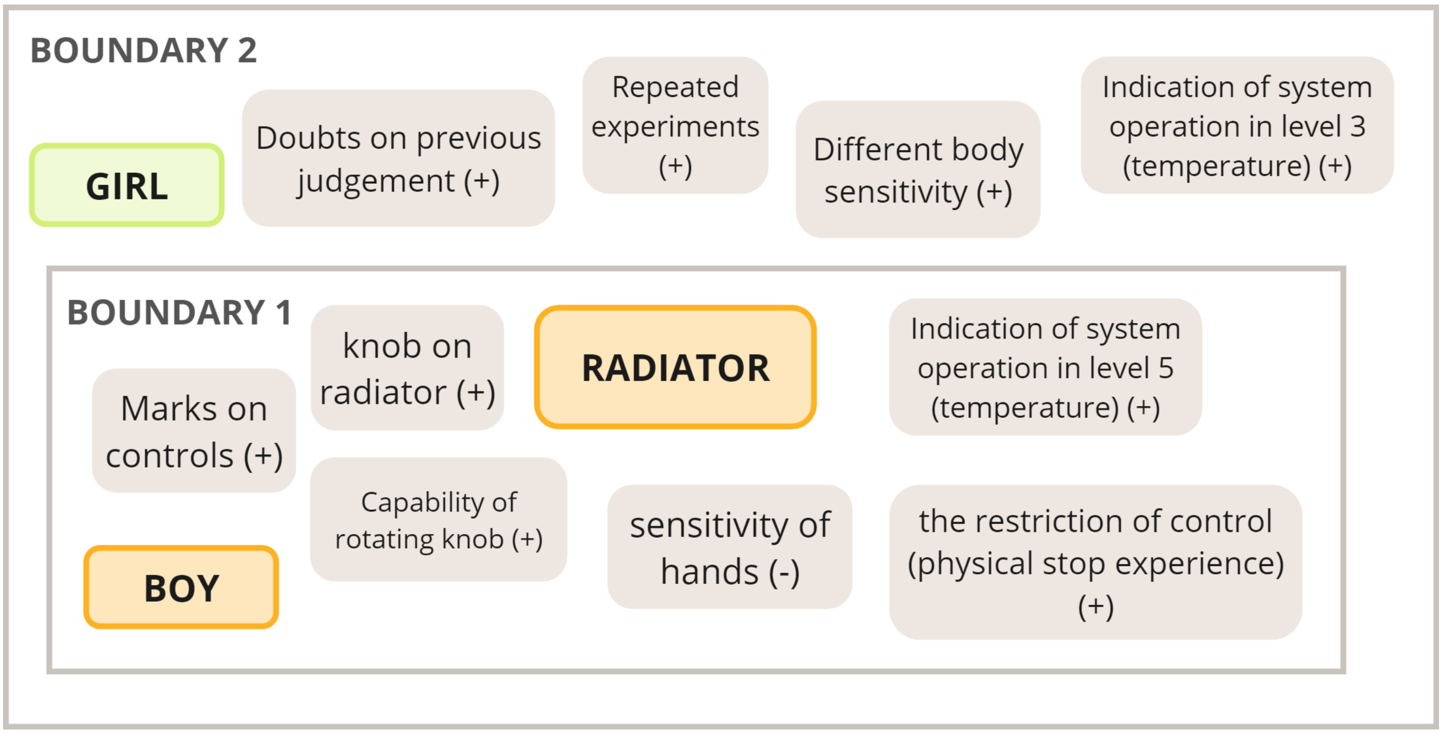


Figure 16: The boundary development of "crisis" 2

In Crisis 2, the male resident and the radiator took on the roles of actors, while the female resident acted as a supporter. The boundary of the crisis was expanded as a result of the involvement of the female occupant. This expansion was fundamentally rooted in the disparities in thermal sensitivity and decision-making agency between the two residents.

Within the initial boundary, most of the elements positively influenced the productivity of the crisis by collectively conveying to the male resident the scope and constraints of interaction with the radiator. However, his relative insensitivity to heat meant that he was only able to perceive heat at the radiator's maximum output (level 5). This element blocked certain information within the crisis, thereby reducing his productivity. The female occupant, who was also affected by the indoor climate and had decision-making authority, questioned the judgement of the male occupant and initiated a series of experiments. These elements facilitated proactive exploration and contributed to the productivity of the crisis. The female resident's higher sensitivity to temperature enabled her to identify that the system was operating at a low temperature on level 3, thereby increasing the productivity of the crisis. Ultimately, they discovered the most harmonious approach to living with the system (Figure 16).

“Crisis” 3: Story of toilet, shower and hot water use

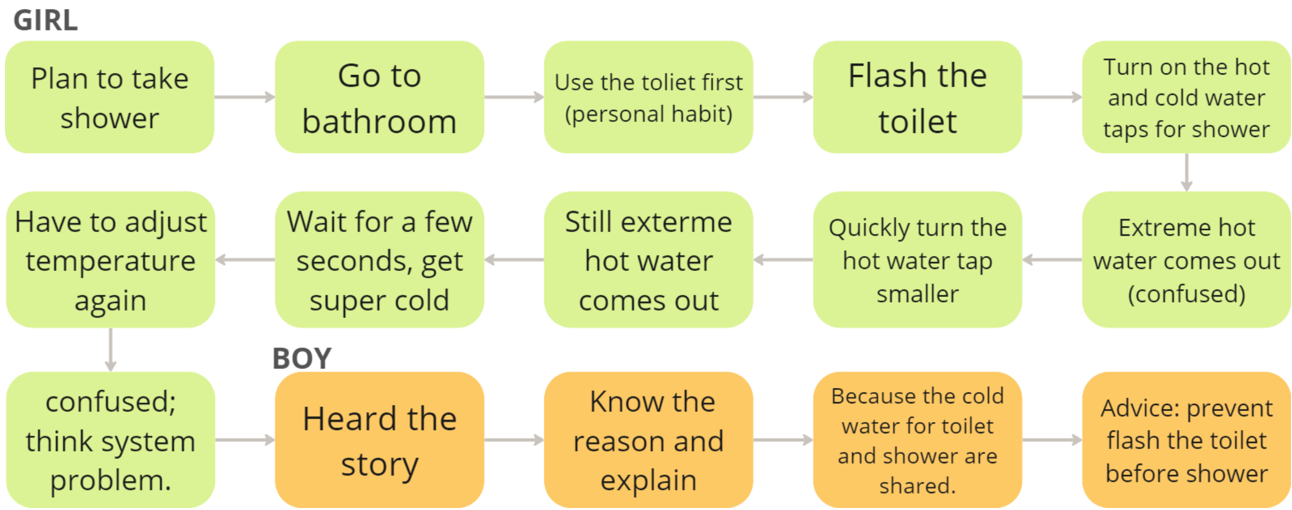


Figure 16: The storyline of “crisis” 3

In this narrative, a 'crisis' arose because of an unexpected conflict between a personal habit and the operation of the system. The resident assumed autonomy in her actions, unaware that flushing the toilet immediately before showering could trigger an unwanted experience. The system was not configured to anticipate such a sequence of activities. The turning point in this 'crisis' was facilitated by family communication and the involvement of another resident who had a rich understanding of the technology and its limitations. His insights made the "crisis" productive. Through this collaborative exchange, the female resident was empowered to develop an adaptive solution that harmonised her personal habits with the system features.

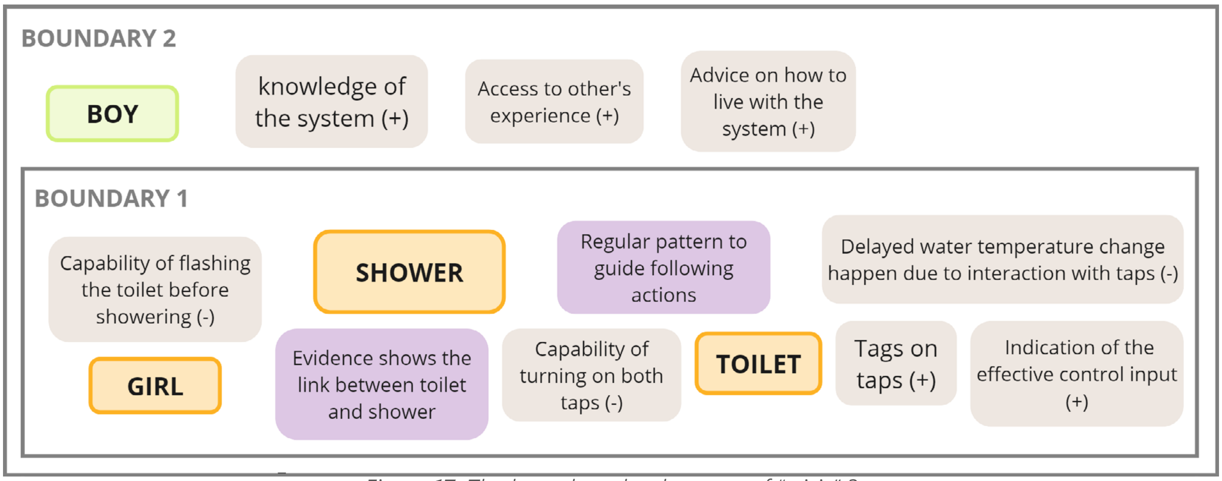


Figure 17: The boundary development of “crisis” 3

In this crisis, the female resident, the shower and the toilet emerged as central actors. The crisis boundary experienced a single expansion due to a dialogue with the male resident, who took on the role of supporter. Within the initial boundary, the extensive capacity of the female resident to interact with both the toilet and the shower inadvertently introduced barriers to understanding the operating rules of the system, rendering the crisis unproductive. This occurred because the actor was unable to discern what constituted prohibited or inappropriate behaviour. The absence of assumed elements and the delayed response to the change in water temperature further obstructed the discovery of the root cause of the crisis. However, engagement with the male resident changed the dynamic. His depth of knowledge and insight significantly influenced the female resident's understanding and moved the crisis into a productive phase. He also made explicit recommendations for future behaviour, in particular not to flush the toilet immediately before showering, which helped the resident to find a solution (Figure 17).

"Crisis" 4: Story of bathroom light and IR sensor control

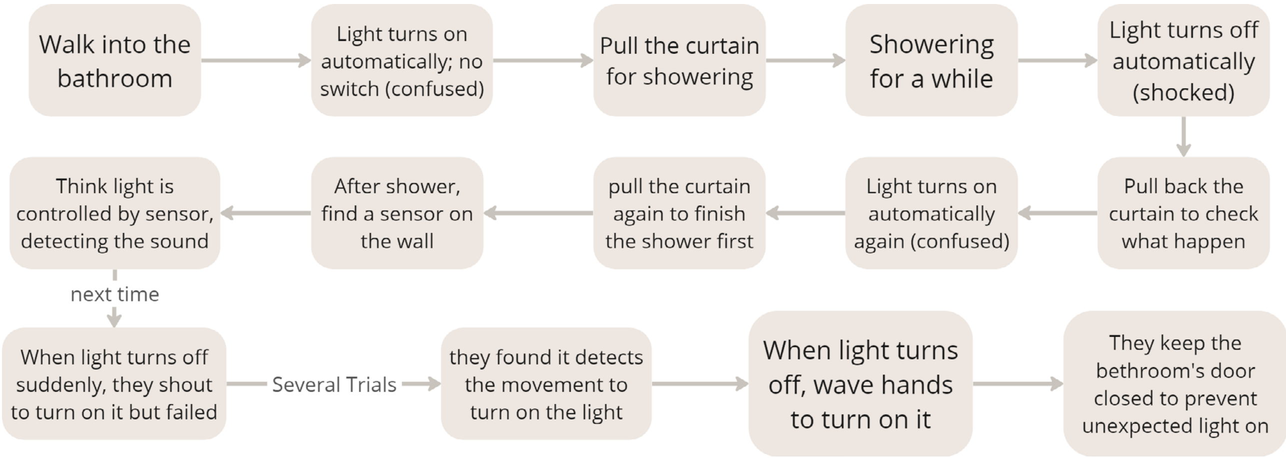


Figure 18: The storyline of "crisis" 4

In the scenario described, the system's assumption that motion detection in the bathroom was correct for lighting control was flawed due to potential obstructions such as curtains. Based on past experience, the occupants expected a manual switch to control the lighting. Despite these challenges, the situation was instructive. Factors such as the visible placement of the sensor and the distinct changes in light, particularly when interacting with the curtain, provided valuable insights and improved understanding of the system's operation and interactions (Figure 18).

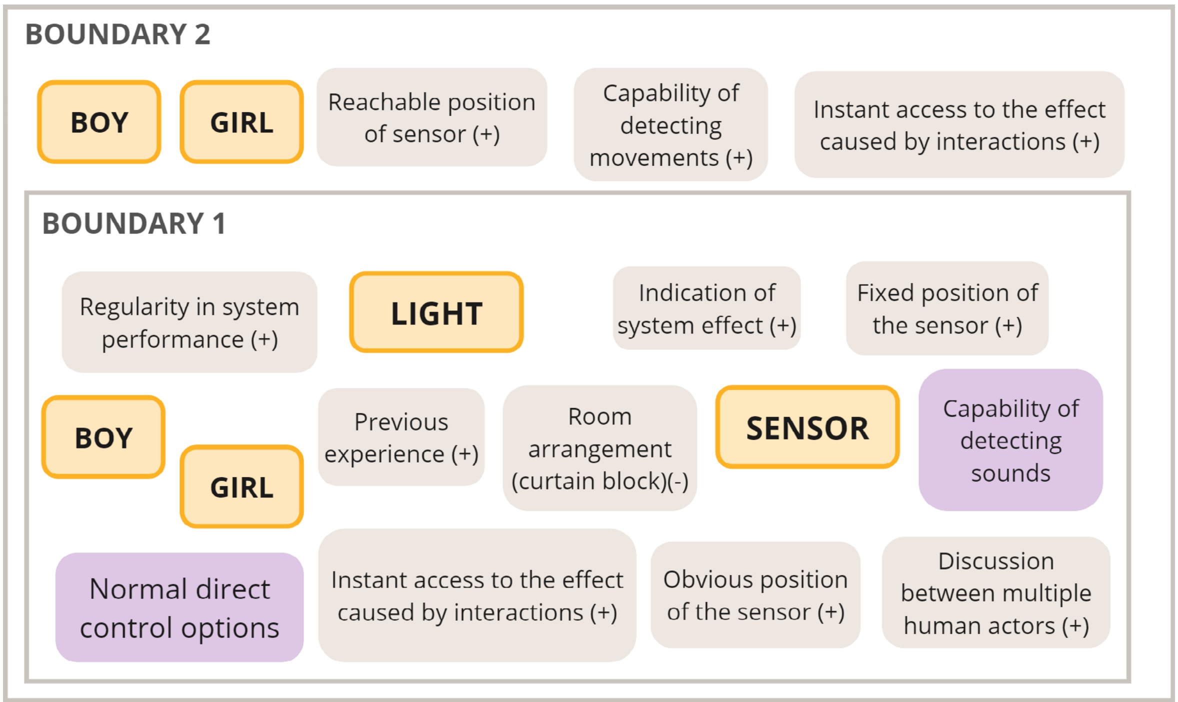


Figure 19: The boundary development of "crisis" 4

In "Crisis 4", unlike other situations, there were no supporters or professionals involved. Both participants are actors (Figure 19). Challenges arose from the layout of the room, in particular a shower curtain that interfered with the design and function of the system. However, the residents' previous experience and the immediate feedback from the system allowed for rapid experimentation and adjustment. Family discussions encouraged further experimentation. Residents used the system's feedback to identify its operating patterns, for example, realising that the lighting relied on motion detection rather than sound detection. Accessible sensor placement facilitated an adaptive strategy in which hand waves prevented unexpected lighting shutdowns.

"Crisis" 5: Story of the ventilation outlet, mysterious switch and sensor box

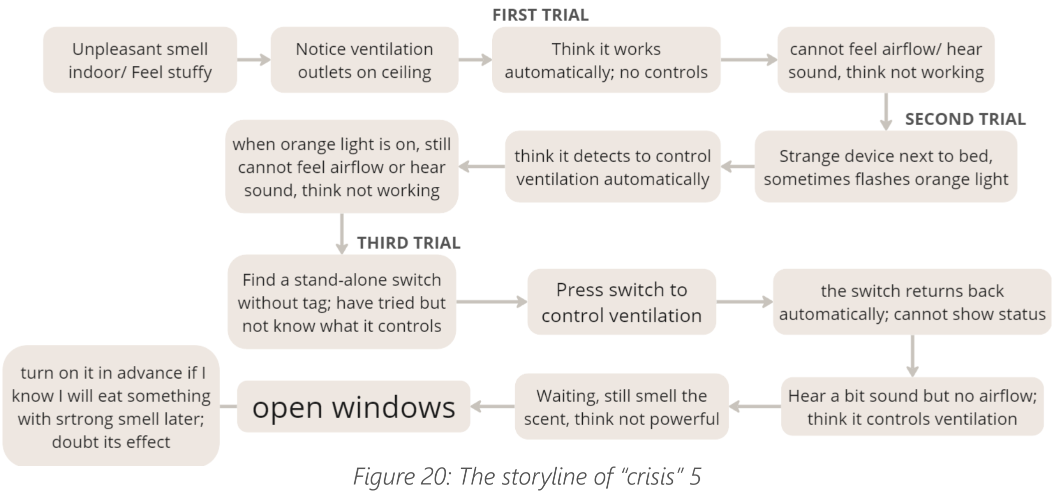


Figure 20: The storyline of "crisis" 5

This is an example of a typical unproductive 'crisis'. The system operates on the assumption that its automated ventilation is effective and can accommodate all required scenarios, while the occupants expect the ability to modulate ventilation levels in response to different scenarios (e.g. cooking). Although the 'crisis' includes some hints that could spark interest and provide direction for exploration, these hints lack clarity and coherence, rendering them confusing to the occupants. As a result, the residents are unable to develop an effective adaptation strategy, leading to a dead end.

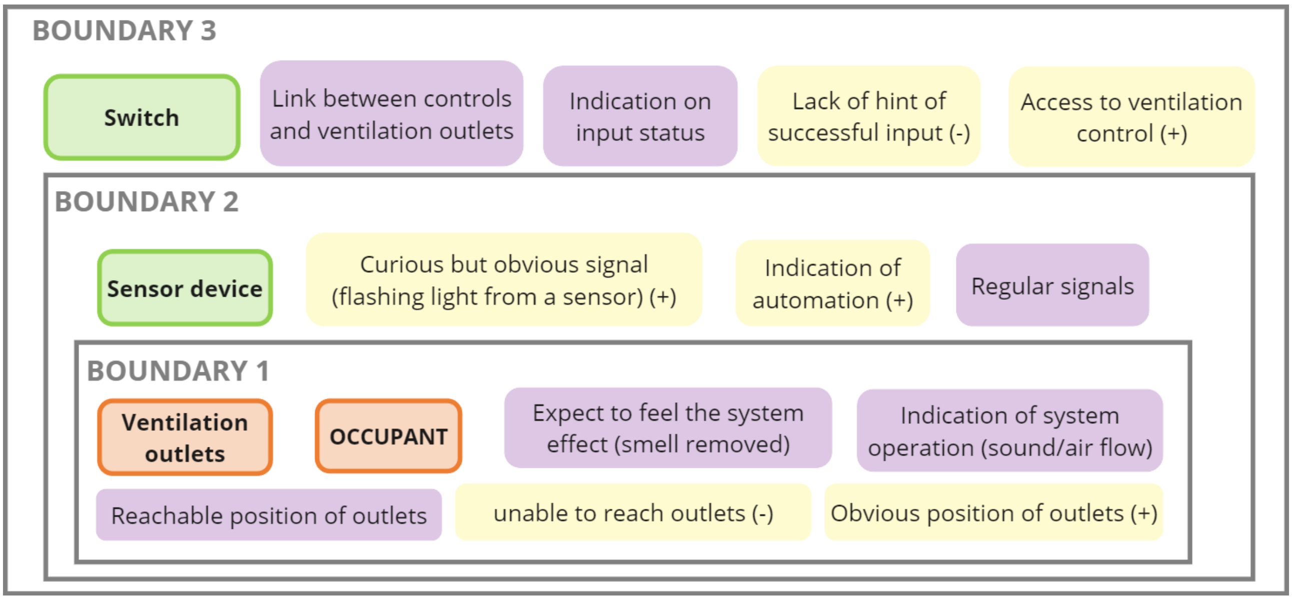


Figure 21: The boundary development of "crisis" 5

In Crisis 5, the focus was on the inmates and the vents. While the clearly placed vents initiated investigation, their inaccessibility limited exploration. This mismatch between occupant expectations and system operation led to an unproductive 'crisis'. When the boundary was extended, a sensor and flashing lights were added, but inconsistent signals further confused understanding. A subsequent boundary extension introduced a switch, revealing more components, but the function of the system remained unclear. The lack of feedback and observable results perpetuated the unproductivity of the crisis. Ultimately, this disconnect caused the occupants to disengage from the system.

Conclusion: Commonality in 5 "crises"

The framework of a common 'crisis'(Figure 22) was extracted from these 5 case analyses. The root cause of the 'crises' was the conflict between the perception of appropriate practice between the system and the residents. The corresponding system operation is not aligned with the households' practice. Thus, the "crisis" occurs. Within the common context of 'crises', I identified 4 key stages and the relationship between which is shown in the figures below. Highlighted in dark grey, "System state" & "People create" will be main focus of my design.

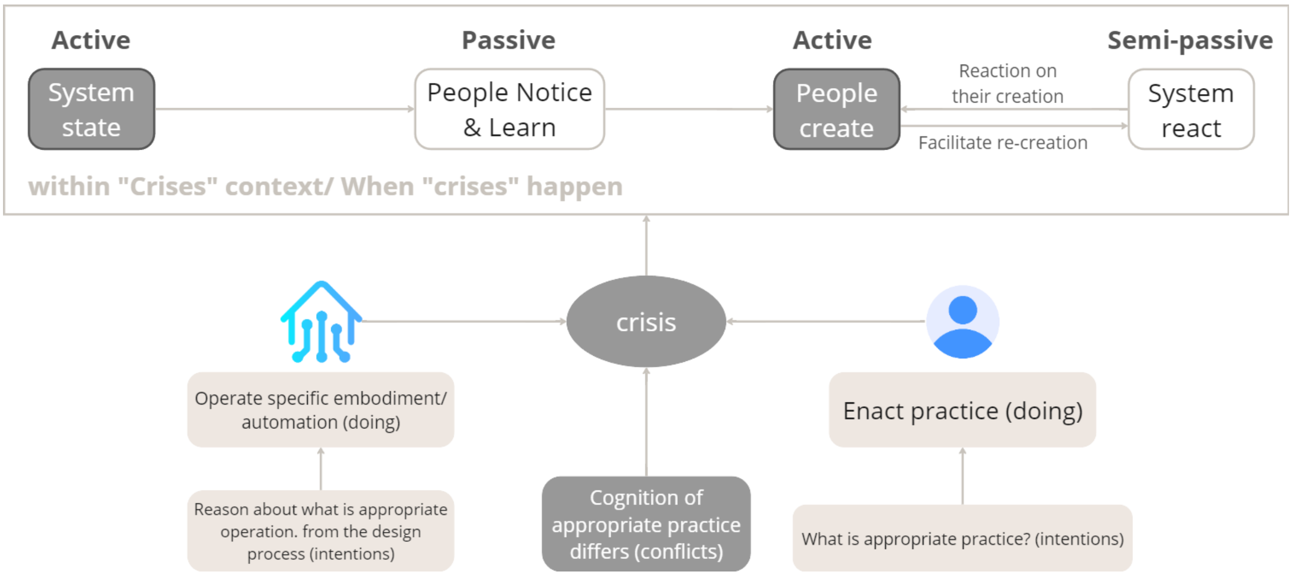


Figure 22: The common breakdown structure of a "crisis"

"System State" refers to the representation of the attributes and conditions of a system in the context of a "crisis". The system can be seen as an active self-expresser, using dynamic mechanisms to communicate information to occupants. The representations, which include the type and manner of information presentation (e.g. visual, auditory) and its accessibility, play a central role in stimulating user curiosity and exploration. A good system state enables households to effortlessly notice and understand system-related information.

"People Notice & Learn" embodies the passive absorption of information by households, facilitated by the system state. The effectiveness of this stage depends on the clarity and expressiveness of the system state. Through passive engagement, households accumulate knowledge about the underlying incongruities and gather stimuli for further exploration. This proves to be crucial in adapting to new system.

"People Create" is characterised by occupants' active engagement, in which they experiment to develop personalised methods for harmonious coexistence with the system. This process is supported by the insights gained during "People Notice & Learn" phase and is also influenced by external factors such as the extension of the "Crisis" boundary and occupant's increased willingness to explore.

"System React" is a semi-passive phase for the system in which it reciprocates with feedback, constraints, guidance and affirmation in response to the efforts of the People Create phase. This perceptible feedback may encourage modification or fine-tuning of the residents' actions, creating an iterative feedback loop between 'People Create' and 'System React' that continues until a satisfactory relationship with the technology is achieved.

There is a dependency of the passive stages on the effectiveness of the active stages. The design of the "system state" has a significant impact on what information is assimilated by the occupants. Consequently, the creation of enacted interfaces is primarily based on acquired knowledge. The system state serves as a foundation on which the "People Create" stage is constructed, emphasising on the design aspects of the active stages.

4.3 Thematic Analysis

The identified elements before are too diverse and specific to different "crises" stories. In addition, the relationship between different elements and the impact of them on the productivity of "crises" are not well analysed. Therefore, the findings before are not inspiring enough to identify the design space. To induce elements and clarify design opportunities, I did a second round of coding to merge and adjust similar elements to formulate different clusters. The elements, which brought either positive or negative impact on the same aspect, were categorised in the same cluster. The times they appeared in the interview and the observation could indicate their power of impact. Among all the clusters, those highlighted in yellow are more objective and harder to be affected by designers. The details can be found in Appendix F.

Second Round of Coding

This table shows the process of second round of coding. I dentified the detailed definition of all the clusters and how many times they appeared during interview and observation.

Cluster	Explanation	Number
Access to evidence	"I can get access to feedback which can reflect my actions and guide next step."	6
Affordance	"I have physical access to actuator/sensor."	4
Curious signal	"I notice some signals related to system performance, arising my interest in exploration."	3
Effect of system working	"I feel the changes of indoor climate caused by system operation."	5
Feel capability of control	"I believe I can control the system successfully."	4
Indication of action input	"I know my behaviour causes change."	3
Indication of automation	"I know that the system can detect variation and solve the problem independently."	2
Indication of progress	"I can feel the system is working hard to reach my expected effect."	4
Indication of system status	"I know what the system is busy with."	4
Links between control and actuator	"I know I am interacting with this control to adjust the performance of that device."	3
Number of human actors	"I am (not) alone in directly facing crisis, and I cannot (can) talk to someone else now."	3
Professional advisor involved	"There exists objective, professional reference for me to check or follow."	3
Restriction of behaviour	"I know the possible range of adjustment/special rules of my action."	3
Regularity in system performance	"There exist some repetitive patterns in the system performance which can be found."	3
Supporter involvement	"I get access to others' experience/ feeling/ opinion for myself doing further experiments."	9

Table 1: The definition of coded clusters

"Supporter Involvements" have the greatest impact on the productivity of "Crises". This category includes greater access to the experiences of others, as well as discussions or debates that arise from differences in individual perceptions and levels of knowledge. Together, these elements facilitate the elucidation of the underlying causes of 'crises' and stimulate actors to develop new interfaces for adaptation, thereby transforming a 'crisis' from 'unproductive' to 'productive'. Particularly in a family setting, supporters, often family members, who are eligible for decision making and have additional perspectives and resources, increasing the possibility of uncovering hidden elements. Next in importance is "access to evidence", which acts as a catalyst in the ongoing exploration of the "crisis". It provides confirmatory feedback that increases residents' confidence in evaluating their actions and determining next steps. Evidenced through the interviews, this cluster includes the most of "assumed elements”, signifying occupants' expectations that are unmet in reality. In some cases, households may actively add to this aspect in order to derive clearer guidance.

"The effect of system working" refers to subjective perceptions such as the warmth or coolness of a room, air quality or instant access to hot water. Previous research (Chapter 2) shows that such perceptions are predominantly influenced by individual diversity and unpredictable external variables, such as indoor activities and daylight levels. In addition, actions are often driven by personal experience and perceptions rather than objective data. As a result, there is limited scope for designers to modify these aspects to improve productivity in a crisis. "Number of human actors" refers to the number of occupants actively engaged during the occurrence of a "crisis". Since "crises" occur unpredictably in daily life and are context dependent, controlling the number of human actors is neither feasible nor within the designer's control. "Regularity in system performance” refers to objective characteristics of the system that are largely dictated by its inherent technology.

In summary, "Supporter Involvements" and "access to evidence" are key to transforming crises into productive states. While "The effect of system working", "Number of human actors" and "Regularity in system performance” are less accessible to designer intervention, which are out of scope in the following ideation phase.

Second Round of Coding

Three distinct themes were discerned through the aggregation of clusters characterized by similar modes of influence in making the "crises" productive. Overlapping was observed among the themes when a cluster exhibited dual modes of contribution. The detailed definition of the three themes and the relationship among them are presented below. The explanation on each element's contribution to different themes will be demonstrate in this section.

Extension of "Crises" Boundary:

Expanding awareness of system features and integrating new insights of "crises".

Entrance to Discovery:

Motivations for occupants to start exploring the "crises" and discovering enacted "interface" for adaptation.

Encouragement from "Crises":

Providing households with feedback, restriction, and guidance to confidently evaluate and adjust the course of their actions during the exploration process.

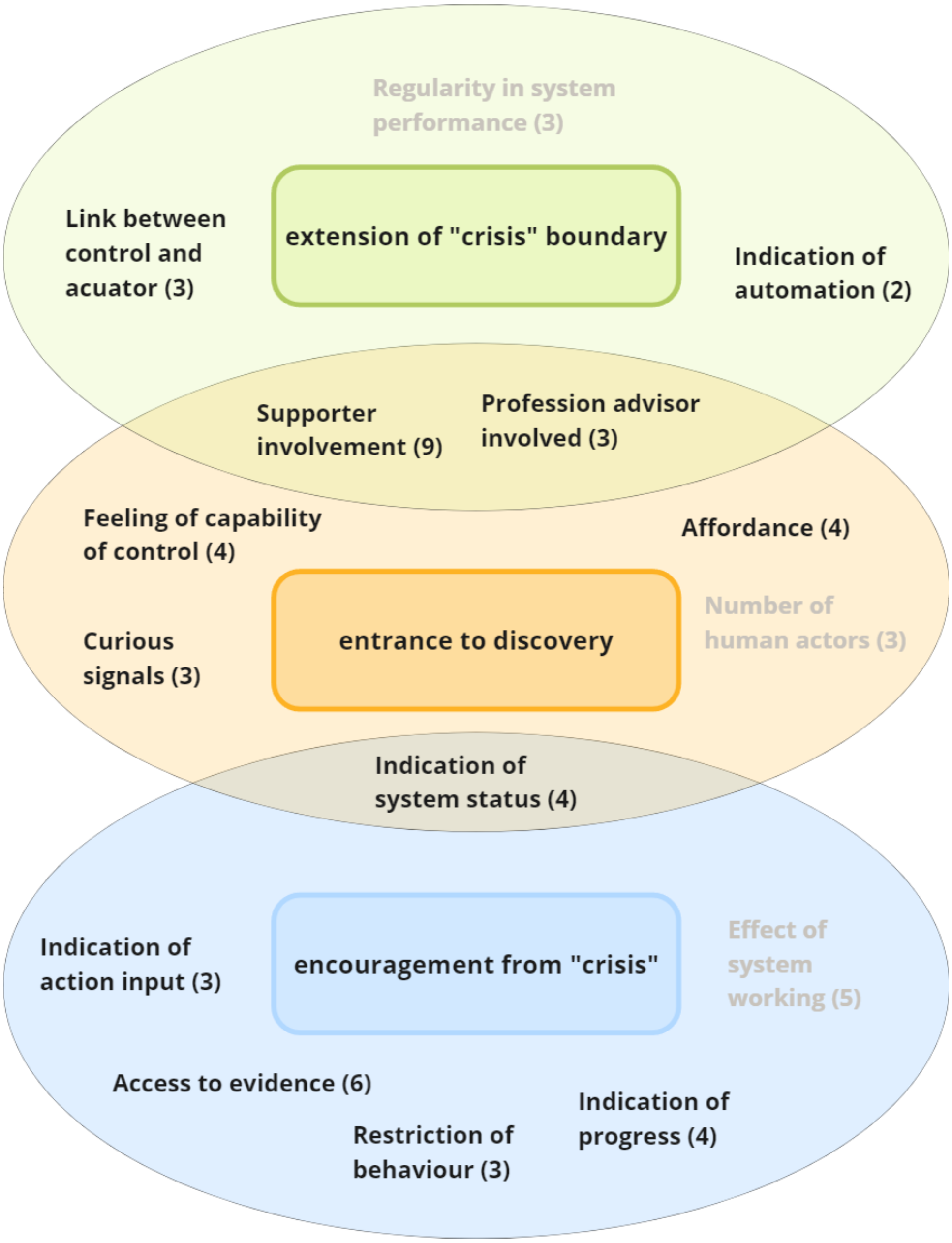


Figure 23: The framework of three themes

Theme1 Extension of "Crises" Boundary

Links between control and actuator: A clear indication of the connection between this control and this actuator helps in revealing hidden elements and broadening the scope of what the system can accomplish during "crises".

Indication of automation: Being aware of the system's ability to self-regulate and solve problems independently expands the understanding of the system's capabilities and touch points, potentially including new elements.

Professional advisor involved: Professional advisors bring their objective knowledge and professional perspectives to the situation, enriching the understanding of the 'crisis" and the system involved, thereby extending the boundaries of the crisis.

Supporter involvement: This helps to broaden the boundaries of the crisis by bringing different perspectives, experiences, and feelings to the table, which helps to deepen and broaden the understanding of the systemic features and the related crisis.

Theme 2 Entrance to Discovery

Supporter involvement: With shared insights from supporters, individuals may find encouragement to initiate an investigation into the crisis. As supporters may be eligible to make decisions, they can also actively participate in the exploration and collaboratively create a new "interface" for adaptation.

Professional advisor involved: Professional advisors offer expert guidance and advice, which can be instrumental in opening the door to discovery. Their involvement can offer a structured approach, spurring individuals to take the first steps in addressing the crisis.

Feeling of the capability of control: It contributes to the "Entrance to Discovery" by instilling a sense of agency in individuals. When occupants believe they can control the system successfully, they are more likely to take the initiative to experiment with the system.

Affordance: It is crucial for "Entrance to Discovery" as it relates to the physical accessibility. When individuals have access to the system's components, they are more likely to engage in exploration and experimentation, leading to discovery.

Curious signals: This can serve as initial sparks for the "Entrance to Discovery." When individuals notice intriguing signals related to system performance, curiosity can drive them to initiate an investigation into the underlying causes and functionalities.

Theme 3 Encouragement from "Crises"

Indication of setting status: It allows individuals to know the current settings of the system. This knowledge serves as a basis on which they can make informed adjustments, fostering the confidence needed to actively engage with the crisis.

Access to evidence: This provides individuals with critical feedback on the impact of their actions. This element is central to the theme, as the availability of tangible evidence enhances inmates' understanding and motivates them to continue exploring possible solutions.

Restriction of behaviour: By knowing the possible range of adjustments or special rules of action, occupants can make more focused and efficient experiments, which promotes constructive engagement with the crisis.

Indication of action input: it confirms for individuals that their actions are influencing the system. This feedback empowers them to make deliberate and informed choices, fostering continuous active involvement in addressing the crisis.

Indication of progress: Knowing that the system is striving to meet their expectations can build confidence and encourage continued engagement with the crisis. It also helps to cultivate patience and tolerance for the system's performance.

Conclusion

The enactment process of the new "interface" needs several rounds of stimulus. All the clusters could be the potential stimulus, while the three themes are three different perspectives. Therefore, the identified frame serves as a well-structured design space to guide the ideation phase. "Entrance to discovery" indicates a relative higher impact compared to the others because the included clusters have appeared for the most times during analysis. Therefore, "Entrance to discovery" will reach more attention among these three, which considers more about how to motivate households to actively start their discovery. Considering the overlapping between the different themes, the other two will also be taken into consideration during ideation.

4.4 Cross Analysis

A cross-analysis is conducted between three identified themes and the crisis framework to elucidate interrelationships, to identify which theme predominantly influences which stage. The figure shows that theme 'Entrance to Discovery' significantly influences both 'System state' stage and 'People create' stage. In addition, 'Extending the Crisis Boundary' primarily influences 'People create' stage, while 'Encouragement from crises' influences 'System react' stage.

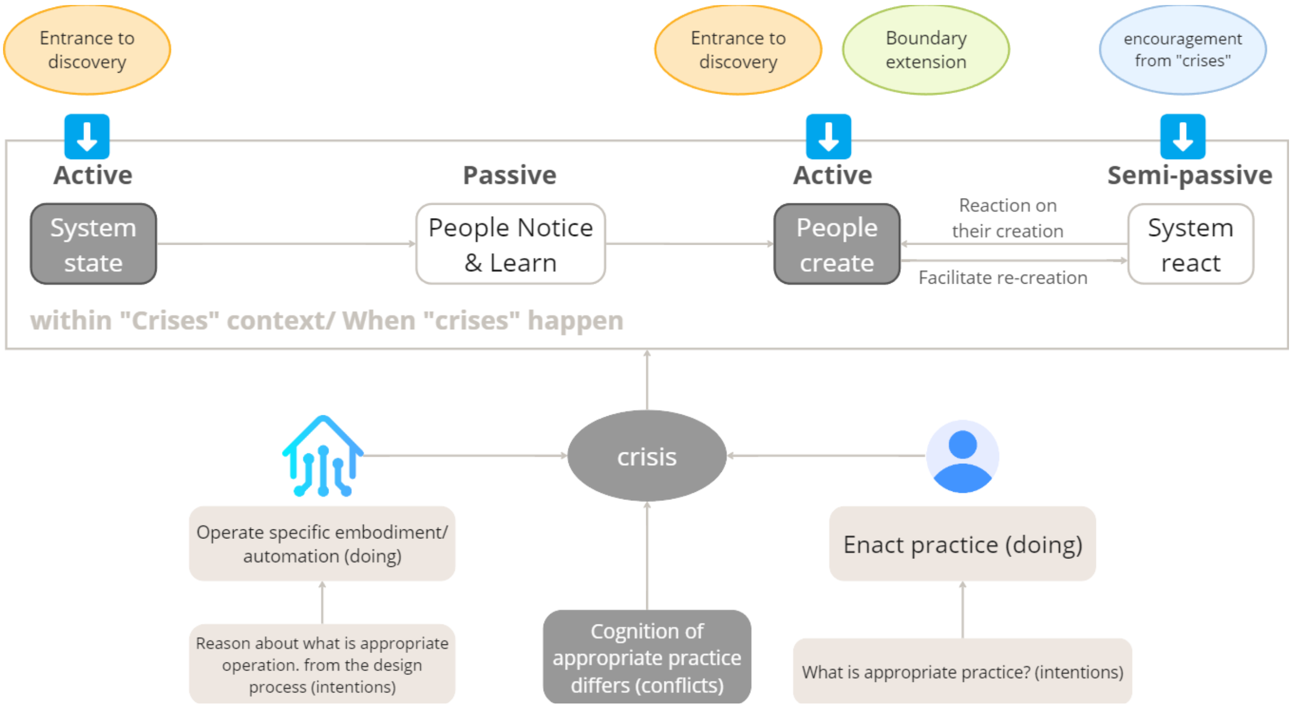


Figure 23: The framework of three themes

The "Entrance to Discovery" theme is pivotal in the "System State" stage as it ignites the initial curiosity and motivates individuals to start exploration of the system. In parallel, it also impacts the "People Create" stage, illustrated by the inclusion of supporter involvement within the theme. The involvement of supporters brings more discussion and debate, facilitating the curiosity of further exploring ways of adaptation. Consequently, the engagement and exploration catalysed by "Entrance to Discovery" fosters an environment conducive to innovation and problem-solving. "Extension of Crises Boundary", which primarily impacts the "People Create" stage, entails the expansion of understanding and access to additional resources. This theme has the capacity to introduce unexpected variations and inspire the process in the "People Create" stage, as it broadens the horizon of possibilities. "Encouragement from Crises is central to the System React phase. This theme is primarily concerned with evaluating and calibrating behaviour based on feedback and guidance. With its focus on building trust and facilitating decision making, Encouragement from Crises is instrumental in exploring appropriate behavioural strategies through iterative refinement during System react phase.

4.5 Key Insights

Identified design direction from thematic analysis:

Raise the interest of households to start exploring the 'crises' and experimenting the new 'interface' to find out tailored adaptations to the new technology. It will focus more on how to motivate households to start.

Identified design goals from cross analysis:

1. System can state its features and situations in a noticeable and understandable way to make households interested and willing to learn about the conflicts behind "crises".
2. The design can facilitate the involvement of supporters to inspire households to create their own "interface" to deal with the "crises".

05

REVISED DESIGN BRIEF

5.1 Key Problem & Opportunity

The indoor climate system based on heat pumps is designed to operate automatically in the background, but in the messiness of everyday life, they often misjudge what is appropriate and thereby get into conflicts with residents in everyday life, causing “crises of routines”. However, “crises in routine” can be productive. When they become productive, they can arise households’ interest in the exploration of their home and facilitate finding their own satisfying relationship with the system to live together peacefully in the context of zero-energy housing. The potential output of the exploration could be enacted “interface”, which exists between the resident and the automatic housing system, operating as a new connection between humans and the system within the daily use case. It refers to residents’ unique relationship with the system, improving the adaptation process.

5.2 Scenario

This project will focus on families who just move into a renovated zero-energy house, indicating the concentration on 1) adaptation phase 2) the interaction between multi-users and the system. This project will also consider the diversity within a family and the effect of family emotional bonds on adaptation to new technology.

5.3 Design Challenge

How to make the "crisis in routine" more productive to facilitate the occurrence of new "interfaces" to help the family adapt to living together with the indoor climate system in a renovated zero-energy house?

5.4 Expected Output

The final output is expected to be a design case which can reflect the design insights well. It is expected to be in the form of experimental prototypes, focusing more on the expression of expected use experience and how it can intervene the “crises in routine”.

5.5 Design Direction

Raise the interest of households to start exploring the 'crises' and the enacted 'interface' to find out tailored adaptations to the new technology. Design will focus more on how to motivate households to start.

Specific Design Goal

1. **System can state its features and situations in a noticeable and understandable way to make households interested and willing to learn about the conflicts behind "crises".**
2. **The design can facilitate the involvement of supporters to inspire households to create their own "interface" to deal with the "crises".**

5.6 Initial Design Requirements

The design requirements outlined here are derived from previous research and analysis, and are aligned with the design directions, 'entrance to discovery'. The categories are structured according to a framework from the thematic analysis (Chapter 4.3). The reqiurements highlighted in red in "need", while the rest are "nice to have".

1 Feel capability of control

1.1 Maintain a balance between automation and manual control to respect residents' independence & decision-making in their home.

1.2 Transparently communicate limitations of the system to encourage a collaborative approach to building expectations together and adapting to the system's capabilities.

1.3 Explain system features in an accessible way to all family members, considering different levels of technological literacy.

1.4 The interactions should resonate with households, using familiar usage patterns.

2 Affordance

2.1 Ensure that the design is accessible and within reach for all family members.

2.2 Design the device with an attention-grabbing appearance and position it strategically within the home environment to enhance visibility.

3 Curious signals

3.1 Use distinctive signals that include visual, auditory or tactile cues to effectively capture attention and convey information.

3.2 Innovative presentation of system status through unconventional means to ensure household engagement but without confusion or misinterpretation.

4 Supporter involvement

4.1 Incorporate features that reflect the comfort or satisfaction of each family members with the indoor climate, promoting family discussion and tailored adaptation.

4.2 Cultivate environment of empathy and communication among family members, encouraging collaborative engagement with the system.

4.3 Implement notifications to remind family members when someone has made changes to system settings, ensuring transparency and family awareness.

4.4 Provides insight into how the actions of one family member can affect the comfort of others, encouraging careful interaction with the system.

5 Professional advisor involvement

5.1 Display the real-time status of the heat pump to ensure occupants are continuously informed of the system conditions.

5.2 Display home condition, such as indoor temperature.

5.3 Provide indicators that represent the system's workload or intensity of operation, enabling occupants to comprehend current situations and be careful about decisions.

06

IDEATION

This chapter introduces the ideation phase, which aims at fulfilling the design direction and design goals outlined earlier. The phase began with an inspirational brainstorming session with fellow designers, focusing on a specific 'crisis' case identified earlier. The insights gained from this brainstorming provided the impetus for idea generation. This led to the development of initial concepts, carefully tailored to the features of the indoor climate system and the family's living scenarios. The process evolved through several rounds of co-creation with end users, facilitating iterative refinement and concept selection. Finally, expert feedback was incorporated for further iterations. This chapter summarises the collaborative and iterative nature of the ideation phase, from brainstorming to expert review.

6.1 Brainstorming with designers

This study examines floor heating "crises" as a representative case because of the characteristics it shares with zero-energy houses that rely on heat pumps. The underfloor heating system requires a pre-heating process, which results in a significant time delay for the room to reach the desired temperature from an off state. The user will experience a similar waiting time as when a heat pump heats a room from an off state. Similar to heat pump systems, the underfloor heating system recommends minimising frequent on/off cycles to save energy, as the preheating process consumes the most energy. This recommendation is consistent with heat pump systems, which are advised to remain in operation to maximise energy efficiency in conjunction with proper insulation. As a result, the insights from this particular case can be applied to and are of value for general ZEHs. All ideas generated during this brainstorming session are primarily contextualised within this framework.

Method

I used a mixed methodology, combining analogical reasoning with brainstorming. The rationale behind this was the intuitive nature of a typical household scenario, as opposed to the complexity and abstraction of a heat pump house situation, which is harder to grasp without first-hand experience. For inspiration from more perspectives, I invited 2 IPD students, 2 DFI students and 2 SPD students to do the brainstorming together. The brainstorming session was based on a 'crisis' story. I first gave the participants a story-driven introduction to help them immerse themselves in the problem landscape. I then introduced the thematic framework as a structure for the brainstorming exercise. The inclusion of all themes was strategic because of their interconnectedness and potential to symbiotically inspire broader insights. All the participants will receive a design task: How to motivate occupants to start learning about the misfit of system features behind and start exploring their personalised solutions to this conflict? The process began with independent brainstorming, followed by a discussion where participants shared and analysed their ideas in the context of design principles. At the end of the session, I synthesised and structured the ideas through analogical reasoning, relating them to actual zero energy house scenarios. This facilitated the extraction of design insights that will guide the initial conceptualisation phase.

Results

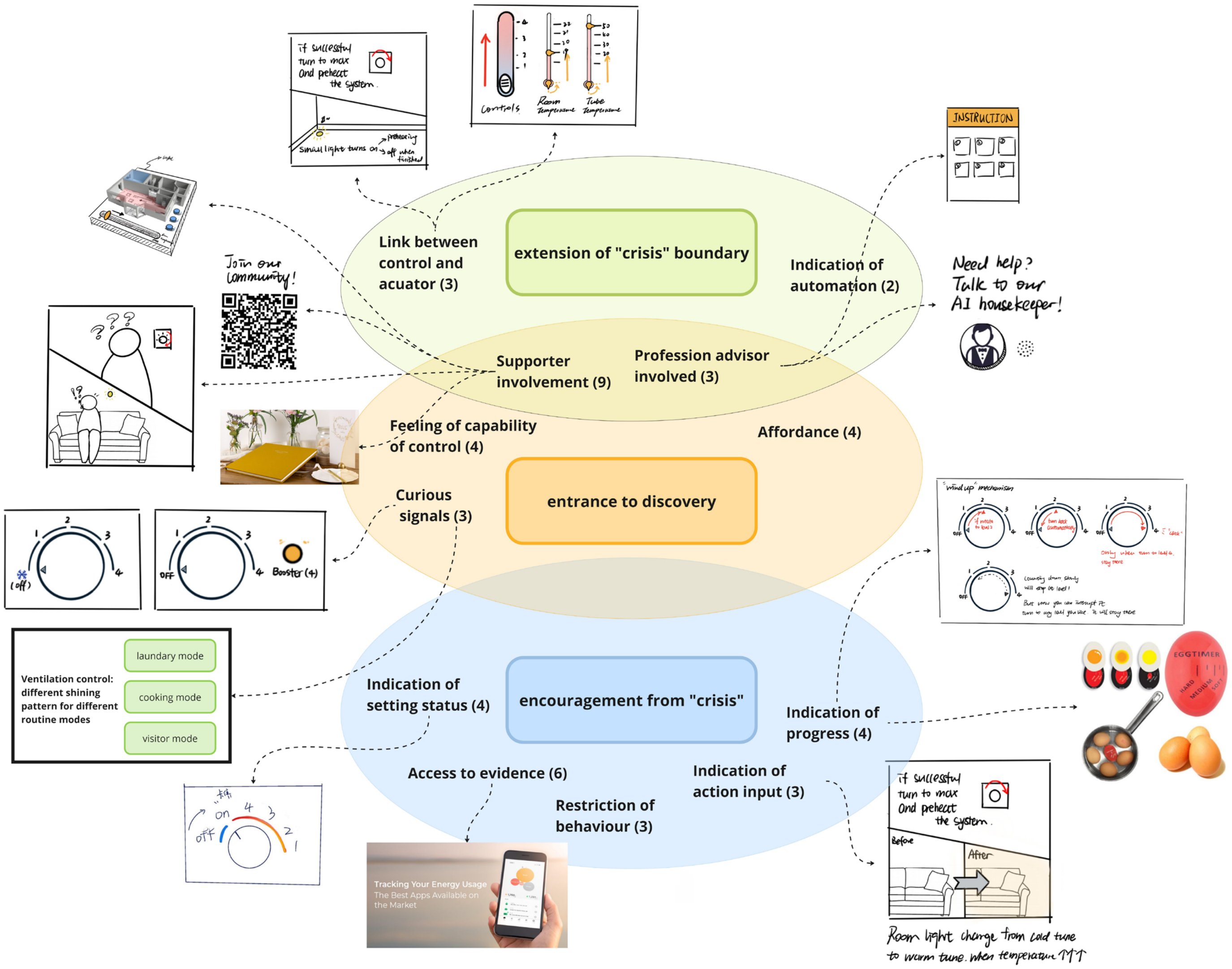


Figure 24: The outcome of brainstorming

This section presents a wealth of ideas that emerged from the brainstorming session and methodically organises them into distinct clusters (Figure 24). The ideas range from subtle control design to more expansive areas that include the home and neighbourhood community. Ideas related to 'supporter involvement' can be divided into two main clusters: fostering open spaces for communal discourse and igniting a sense of care among family members to activate family engagement in solving the 'crisis'. The 'curious signals' segment is mainly about reconfiguring the understanding of functions or system performance using metaphors; for example, renaming the highest ventilation setting as 'cook/shower mode' rather than a generic 'level 3'. Regarding "Involvement of a professional advisor", an innovative concept emerged to create a device that could act as an in-house professional advisor. In addition, an interesting suggestion in relation to 'indication of progress' was to associate the act of setting the temperature with a winding mechanism, thus influencing the expected waiting time. Apart from this, the visual display of the progression of room temperature changes, provides an alternative means of illustrating system features through the lens of contextual situations.

Design opportunities

Consequently, I extract the common insights and analogize them to the zero-energy house to highlight design opportunities for this project.

Metaphors in settings and behaviour

Enhance the interface or settings with new meanings or metaphors that resonate with households' daily routines, emotions associated with the home, or challenge their existing cognition. Such design can create a new bond with the system and home and make it easier for households to relate their actions to broader values.

Simulations of familiar interactions

Draw inspiration from the interaction modalities of everyday products in users' lives and incorporate them into the system. This mimicry or simulation can spark new understanding and create a sense of familiarity, potentially increasing engagement and changing cognitions of system role.

Connection to context

Design the system to be more connected and responsive to the changing context or household situation. The ability of the system to adapt and respond to contextual changes promotes more harmonious integration into the home environment and create a deep bond with residents.

Eye-catching signal to encourage family engagement

Incorporate intriguing signals that reflect the experiences of individual family members. These signals can stimulate curiosity and concern in other family members, encouraging dialogue, sharing of experiences and a sense of community engagement.

An 'open space' design element

Create an 'open space' within the system that facilitates and motivates sharing and communication between household members. This space could serve as a community hub for exchanging ideas and experiences and fostering a sense of community involvement in adapting to the new system.

Conclusion

Figure 25 illustrates the interrelationship between design insights and prior research, all of which converge on the design direction. The light purple represents the identified design opportunities. Incorporating metaphors can create cognitive shifts in the occupant, fostering novel associations that may inspire further experimentation. This is inherently linked to how the system states itself. The simulation of familiar interactions attributed to 'system state' makes the interaction unexpected, but not radically new. This recalibrates users' expectations of functionality and latency, facilitates understanding of system attributes, but prevent adds learning difficulty. The connection to the context primarily relates to the content of the 'system state' and helps to establish an emotional connection with the occupants, possibly changing expectations of system performance or increasing tolerance to system inconsistencies, thereby facilitating the adaptation phase. The last two design opportunities mainly emphasise intercommunication between family members, actively inspiring occupants to develop multiple interpretations of the system and individual strategies for living with the technology.

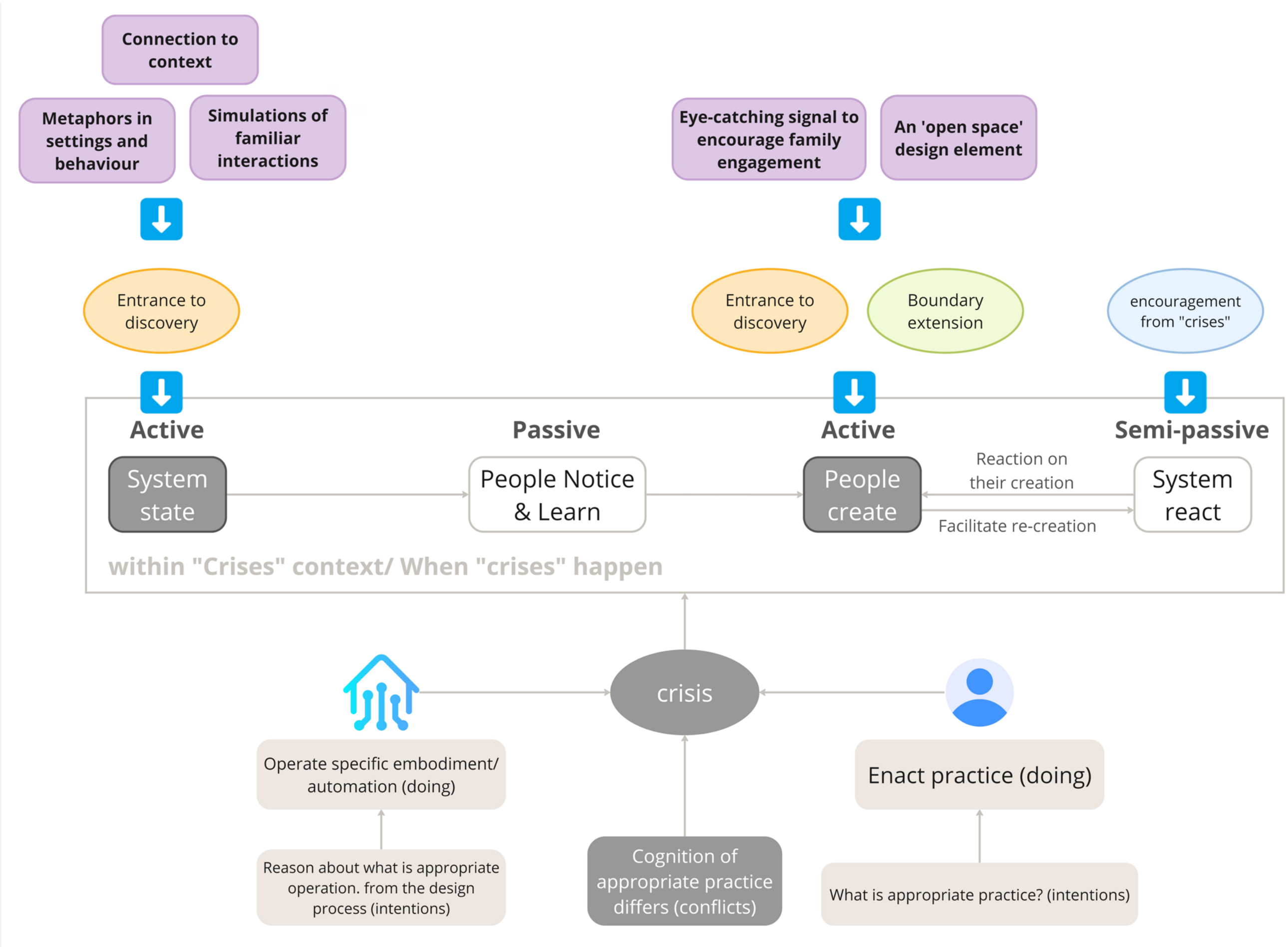


Figure 25: The relationship between design opportunities and three themes

6.2 Initial concepts

This section presents the 5 initial concepts I have come up with, inspired by the previous design insights. I will explain what design is, where it comes from and how it can intervene in the 'crisis' one by one. All these will be the basic materials for the co-creation session.

Concept 1: knob control

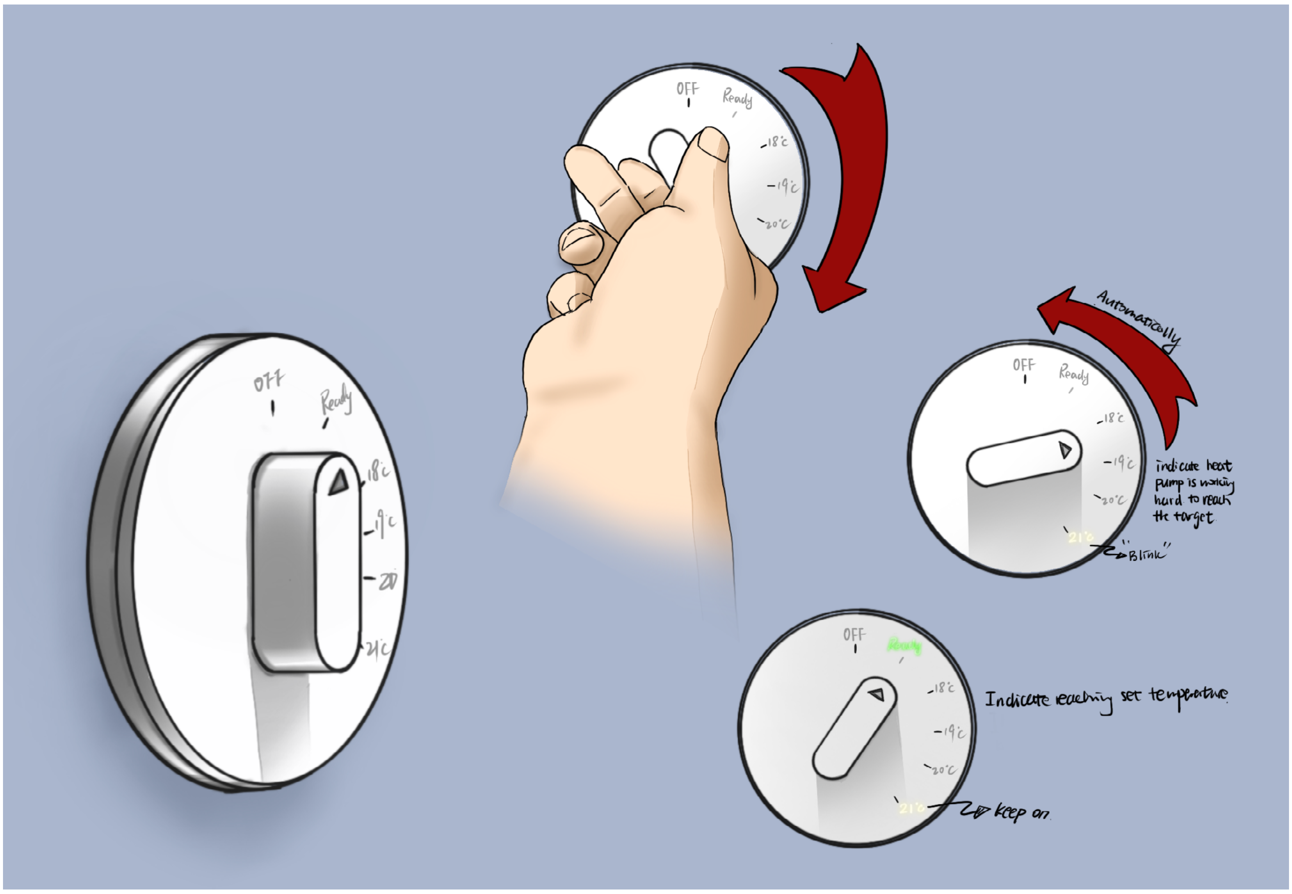


Figure 26: Initial concept 1 - knob control

This design features a temperature control device with a rotating bar, similar to the operation of a microwave, to set the desired temperatures (Figure 26). After setting, the bar gradually retracts, symbolising the system's working progress, with a flashing white light indicating the selected temperature. When the set temperature is reached, the bar moves to the 'ready' position, a green light activates, and the white light remains steady to indicate completion. Users can't change the settings until the 'ready' position is reached.

This approach, reminiscent of a microwave's wait time, adjusts user expectations from immediate radiator effects to a more gradual adjustment. Visible progress provides transparency and builds confidence. The design doesn't facilitate seamless interaction but emphasises that frequent setting changes are not optimal for heat pumps. Restricting immediate setting changes encourages users to think about their temperature choices and encourages self-adaptation. In essence, understanding the nuances of the system helps with 'crisis management'.

Concept 2: control based on personal feeling

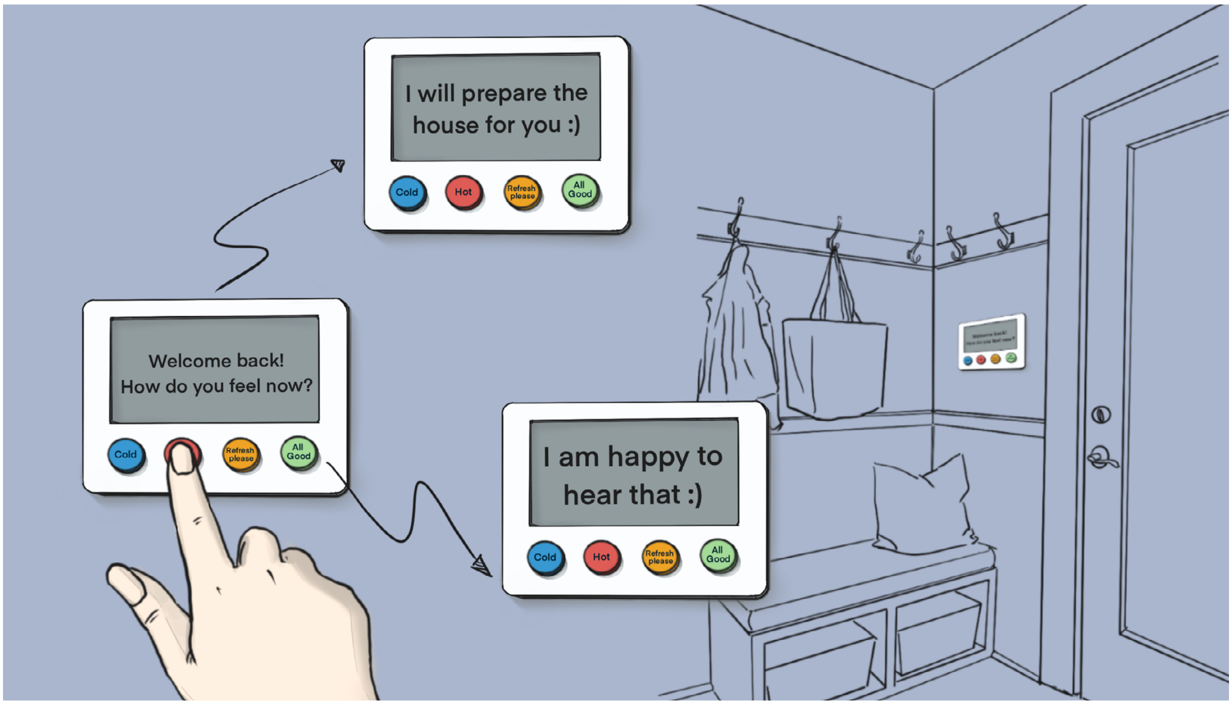


Figure 27: Initial concept 2 - control based on personal feeling

Located on the porch, this concept encourages anticipation of indoor comfort, prompting early system adjustments and mitigating 'crisis' delays. By signalling 'I will prepare the house for you', it personifies the system, encourages patience and redefines user perceptions. The system evolves from a passive mechanism to an active collaborator, enhancing the home experience. Built-in learning capabilities allow the system to adapt based on user preferences, temperature readings and external conditions. This shifts user responses during 'crises' and inspires adaptive solutions.

Concept 3: “smile face” thermostat

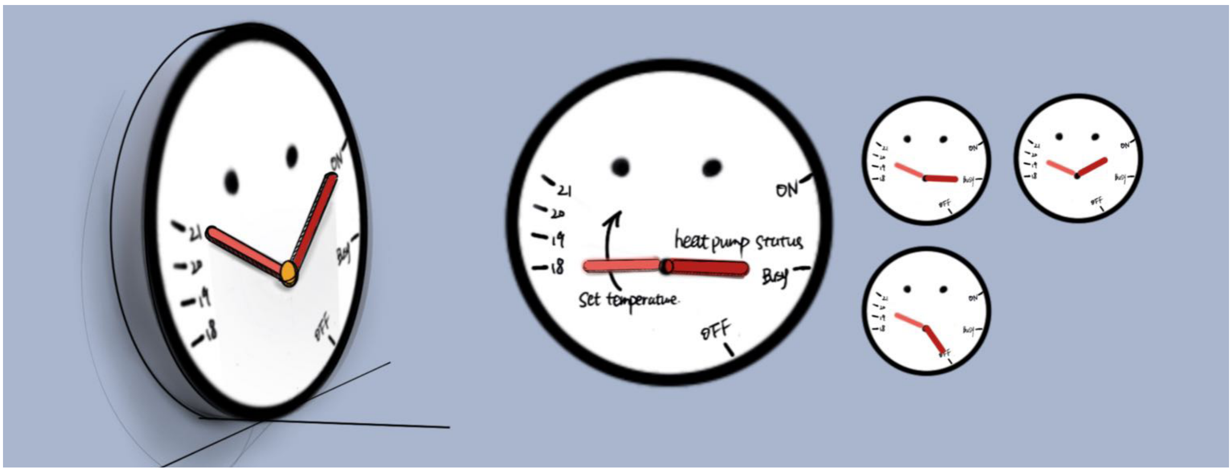


Figure 28: Initial concept 3 - “smile face” thermostat

This thermostat uses metaphorical visuals (Figure 28). The left bar allows the user to set the room temperature, while the right bar responds to system status. When aligned to 'busy', it signals that the heat pump is focusing on hot water production, delaying room heating. This orientation resembles a half-smiling emoji. When pointing to 'on', it indicates active room heating, symbolised by a full smile. The smiley face representation helps family members identify system status and potential problems, promotes informed expectations and responses during 'crises', and improves understanding of how the system works.

Concept 4: voting board in common space

Figure 29: Initial Concept 4 - voting board in common space

This concept (Figure 29) introduces a communal 'open space' using a colour-coded voting system on a whiteboard, allowing residents to visually express satisfaction levels: green (satisfied), yellow (acceptable) and red (dissatisfied). Reset weekly, the board captures the mood of the community, prompting individual reflection on wider experiences and potentially triggering insights into personal 'crises'. Located in communal areas, the board facilitates discussion, encouraging shared experiences, collaborative problem-solving. This initiative captures collective feelings and fosters a supportive problem-solving environment.

Concept 5: awareness of other family member's change

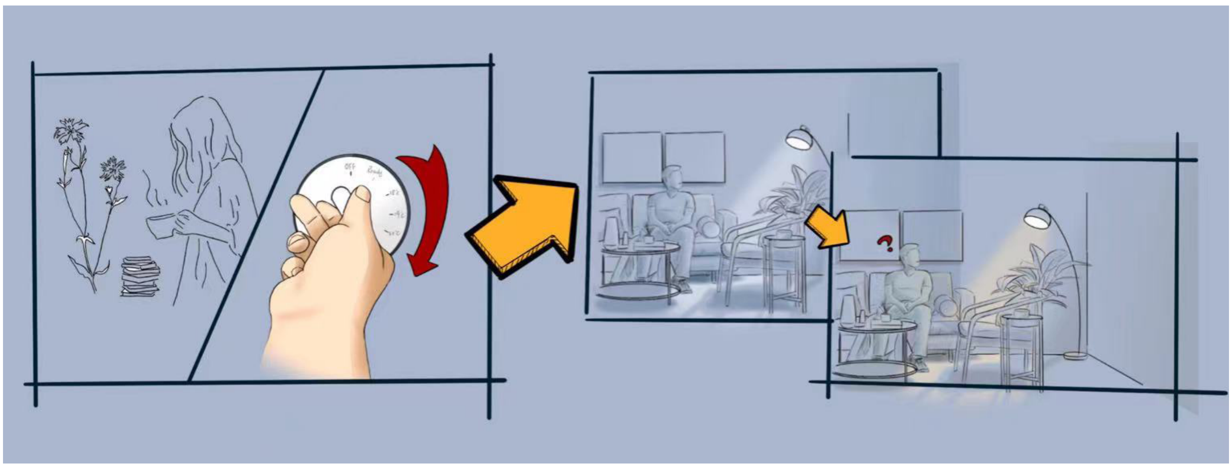


Figure 30: Initial Concept 5 - awareness of other family member's change

This concept emphasises family's involvement in heat pump systems through visual cues. Because of the integrated nature of the system, adjustments in one room affect the whole house. When one member changes the temperature, the hue of the light in the room changes from cool to warm, stimulating others' curiosity (Figure 30). This not only sparks conversation, minimising frequent system changes and potential 'crises', but also integrates "expert", increasing collective understanding. The design emphasises the importance of family communication and cooperation in adapting to the new system.

6.3 Co-creation with real residents

The main objective of the co-creation was to assess the alignment of the initial concepts with actual zero energy house scenarios, and to identify the design features that effectively promote the development of personalised 'interfaces' to address the 'crises'. I conducted three round of co-creation sessions with six end-users at their homes. In addition, I also conducted three rounds of iteration and selection between the co-creation sessions. The expected outcome of this co-creation is a concept with the capacity to intervene in the 'crises' within a Zero Energy House. This approach emphasises the importance of end-user engagement and iterative design in tailoring solutions to the unique challenges of zero-energy homes.

Research questions

1. How to use design features to affect households' interest and willingness to learn about the conflict behind "crises"?
2. How to use design features to involve supporters (e.g. other family members) in the learning, exploration and creation process?
3. How to make the design more fit more in the real case?
4. What are other possible elements or methods that may have a positive effect on promoting the creation of personalised adaptation to address the 'crises'?

Method

Participants

In this study, the target population consisted of adults living in zero-energy houses in the Netherlands, with a preference for those living with family members. A total of four households with six participants were recruited, ranging from single persons to families. In particular, one of the households had previous experience of living in a zero-energy house equipped with a similar system. The details are shown in the table below.

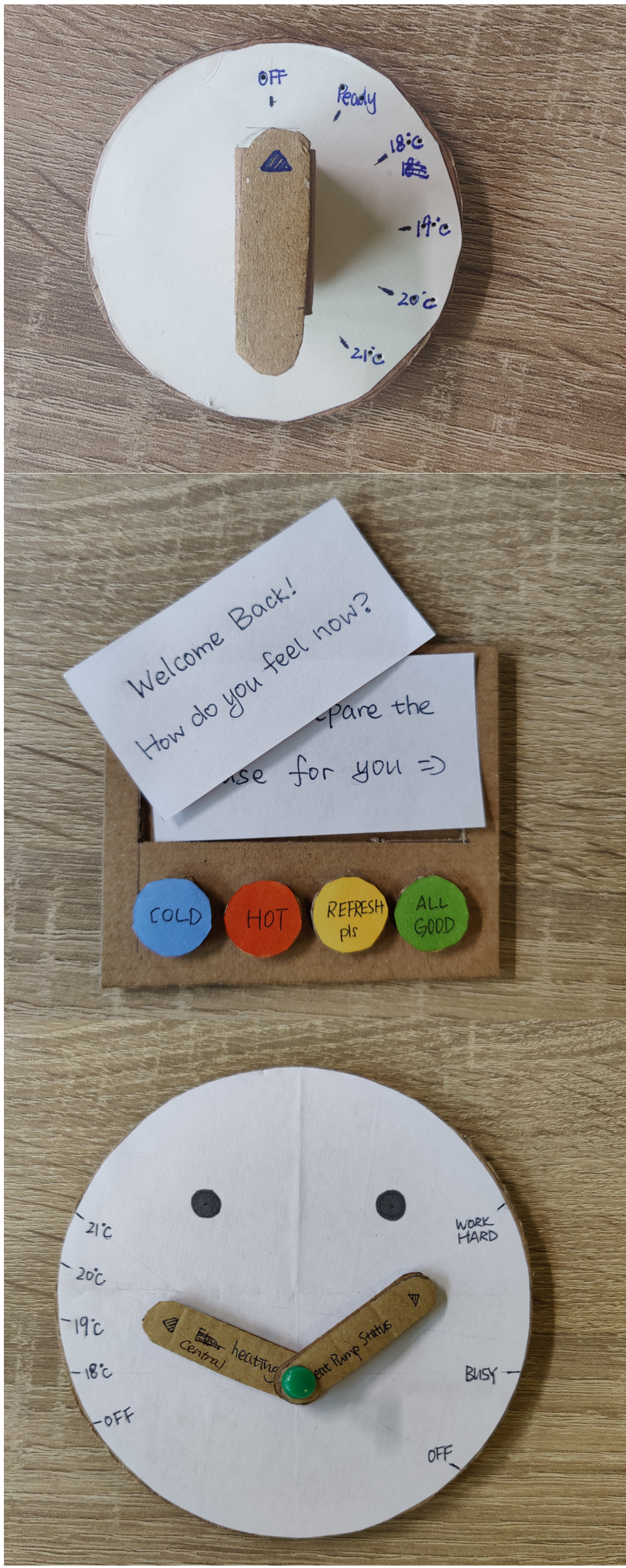
Household 1	Household 2	Household 3	Household 4
1 participant	2 participants	2 participants	1 participant
A female who lives alone; but sometimes her son will live here for a period	A couple with 2 children living together	A couple with 1 child living together	A male who lives alone
House	House	House	Studio apartment

Table 2: Co-creation participants

Approach

The co-creation session, which lasted around one hour, took place in participants' homes and was camera documented. An initial 20-minute interview explored their existing heat pump systems and adaptation methods. The final 40 minutes allowed participants to engage with sketches and prototypes, followed by an open discussion. The sketches, detailed in Chapter 6.2, familiarised participants with the concept's functions and interactions, while these 1:1 scale paper prototypes allowed for realistic engagement (Figure 31). To facilitate positioning and increase contextual relevance, clay was applied to the backs of the prototypes. I demonstrated device responses as participants interacted. Throughout the co-creation process, sketches and prototypes were updated, with initial prototypes shown in the following images. The use of sketches and prototypes deepened participants' immersion and streamlined iterative design, making use of feedback and observations. Further details can be found in the Appendix G.

Figure 31: Paper prototypes of initial concepts 1,2,3



- RESULT -

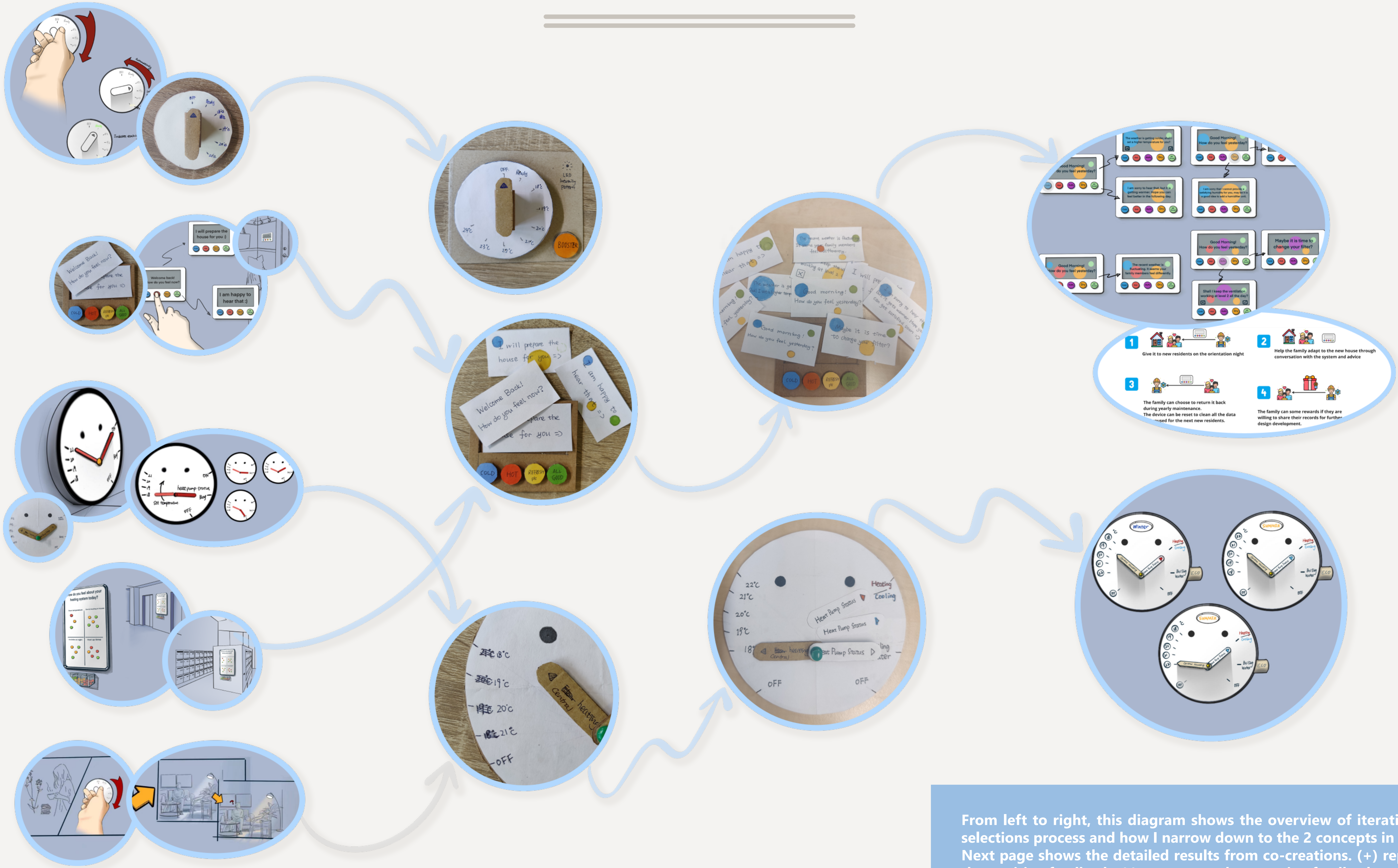


Figure 32: Overview of co-creation

From left to right, this diagram shows the overview of iterations and selections process and how I narrow down to the 2 concepts in the end. Next page shows the detailed results from co-creations. (+) represents the positive feedback, (-) represents the negative feedback, and *italic represents the iteration advice from users' perspective.

First round of co-creation

Concept 1: knob control

(-) Uncertain about effectiveness of the design due to infrequent interactions with room thermostat.

(-) A need for comprehensive information; the device should not aim to replace central panel.

(+) It is of value to know that the heat pump is working hard though slowly.

(+) The display is easy to understand and no need to check the manual anymore.

Mention special mode for boiling water function, like "speed up". Although it refers to start boiling according to the detected water temperature instead of quicker boiling, it still makes the occupants more satisfied with the system.

Concept 2: Control based on personal feeling

(-) The incentive to interact regularly depends on the tangible impact of the system's performance instead of the design.

(-) Long time required for successful temperature adjustment makes the concept less practical for daily reporting.

(-) As adaptation to the system increases, the perceived need for the device decreases.

(+) A conversational interface improves understanding of system expression.

(+) Regular interactions are believed to enable the system to learn and adapt to user preferences.

(+) Receiving such feedback from the system can provide a sense of autonomy, reducing perceived user intervention.

(+) Confidence in the system's ability to learn preferences based on her continuous interactions.

Concept 3: "Smile face" thermostat

**Expect information on solar intensity, beneficial for their homes that have solar panels, as occupants will be inclined to optimise their use.*

**Place energy efficient choices at the top for positive reinforcement, such as achieving the biggest smile, is desirable.*

(+) Easy to understand the concept.

(+) The way of displaying the system status is clear and helps understand system features better.

(+) She loves the smile face to indicate the house is in good quality.

Concept 4: Voting board in common space

(-) More effective in larger, multi-occupancy buildings, as opposed to her less dense community, which lacks appropriate public spaces.

** Integration with concept 2 could enable viewing of advice from other residents within the same building. Different residents' schedules make the ability to see messages left by others at different times appealing.*

Concept 5: Awareness of other family member's change

(-) *Confused about the idea.*

(-) *Concerned about potential for disturbance, especially caused by children, which could be aggravating.*

(-) *Prefers not affecting the whole house to avoid disturbance depending on occupants.*

(-) *The design may cause negative emotions or complaints among family members.*

**Suggests personal colour coding to indicate which family member is changing settings, but notes that this would require the collection of identifiable information.*

First round of iteration

As a result of the study, concepts 1, 2 and 3 were refined. Concept 1 added a 'booster' button, increasing user engagement and simplifying understanding through metaphorical expression. Concept 2 merged with Concept 4, introducing a 'bubble' display to reflect the comfort level of family members, encouraging collective problem solving during 'crises'. Concept 3, which merges with Concept 5, uses synchronised thermostats where changes in one device are reflected in others, encouraging collaboration and informed adjustments. This design speeds up familiarisation with the system and helps to adjust human expectations, which is crucial for crisis resolution. In addition, repositioned temperature markers now equate wider smiles with more sustainable choices.

Second round of co-creation

Concept 1 (v2): Knob control

(-) Perceived as weird that the knob takes a day to return to 'ready'; mismatch with the real case.

(-) Possible increase in confusion due to slow countdown, hindering understanding of system.

(-) Infrequent adjustment of temperature settings reduces usefulness of design.

Concept 2 (v2): Control based on family feeling

(-) Likely to be useful during the adaptation phase; applicability diminishes thereafter.

(-) The phrase "Prepare the house for you" was ambiguous, concerns about system alignment with user expectations. Preference for direct control on the system.

(+) Facilitates family involvement; potentially involves children by gameful simple interaction.

**Good to know the system limitations, never expect it to solve everything, but only when occupants know the limitations, they can then figure out their own solutions.*

Concept 3 (v2): Connected “smile face” thermostat

(-) Confused about the status, what does “busy” mean in reality?

**Should be more helpful to know more system features, especially the progress to reach ideal temperature.*

**Colour and LED may be a better way to express the current system status more accurately*

**Indication of levels of "working hard" can help occupants aware of saving energy and become cautious about their decision.*

(+) The fun & curious appearance is attractive for children to actively participate in indoor climate decisions.

(+) Good to know what is happening at home and what other has changed.

(+) The existence and meaning of “big smile” help you become more conscious about whether you are using more energy.

Second Round of iteration

Following feedback from participants, I developed concepts 2 and 3 further. Concept 2 evolved into an advisory tool that interacts with residents, understands their preferences, and then provides guidance and potential system adjustments. This shift from controller to facilitator promotes system understanding and proactive adaptation. For Concept 3, I improved the communication of system status by adjusting the wording and incorporating colour and LED cues for heating and cooling. This transparent information educates occupants about system behaviour, shapes expectations and promotes more informed decisions for optimal adaptation.

Third round of co-creation (with 2 households)

Concept 2 (v3): Advisor based on family feeling

(-) Limited current applicability due to existing awareness of spouse's climate preferences and willingness to compromise for wife's comfort.

(-) Fixed display on wall creates perception of device as controller.

(+) Good for children to participate in interaction so that parents can learn about their changing feelings over time.

(+) Prefer device to record feelings and provide information without autonomous adjustments.

Concept 3 (v3): Connected "smile face" thermostat

**Suggestion to include a seasonal display to make "big smile" always represent the best setting.*

**Favourable view of providing more information on how the system works to facilitate understanding of underlying mechanisms and rationale for features.*

(+) "Big smile" can be appealing and meaningful to always display the most sustainable choice.

(+) Guidance on sustainable choices highly valued because satisfaction linked to reduced bills and increased acceptance of system suggestions.

Discussion

The discussion section aims to answer the research questions below raised in the beginning by illustrating the third round of iteration.

Ultimately, I decided to retain both concepts due to their complementary attributes; they address different aspects and operate on different time scales, which synergistically enhances effectiveness in transforming 'crises' into productivity and promoting personalised adaptation.

Concept 2 focuses primarily on context and advisory perspectives and operates on a shorter time scale. In contrast, Concept 3 acts as a thermostat with a more utilitarian approach, focusing specifically on the heat pump system and designed for long-term application. This balanced integration of the two concepts ensures a comprehensive solution that effective help adaptation to the new technology through learning and inspiring from "crises in routine".

Last round of iteration

Concept 2 (v4): Feeling Message Board

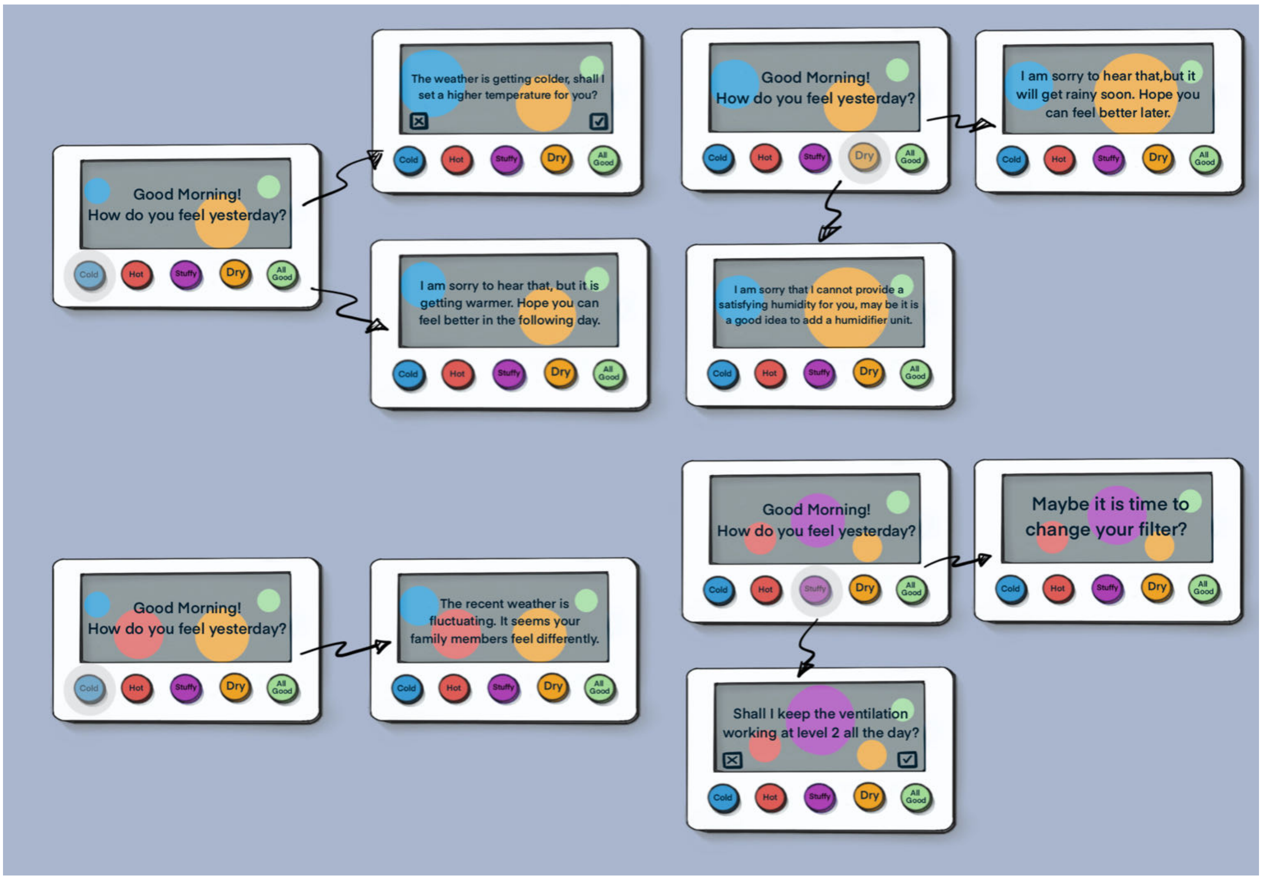


Figure 33: Concept 2 (v4): Feeling Message Board

Concept 2 serves as an in-house profession advisor, providing insight into occupants' feelings, explaining the causes of their perceptions and suggesting adaptive living strategies. Unlike a static manual, its adaptive feedback, informed by occupant sentiments and evolving contexts such as system configurations, climate changes and maintenance needs, positions it as an 'advisor'. This deep contextual integration enhances occupants' willingness to identify the underlying reasons for system behaviour, expanding their understanding beyond mere technicalities to comprehensive wellbeing strategies.

By prioritising occupant autonomy, the device facilitates discourse without directly modifying system parameters, thereby preserving occupants' authority over their home. This empowerment sparks an intrinsic curiosity that leads to exploratory learning about the origins of 'crises' and strategies for aligning individual preferences with system efficacy. Acknowledging system constraints, such as humidity limitations, refines user expectations and stimulates innovative personal adaptations.

Emotions are visualised as colour-coded bubbles (Figure 33), with each hue representing a different emotion and the size of the bubble indicating frequency. Occasionally, the device highlights divergent perceptions within the household, potentially fostering empathy and encouraging intra-family conversation. This collaborative atmosphere reinforces collective engagement, catalysing discussions about system complexity, interaction modalities and individual adaptation tactics. Such collaborative dynamics are crucial in guiding families towards a harmonious balance that satisfies the comfort criteria of each member. Acting as a mediator, the device guides families in collaboratively uncovering response to prevalent 'crises'.

Concept 2 (v4): Feeling Message Board

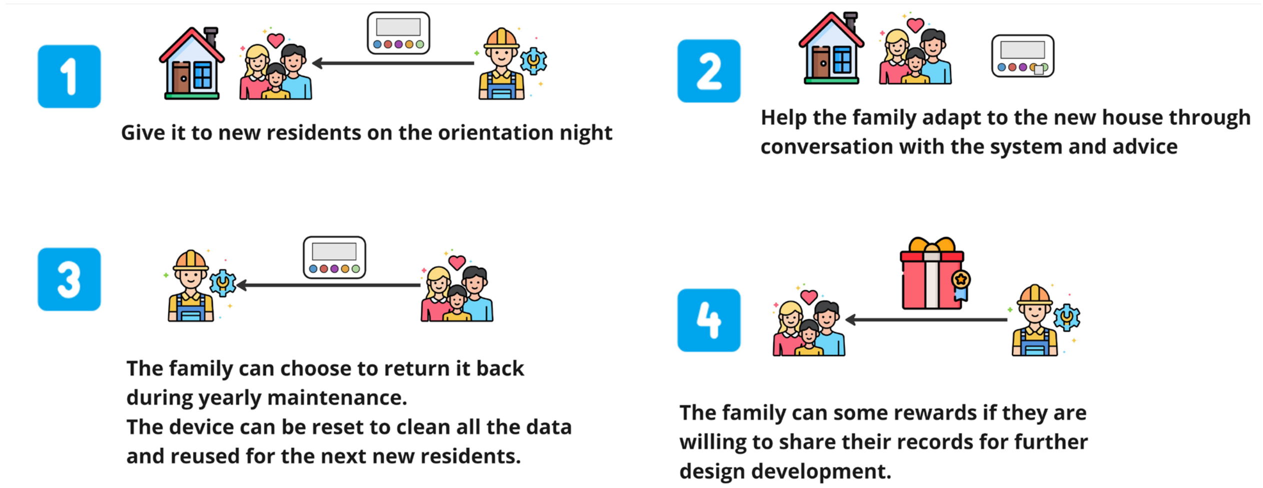


Figure 34: The relevant service design of Concept 2 (v4)

In response to real-world needs, Concept 2 is streamlined as a temporary tool for the adaptation phase. As familiarity with the system grows, residents can choose to return the device for annual maintenance, having formulated their personal "crises" strategies (Figure 34).

Concept 3 (v4): "Smile Face" Thermostat

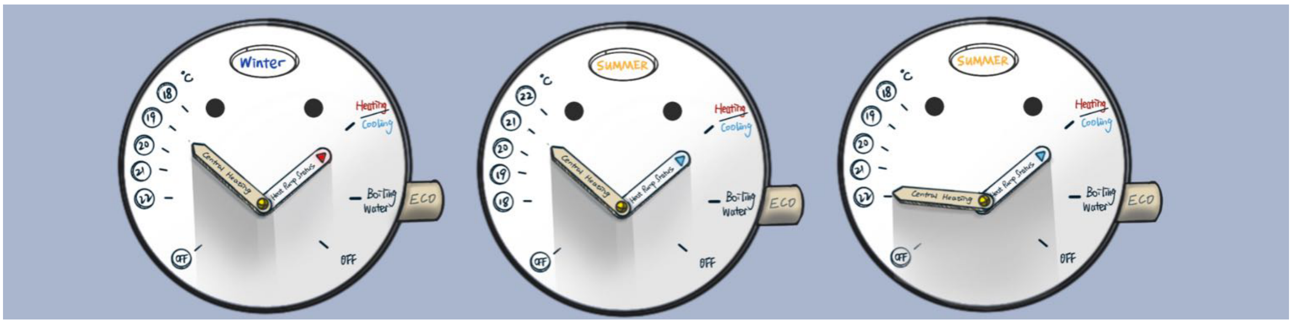


Figure 35: Concept 3 (v4): "Smile Face" Thermostat

Concept 3 uses a metaphorical design, using a 'smile' to represent an efficient heat pump system. This playful representation captures the attention of the occupants and encourages them to explore the system's characteristics and the reasons for specific 'crises'. Such transparent system states guide decisions and exploration of adaptive strategies. For example, an 'unhappy face' during water heating alerts users to a potential 'crisis' and prompts them to reconsider temperature settings. This encourages a more informed approach to problem solving.

To accommodate seasonal changes, the thermostat seamlessly switches between 'winter' and 'summer' modes. To encourage eco-conscious choices, the design uses emotive icons such as a 'smile' to represent optimal settings, nudging users towards greener choices. This emotive presentation stimulates curiosity, encouraging occupants to understand the impact of their actions on system efficiency and encouraging exploration of adaptive strategies.

In addition, the presence of interconnected thermostats throughout the home encourages collective engagement. Notifications of changes on one thermostat discourage impulsive adjustments and stimulate broader discussions, fostering a shared understanding of 'crises' and encouraging collaborative problem-solving.

To fit better into the real case, I added a small knob on the side to change the water boiling modes. Accordingly, the look and feel (turning the bar to set the temperature) becomes more integrated, as it looks more like a special "clock" at home, displaying the current system status without disrupting the occupants' routines. This can give them the feeling that they can effortlessly monitor the system to discover the conflict behind 'crises'.

Key insights

1. The key insights from the brainstorming session are validated as useful and applicable in the real scenario.
2. The design itself can play the role of a professional advisor. Its main role is to help the occupants live comfortably, rather than simply to educate them on how to interact correctly. Therefore, it should provide advice based on occupants' sensory feedback from system operation to appropriate living strategies and be actively involved in occupants' decision making and expectation.
3. The design should work more like a "silent display", balancing automation and user control, aiming to promote a sense of equality and encourage active involvement of the occupants in exploring "crises" and the system.
4. The form of expression of the system should be straightforward and simple, accessible to all family members, considering different levels of technological literacy.
5. Good design of metaphorical displays can help broaden users' understanding and stimulate their interest in experimenting with their optimal personalised settings.

6.4 Updated Design Requirements

Based on the findings from the brainstorming and co-creation sessions, I have updated the design requirements, which aim to fulfil the design direction “entrance to discovery”:

Raise the interest of households to start exploring the 'crises' and the new 'interface' to find out tailored adaptations to living with the new technolo

The categories are structured according to clusters within the theme ‘entrance to discovery”, identified in the thematic analysis before (chapter 4.3). The highlighted requirements in blue are the new ones from brainstorming and co-creation.

1 Feel capability of control

1.1 Maintain a balance between automation and manual control to respect residents' independence & decision-making in their home.

1.2 Transparently communicate limitations of the system to encourage a collaborative approach to building expectations together and adapting to the system's capabilities.

1.3 Explain system features in an accessible way to all family members, considering different levels of technological literacy.

1.4 The interactions should resonate with households, using familiar usage patterns.

1.5 The design should act as a "non-intrusive display" in the home, prominently presenting the status without disrupting residents' routines, and giving them the feeling that they can effortlessly monitor system, immediately identify unsuitability.

1.6 The incorporation of subtle interlocking design can highlight the area of control, thereby increasing occupant confidence in their effective operation of the system.

1.7 The interaction input should be clearly displayed to the users to make them confident about their behaviour.

1.8 The design should promote a sense of equality between the user and the system, thereby facilitating understanding of the technology, increasing perceived control, encouraging exploration of system and conflict resolution.

2 Affordance

2.1 Ensure that the design is accessible and within reach for all family members.

2.2 Design the device with an attention-grabbing appearance and position it strategically within the home environment to enhance visibility.

3 Curious signals

3.1 Use distinctive signals that include visual, auditory or tactile cues to effectively capture attention and convey information.

3.2 Innovative presentation of system status through unconventional means to ensure household engagement but without confusion or misinterpretation.

3.3 Design a symbolic goal to stimulate user interest and encourage experimentation to find the optimal personalised setting.

4 Supporter involvement

4.1 Incorporate features that reflect the comfort or satisfaction of each family members with the indoor climate, promoting family discussion and tailored adaptation.

4.2 Cultivate environment of empathy and communication among family members, encouraging collaborative engagement with the system.

4.3 Implement notifications to remind family members when someone has made changes to system settings, ensuring transparency and family awareness.

4.4 Provides insight into how the actions of one family member can affect the comfort of others, encouraging careful interaction with the system.

5 Professional advisor involvement

5.1 Display the real-time status of the heat pump to ensure occupants are continuously informed of the system conditions.

5.2 Display home condition, such as indoor temperature.

5.3 Provide indicators that represent the system's workload or intensity of operation, enabling occupants to comprehend current situations and be careful about decisions.

5.4 Remind maintenance, such as filter replacement.

5.5 Care about the real-life experiences and feelings of occupants and proactively suggest suitable options to improve comfort.

6.5 Design Iteration

This section aims to show the detailed process of iterating the concepts based on self-exploration and the advice from experts. It mainly illustrates what is still missing after co-creation and how to improve the function design to better arise residents' interest in learning the conflicts with systems and encourage family collaboration in exploring "crises" and new "interface". Additionally, I will adjust the concepts to better fit in the real context.

Figure 36: The overview of iteration from "smile" to "clock" thermostat

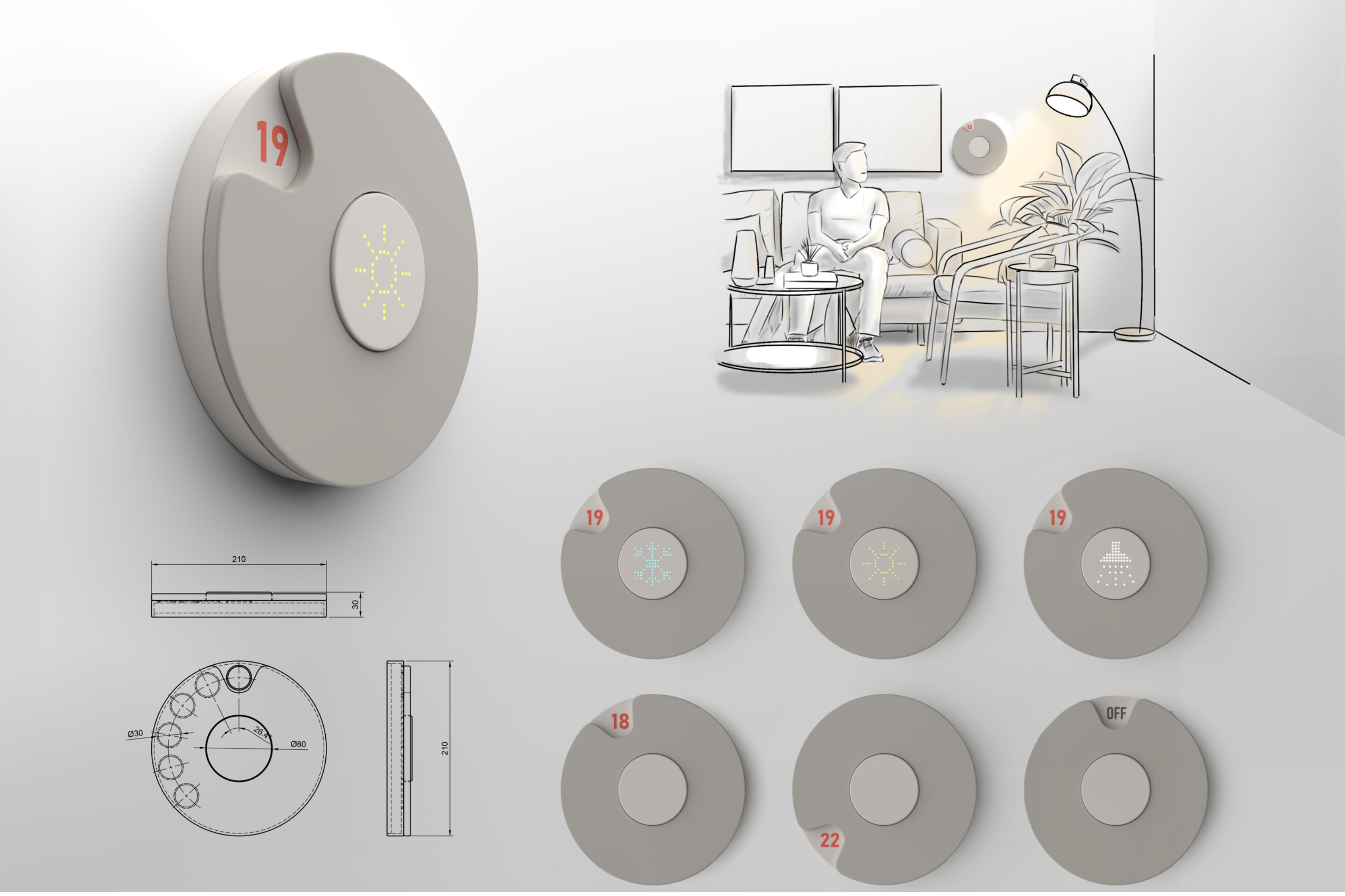


Figure 37: Version A of "clock" thermostat

Iteration from "smile" to "clock" thermostat

Version A

The primary purpose of the 'smile thermostat' is to transparently communicate the real-time status of the system, fostering an informed understanding of its functionality and possibly prompting occupants to reassess their choices and expectations. However, its distinctive and playful 'smile face' may not be universally compatible with the aesthetics of the home, potentially compromising its credibility. To address this, the refined design (version A) blends seamlessly into different interiors, exuding professionalism while maintaining the system status information through variable light patterns.

In Version A (Figure 36), a rotating dial reveals a red numerical display of the desired temperature, highlighting the system settings more prominently than in the previous version. This system limits temperature changes to one degree within a range of 18 to 22 degrees. A proximity sensor activates the central light when approached, optimising energy efficiency. Symbolic light patterns indicate different modes: a blue snowflake for cooling, a yellow sun for heating and a white drop for boiling water. The sun motif in particular raised concerns about ambiguity in homes equipped with solar panels.

In keeping with the original concept, several interconnected thermostats serve different rooms, given the inherent characteristics of the heat pump. In version A, the obvious temperature setting emphasises the system's integrated whole-house control, especially as spontaneous dial rotation could occur. In addition, the variable speed of the light pulsation reflects the intensity of the system's operation and guides the occupants' adjustments. Such enhancements reinforce the occupant's awareness of their direct influence on the system's back-end performance.

Figure 38: Version B of "clock" thermostat

Version B

In real-world contexts, the display of both environmental and setpoint temperatures is essential during system 'crises'. As occupants familiarise themselves with the system, the display of real-time temperatures becomes more relevant than setpoint temperatures, especially with potential variations between floors. In the revised design (version B: Figure 38), the red text indicates the ambient temperature, while the minimised dial indicates temperature variations. If the temperature deviates from 18-25 degrees, a sad face emoji appears to indicate sub-optimal conditions. A rubber ring has been added to the centre of the design to encourage users to adjust settings. Adjustments are now made in half-degree increments within a range of 18-22 degrees. The heating icon changes from a sun to a radiator, changing from yellow to red to reduce the potential for misinterpretation (Figure 39 & 40).

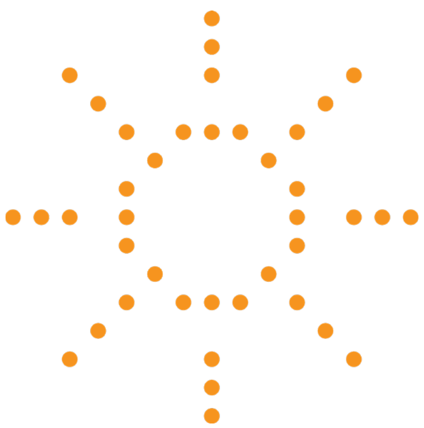


Figure 39: The light pattern of heating in version A

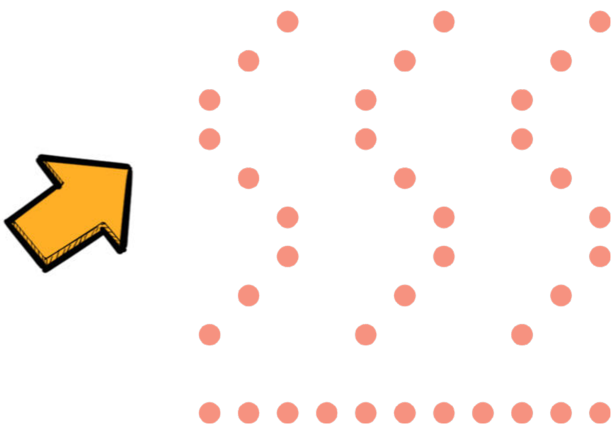


Figure 40: The light pattern of heating in version B

Version C

After consulting with experts, I iterated version C (Figure 41). It simultaneously displays system and target temperatures, helping occupants to track progress and set realistic expectations for waiting times. The slow-moving red pointer reflects the gradual heating of the system. Its shape harmonises with the notch of the dial, symbolising the system's responsiveness. This design enhances the user's understanding of the system's functionality and "crisis" insights. A transparent cover protects the pointer from accidental adjustment. The watch-like appearance emphasises its 'silent display' function, nudging users towards appropriate interaction frequencies and recognising the role of the system.

Figure 41: Version c of "clock" thermostat

Iteration to Feeling Message Board

The concept acts as an in-house profession advisor, exploring the residents' feelings and offering suggestions for living. Co-creation sessions have refined its functionality, aesthetics and conversational design. Coloured bubbles represent current family feelings: blue (cold), red (hot), light purple (stuffy), yellow (dry) and green (satisfied), with bubble size indicating recent input frequency. As determined in the sessions, the use of the device is short term, ideal for the adaptation phase, and can be returned for reuse. Details of the conversational design follow.

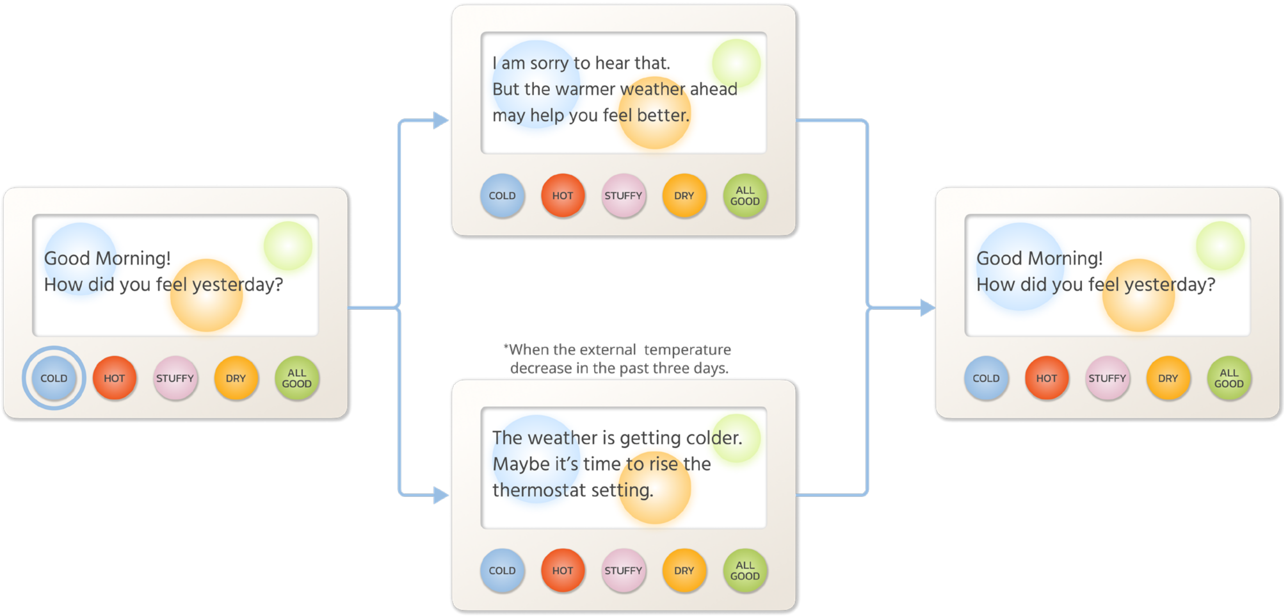


Figure 42: Response when inputting "cold"

As shown in the figure 42, when a person reports feeling cold, the corresponding bubble enlarges slightly to record the input. The device then checks the weather forecast via Wi-Fi. If the forecast indicates warmer days ahead, the device takes note of the outside conditions and suggests that the occupant wait a while. However, if the forecast is for colder weather, the system will recommend adjusting the system settings. After five seconds, the interface returns to the welcome page, where the next user can see the updated bubble view.

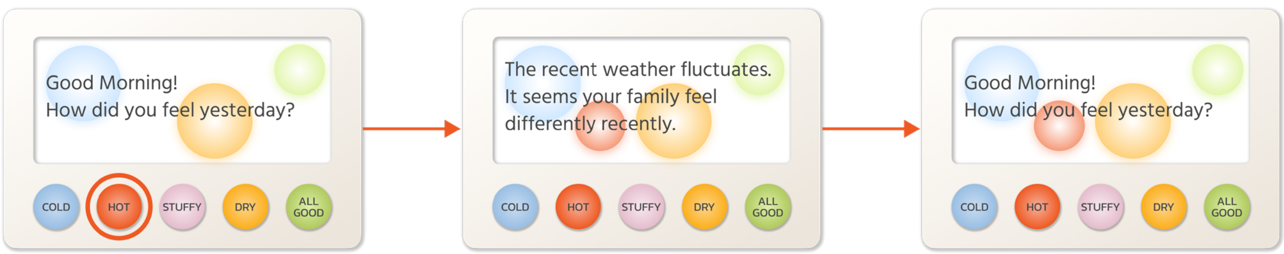


Figure 43: Response when inputting "hot"

When a resident reports that the house is dry, the device first consults the weather forecast. If a significant increase in humidity is predicted, such as rainfall, the device recommends patience. If, however, the weather forecast indicates persistently dry conditions, the device will acknowledge the limitations of the indoor climate system in regulating humidity. Nevertheless, it may suggest alternative or additional product solutions to address the problem (Figure 43).

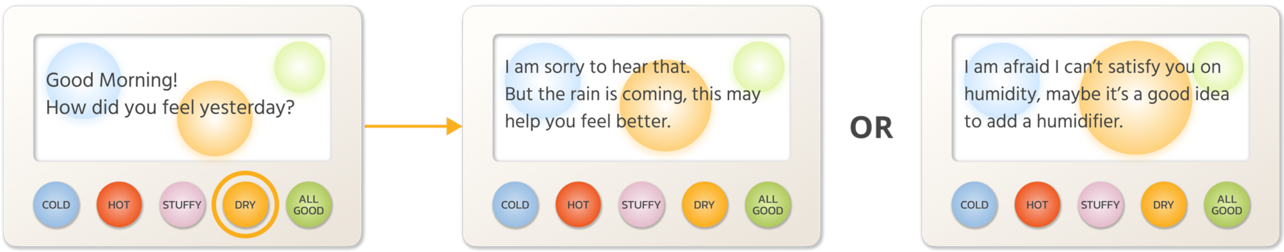


Figure 44: Response when inputting "dry"

When a resident reports that the house is dry, the device first consults the weather forecast. If a significant increase in humidity is predicted, such as rainfall, the device recommends patience. If, however, the weather forecast indicates persistently dry conditions, the device will acknowledge the limitations of the indoor climate system in regulating humidity. Nevertheless, it may suggest alternative or additional product solutions to address the problem (Figure 44).

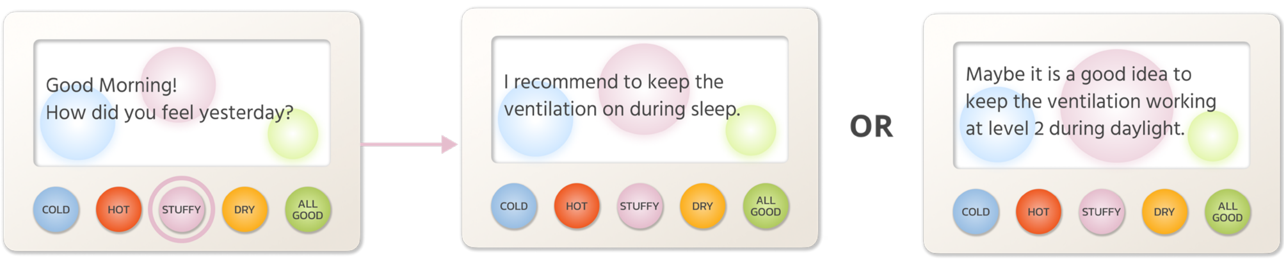


Figure 45: Response when inputting "stuffy"

When people report feeling stuffy (Figure 45), the device checks recent data. If the most recent reports are in the morning and reflect last night's experience, it will first suggest a better sleep period setting. If the complaint persists, it will recommend setting the daytime ventilation to level 2. Detected filter changes or approaching winter (using weather forecasts) trigger reminders for maintenance or possible automatic defrosting to prevent heat pump noise confusion.

07

FINAL DESIGN PROPOSAL

This section introduces the final design which is the results of ideation phase. It illustrates how the design can raise the interest of households to start exploring the 'crises' and the enacted 'interface' in the context of living in ZEH, thus facilitating tailored adaptations. The narrative of the section will focus more on problem solving than on implementation details. How the design meets two design objectives (section 5.5) will be explained in detail.

The design comprises two concepts: the 'clock' thermostat and the Feeling Message Board. The former acts as a functional control, designed for long-term use, while the latter acts as a support device, more suitable for short-term use. The harmonious integration of these two concepts ensures a comprehensive solution that effectively supports adaptation to new technology. This adaptation is achieved through the learning of system features and the insights gained from exploring 'crises in routine'.

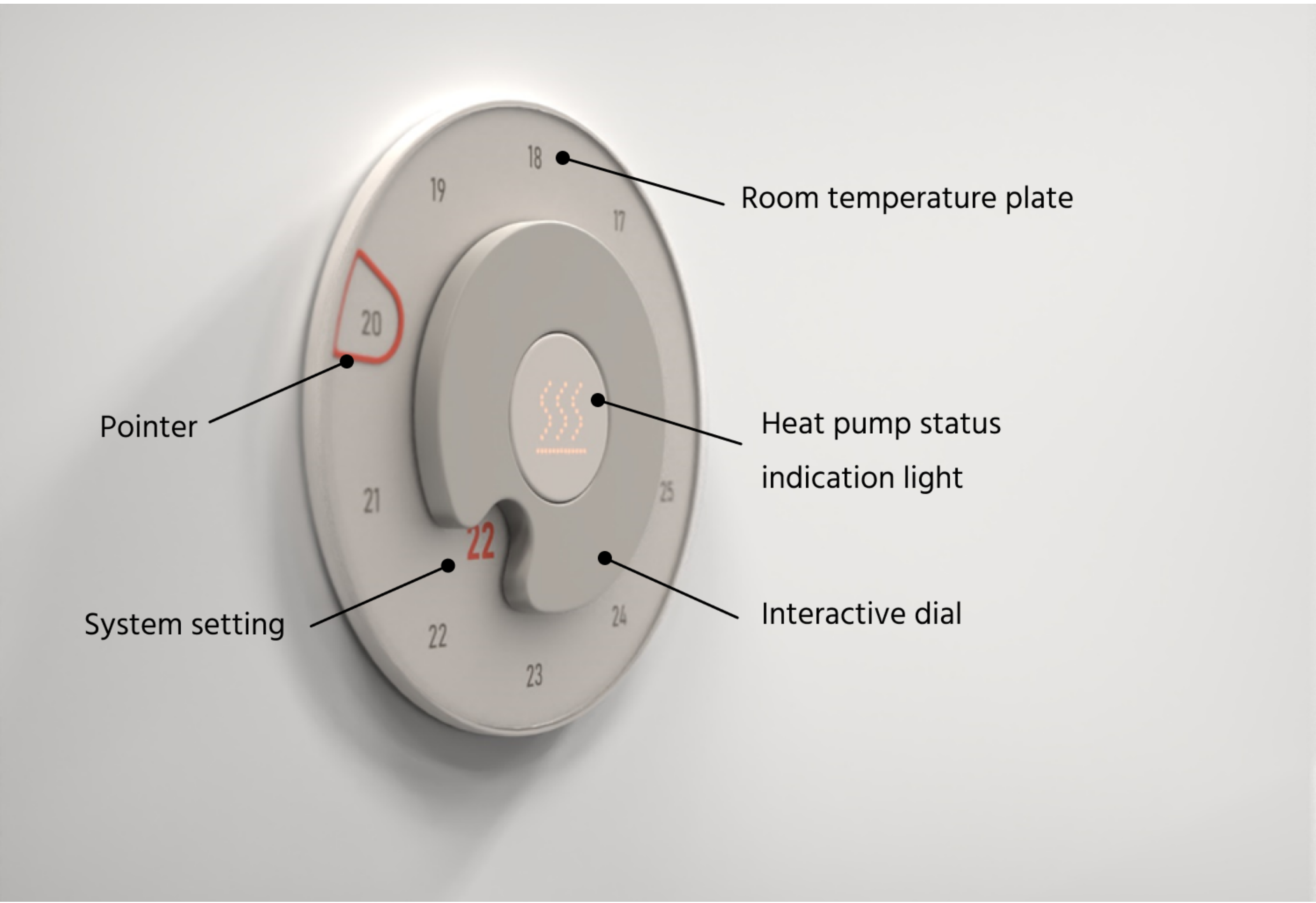
7.1 "CLOCK" Thermostat

"Clock" display

Figure 46 shows the "clock" thermostat design and highlights the key components. The thermostat design, resembling a domestic clock in size and appearance, uses the 'clock' metaphor to subtly shift the user's perception from an active controller to a nuanced display, suggesting that detailed, frequent interactions may not be paramount (Chapter 2.3). The design's size and metaphor may suggest that users limit the installation of controls, perhaps choosing to place them only in high-traffic spaces such as living rooms or bedrooms. Such a placement could emphasise the heat pump system's ability to regulate the house temperature evenly, thus discouraging efforts to achieve pronounced temperature differences between rooms and potentially averting 'crises' (see cluster: 'Indication of automation').

A grey number surrounded by a red pointer indicates the room temperature, while the static red number indicates the current temperature setting. The gap between the pointer and the dial notch indicates the difference between the room temperature and the user's preference. The decreasing gap visually communicates the system's effort to heat the room, which helps to set user expectations in terms of waiting times and understanding of the system's features (reflected in the cluster: "Indication of Progress"). By observing the movement of the pointer towards the notch, users understand

Figure 46: Final Design - "clock" thermostat



the effort of the system and its consequent influence on its operation (Requirement 3.2). As implied in Chapter 2.3, understanding the system modulates user responses, likely leading to pre-emptive adjustments or caution. For example, users may be better mentally prepared for 'crises' by showing more adaptability, such as wearing warmer clothing before adjusting system settings. In addition, the identical shapes of the pointer and notch symbolise a goal, which may increase user curiosity and encourage adjustment efforts (see cluster: 'curious signals'). During a 'crisis', when indoor temperatures might be slightly off, observing the near alignment might inspire patience (requirement 3.3).

Both room temperature and system settings are clearly displayed (requirements 5.2 & 5.3). Coupled with an eye-catching design and multiple placements around the home, the information is universally accessible, catering for varying levels of technological literacy (requirements 1.5 & 2.2). Unlike traditional small-screen control panels, this design presents information openly, promoting a common understanding and encouraging family involvement. During 'crises', the dynamic isn't just between an individual and the system, but becomes more communal, facilitating family discussions and potentially minimising unnecessary adjustments by non-experts, thereby aiding 'crisis' resolution (see cluster: 'supporter engagement').

In essence, these design aspects reinforce the expressiveness of the system (design goal 1) in a conspicuous, intelligible way, motivating users to engage with its features. This methodology encourages a new perception of recurring 'crises' and supports the exploration of individual adaptations.

Light use & Interaction

The thermostat has a hidden pointer under a transparent cover to prevent direct tampering. Users are intuitively guided to turn the dial using the notch. The system allows half-degree temperature changes from 18 to 22 degrees, depending on its capabilities. Getting close to the thermostat activates the central light, which uses different colour-coded patterns to symbolise the system modes, such as heating and cooling (Figure 47). This transparently displays the status of the system without disturbing the occupants, enhancing the sense of effortless monitoring (Requirement 1.2). This real-time status visualisation promotes user-system trust by helping users to interpret light cues about system operation (Reflect cluster: 'indicate of system status'). When the indoor climate is unsatisfactory, the light cues can provide clarity for occupants. For example, a flashing heating indicator might encourage patience, while other signals might encourage further investigation of the system, promoting a better understanding of 'crises' and system functionality rather than rejecting the technology.

Interaction with the system involves turning the dial to set the desired temperature, mirroring the mechanism of a safe deposit box. Meeting resistance in this act slows down decision making, potentially discouraging frequent adjustments and subsequently minimising potential 'crises' (Chapter 2.3). The design reveals only the selected temperature, facilitating easy identification by family members (requirement 1.7). This simplicity of interaction promotes user involvement (Requirement 1.6) and emphasises the automated nuances while maintaining user control over key settings (Cluster: "Feeling of control"). Such an approach emphasises the system's respect for the user's autonomy, catalysing a new perception of system dynamics and personal 'crisis' resolution (requirement 1.1).

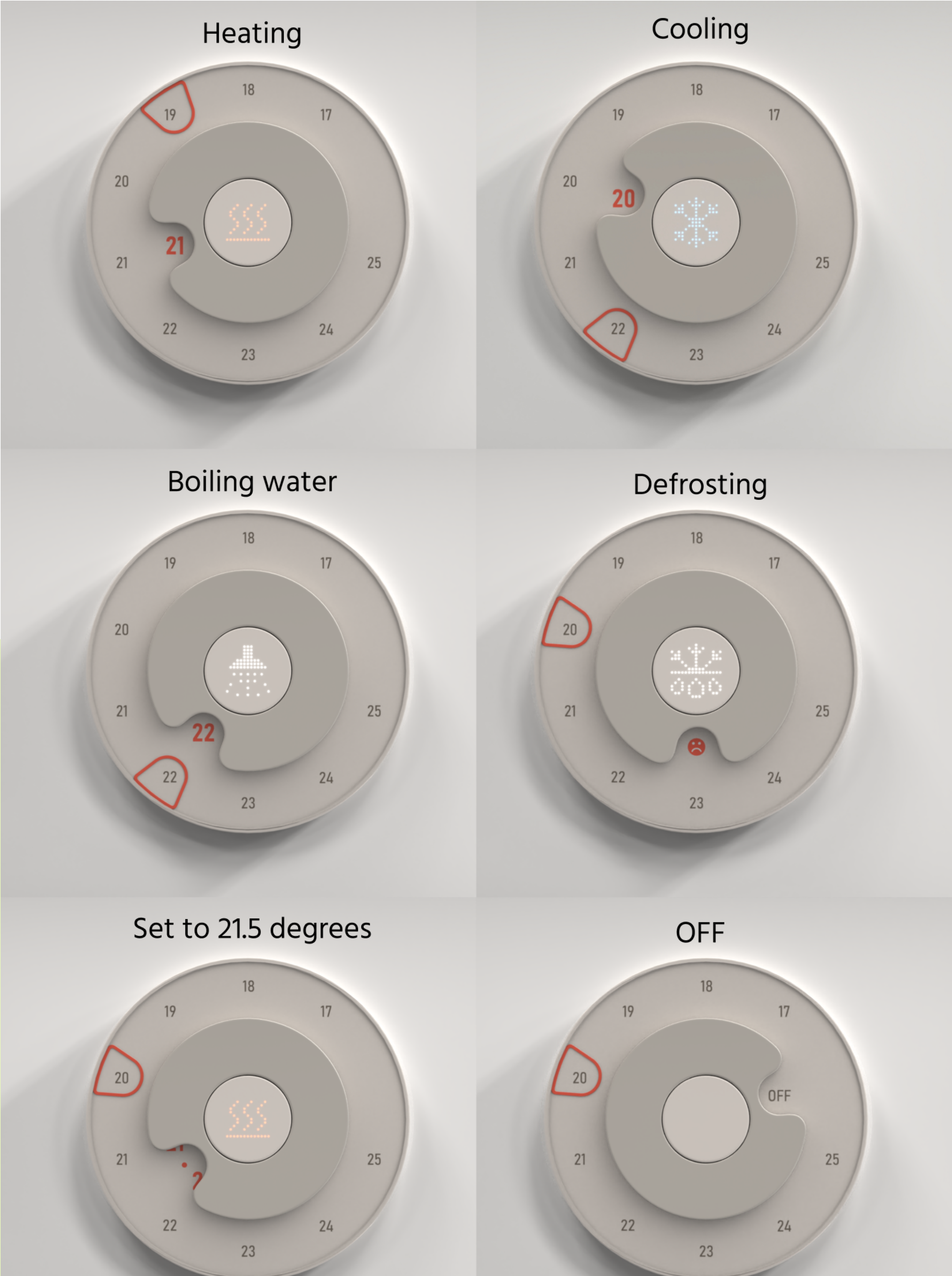


Figure 47: Final design - light & details of "clock" thermostat

For certain system tasks, such as boiling water, temperature changes are limited to ±0.5 degrees, which can be achieved through insulation and maintenance of ambient heat. The interconnectedness of this design highlights system constraints (cluster: restriction of behaviour). Non-responsiveness at times educates users about system capabilities and facilitates adjustment of expectations (requirements 1.3 & 1.4). For example, a midnight attempt to shift the temperature might fail and the light informs users of the system's commitment to preparing hot water for next day. Such insights help occupants understand the challenges of drastic night-time temperature shifts and reshape responses to 'crises'. Exceeding the 22 degree setting prompts a 'sad face' icon, signalling a choice that is negative for both health and system compatibility (requirements 3.2 & 5.7). There is an 'off' option for extended absences, allowing users to deactivate the heat pump.

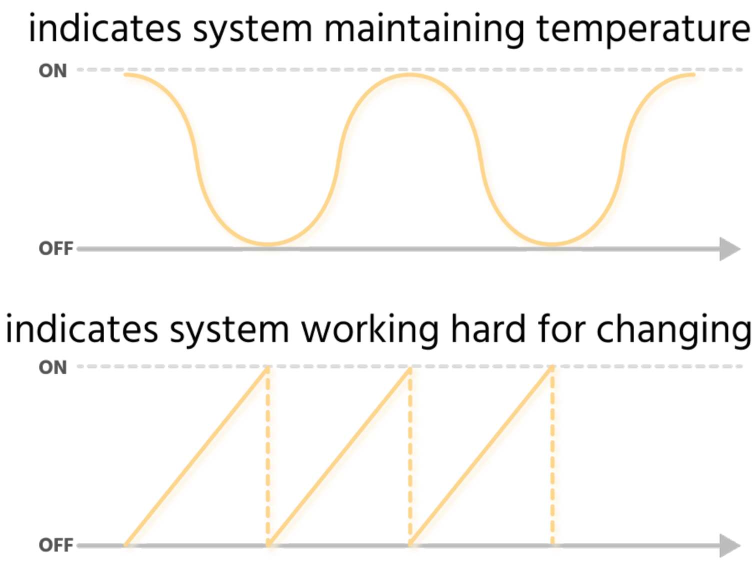


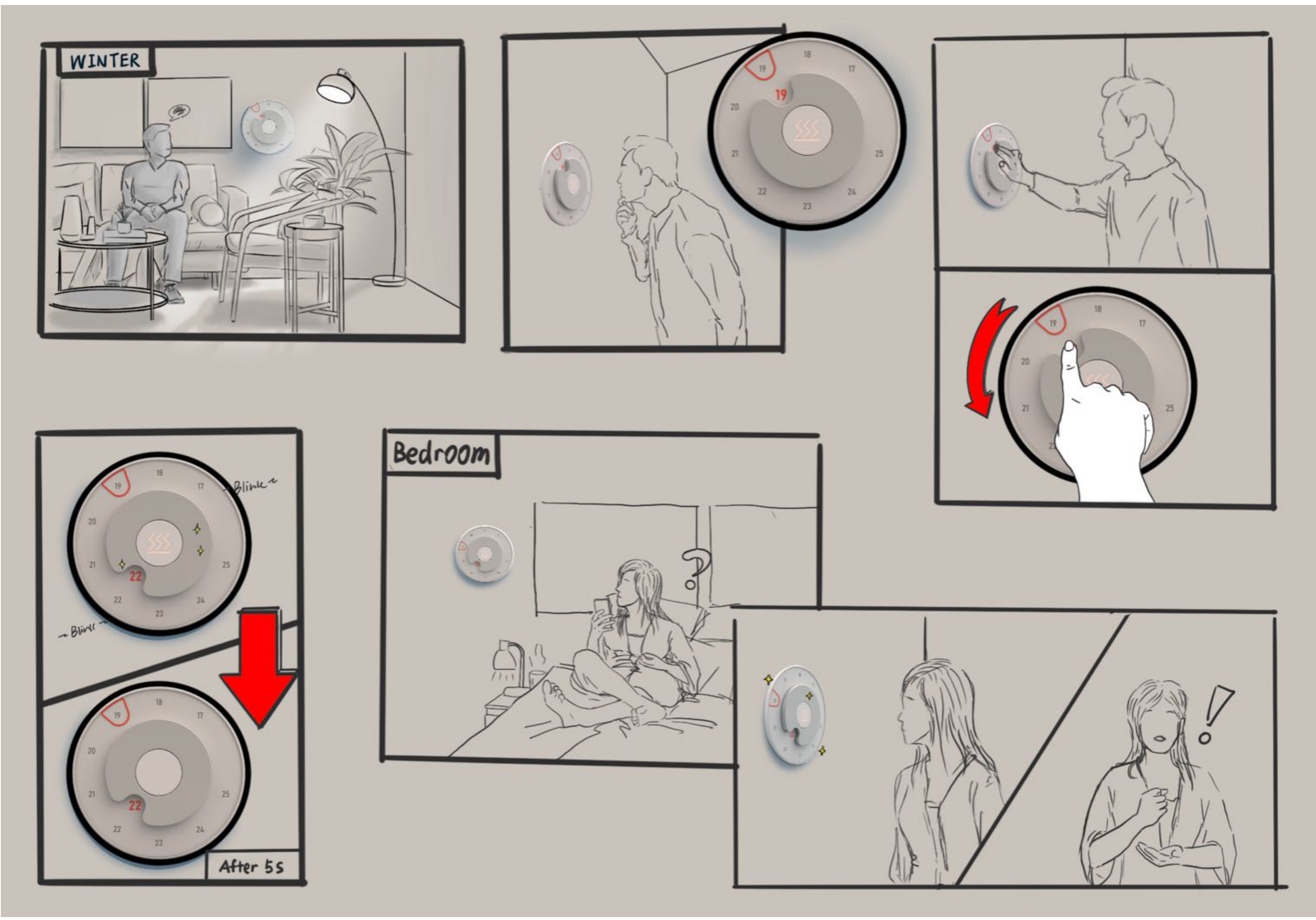
Figure 48: The flashing light pattern design

As shown in the figure 48, the light also has different flash patterns and speeds to indicate different system performance statuses (requirement 3.1). Soft flashes indicate low efficiency system operation to maintain the room temperature, while fast flashes indicate high efficiency efforts to reach the set temperature (requirements 5.2 & 5.5). Such visual cues help users understand the fluctuating workload of the system and discover details about the "crises" (cluster: "curious signal"). It can also be seen as a new form of collaboration if the flashing is perceived as a "complaint" from the system, which can increase users' empathy for the system or concern about energy consumption (chapter 2.3). Precise performance is deliberately omitted, as the design only aims to promote immediate perception that influences quick decisions. When the "crises" occur, the occupants may choose to interact with the device. However, when they approach the device and notice the rapid flashing of the light, they may have a better understanding of the current context and change their decision or wait a little for the system.

Interconnection

The system has interconnected thermostats in different rooms. Although it is technically possible to have small temperature differences between different rooms, the operation of the system remains consistent across all the thermostats. This means that the system cannot change the room temperature independently and cannot achieve large temperature differences like a central air conditioner. At present, however, there is usually a thermostat in each room, which gives the occupants the impression that the heat pump can provide precise heat control for each room. This has led to some 'crises' because the heat pump may not meet the user's expectations for the detailed room temperature, e.g. the heat pump may not meet the room on the third floor at 18 degrees but the room on the ground floor at 22 degrees. In this design, there could be several thermostats in a house, depending on the household's choice, but all the thermostats are connected, which means that it does not support different temperature settings in different rooms. When one thermostat is adjusted, the others immediately reflect the change by turning the dial automatically and activating the status light (requirement 4.4). This design aims to inform family members of system changes, increasing transparency and family awareness (cluster: 'supporter involvement'). For one hour after the change, adjustments in different rooms are limited to a range of one degree (Figure 49) (clusters: 'Restrictive behaviour', 'Curious signals'). Exceeding this range results in an automatic reset. This constraint discourages frequent adjustments due to miscommunication, emphasises the collective impact of individual decisions, and encourages thoughtful system interaction (requirements 4.3 & 4.2). The accurate room temperature display on each thermostat allows occupants to see temperature differences between rooms. Such a feature could stimulate interest in the functionality of the system, discourage unnecessary adjustments and encourage collaborative efforts to develop optimal adaptation strategies.

Figure 49: The storyboard of final design - "clock" thermostat



7.2 Feeling Message Board

This is a wireframe of some example conversation design. The 5 cirles at bottom actually represents the physical buttons. Only the rectangle with colourful bubble and white background represents the real screen. The detailed rendering picture of this feeling message board will be shown on next page.

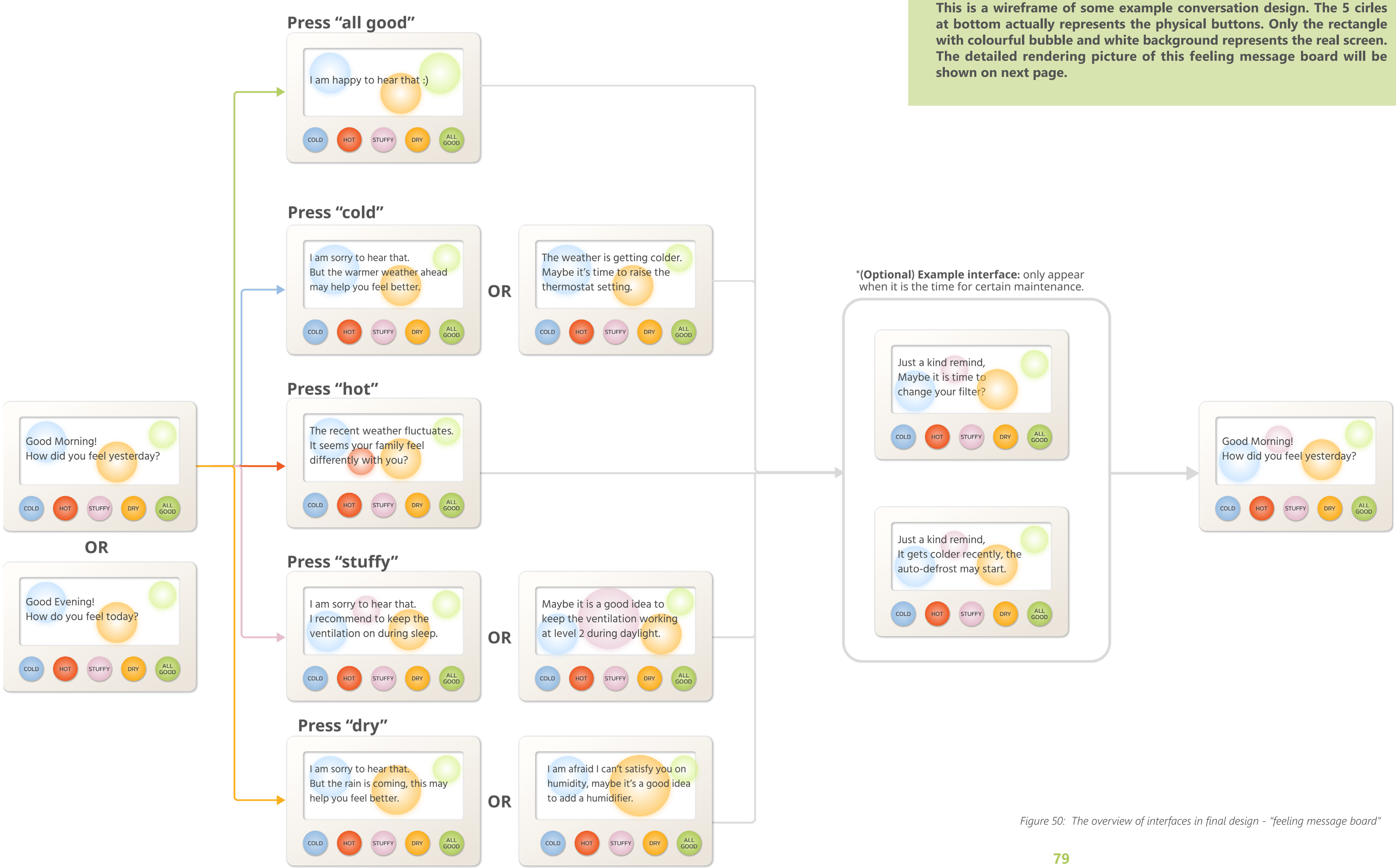


Figure 50: The overview of interfaces in final design - “feeling message board”

Conversation & Advice

The above wireframe (Figure 50) shows the overall response design, whose details can be found in chapter 6.5. In its role as an internal professional advisor, the device provides proactive recommendations to improve comfort in response to 1) user input about feeling, 2) the weather forecast accessed through wifi, 3) the date and time accessed through wifi, 4) the room temperature and humidity detected by inner sensors (requirements 5.3 & 5.4). The difference between outdoor weather and the indoor environment has a significant impact on occupants' perceptions and subsequent comfort expectations. As a result, devices that alert users to weather changes and provide guidance on system adjustments can better align user expectations with actual system performance, potentially advising patience during system optimisation.The aim of these features is to identify optimal times to change system settings and to avoid unnecessary or frequent changes. It also openly communicates its limitations - for example, if the heat pump-based system is unable to meet expected humidity levels. This transparency prioritises concern for the real-life experience of the occupants over education about the 'right choice', thereby fostering a sense of equality between human and technology (requirements 1.4 & 1.8). Based on time factors, the device occasionally provides reminders for maintenance or unique system performance issues, such as the need for filter change or automatic defrost activation. However, it only provides advice and does not automatically adjust system settings on behalf of the occupants, thus respecting their autonomy and decision-making in their home (requirements 5.1 & 5.6). All these features facilitate a better understanding of the functionalities and capabilities of the system and encourage active exploration of solutions to perceived 'crises'. This subtle effect on the occupants' perception helps to change their first impression and judgement when the 'crises' occur. For example, having been reminded of the defrost mode in winter, they may not be too shocked when they hear the noise and will also react to it differently.

Figure 51: The overall design of "feeling message board"

Figure 52: Bubble change design

Figure 53: Design of cleaning up the bubbles

Feelings are represented visually as colour-coded bubbles, with each colour representing a different feeling and the size of the bubble corresponding to the frequency of the input (Figure 52). When a bubble fills the screen, the device resizes all the bubbles, keeping only the previous top three for ongoing comparison (Figure 53). The device is designed to be used twice a day per person - once in the morning and once in the evening. With access to the time of day, the welcome page can be changed automatically. The morning feel input is more likely to reflect the stable indoor experience, particularly the sleep experience, while the night feel input is likely to reflect the mix of the overall outdoor and indoor experience during the day. Therefore, encouraging occupants to report twice a day can also help them to recall their daily lives and unconsciously discover the impact of system performance. It acts as a reminder, encouraging users to reflect on their subtle changes in sensation and increasing their awareness of comfort. It acts as a reminder, encouraging users to reflect on their subtle changes in sensation and increasing their awareness of comfort. In addition, continuous observation of the bubbles allows users to identify patterns in the operation of the system and to understand the inherent latency of the system - typically about a day to reach expectations after adjustments. Such insights can improve understanding of the system and adjust anticipation of 'crises'.

In addition, the device promotes engagement of all occupants, fostering an understanding of each other's experiences. By comparing the change in the bubble between an individual's two interactions, it is easy to see how others are feeling. So even if residents are not home at the same time, they can gain insight into each other's feelings from the bubble display (cluster: "supporter involvement"). This magnifies individual differences and serves as a good reminder to promote empathy and communication between family members, facilitating joint efforts to make everyone feel comfortable (requirements 4.1 & 4.2). This could help expose more hidden "crises" and make interaction with the system more like a family activity, encouraging more active and collaborative exploration of new "interface".

Relevant Service

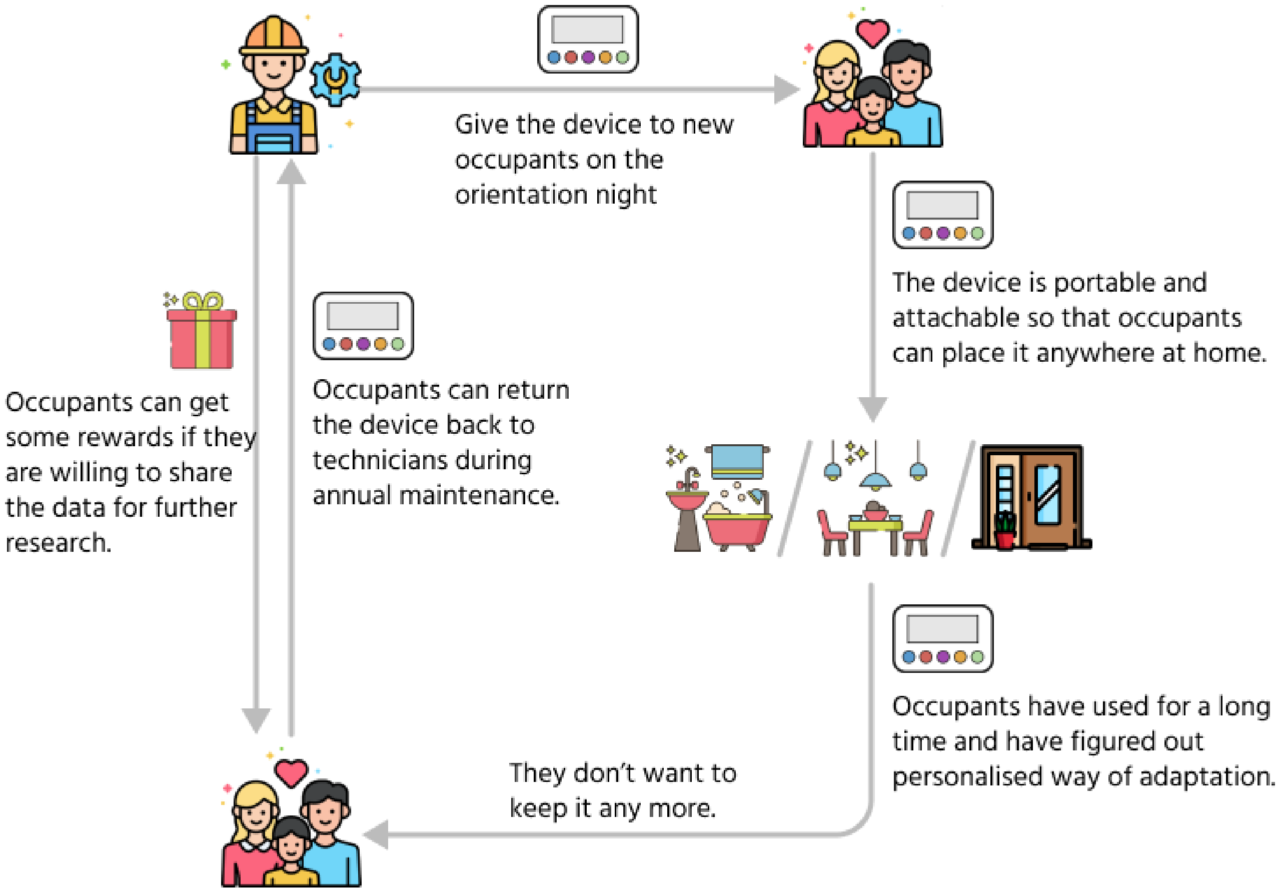


Figure 54: The service flowchart of final design - "feeling message board"

Designed primarily to facilitate the adaptation phase, this device becomes less necessary for daily interaction once residents have established their preferred living conditions with the system. For sustainability and energy savings, residents can choose to return the device to technicians for annual maintenance. The stored data can be erased, and the device reset, making it ready for the next resident. In cases where residents are willing to contribute their recorded data for further research, they could receive a reward from the technicians, such as an extension of the free maintenance year or cash back. The service design aims to be more in touch with reality, but without adding much to the cost. The user experience data could also benefit the next iteration and further research.

08

EVALUATION

The primary objective of this research is to assess the effectiveness of the design in increasing household members' interest in understanding the conflicts behind 'crises' and discovering their own solutions. The detailed research questions serve as hypotheses related to the key design features derived from the design requirements (see chapter 6.4). Considering test time and experts' advice, the study aims to validate the effectiveness of only these three design features and explore some insights for further improvement.

8.1 Research question (hypotheses)

1. **Can the dial design and the light design in "clock" display concept convey the real-time system status effectively to improve understanding and inspire experiments?**
2. **Can the interlocking design in "clock" display concept highlight heat-pump system features to inspire new response?**
3. **Can the bubble design in Feeling Message Board concept effectively raise user's awareness on individual difference in perceiving indoor climate to inspire family discussion and tailored family adaptation solution?**

8.2 Method

Participant

Three households (1, 2, 4) participating in this study are considering a transition to living in a zero-energy house in the future. Households 3 and 5 are currently living in such a house. To encourage discussion within the households, participants from the same household were interviewed together. In total, 9 participants take part in the interview evaluation. The following table gives a detailed description of the participant profiles.

Household 1	Household 2	Household 3	Household 4	Household 5
2 participants	2 participants	2 participants	1 participant	2 participants
A couple with a child living together	A couple living together	A couple living together	A couple living together	A couple living together
Have pet	Have pet	No pet	No pet	No pet
Apartment	Apartment	Apartment	Apartment	Apartment

Table 3: Evaluation participants

Approach

In order to test the three hypotheses, I developed three different "crisis" scenarios, each based on information gathered from previous interviews. During these sessions, I used role-playing techniques (Van Boeijen et al., 2014) and invited participants to interact with the digital prototypes in the context of each 'crisis' scenario. Imagining that they have just moved into the renovated house, I will first take the role of the technician and give them a small orientation meeting in the house to introduce the changes and the new system in their house. Then, just like in a game, I will lead them through the scenarios step by step and experience digital prototypes through conversations. During this process, I use context mapping (Van Boeijen et al., 2014) to develop picture probes to encourage participants to express feelings and thoughts evoked by the design and to simulate reactions to the evolving scenarios. Participants' feedback is then compared with the design intentions to assess the effectiveness of the design in conveying pertinent information and facilitating understanding of the underlying conflicts inherent in these 'crises'. By observing participants' attitudes and reactions, I can discern the influence of the design in motivating proactive discovery and engagement with the system in the 'crisis' scenarios.

8.3 Result

Dial design and the light design in "clock" display concept

Participants unfamiliar with Zero Energy Houses (ZEH) equated the 'OFF' setting with a complete shutdown of the heat pump, leading to concerns about hot water supply. They recommended using 'OFF' during long periods of absence. Conversely, ZEH occupants perceived 'OFF' as disabling temperature control without affecting hot water. In mild seasons, they prefer this mode to take advantage of efficient insulation. The icon or visual design needs to be clear about these modes.

All participants recognised the 'sad face' icon as an uncomfortable and system-demanding condition. They would adjust the settings to prevent it being displayed. The half-degree intervals of the red dot were clear, but participants preferred integer temperatures, adjusting in half-degrees as they understood system performance over time.

Icons were understood based on orientation recall. Heating and cooling icons were self-explanatory, while defrosting and boiling water icons required reference. Participants identified flashing lights as the system adjusting. However, differences in flashing speed were often overlooked. Five out of nine participants expected a constant light when a set target was reached. This highlights areas for design refinement.

Six participants who overlooked instructions found the defrost icon confusing, particularly due to the sounds associated with it. Some assumed the system was malfunctioning and sought expert advice within the household. Others assumed an automatic system mode switch, associating noises with increased system activity. Half were patient, observing for days before making a judgement. This suggests that the design effectively encourages proactive user interaction.

Most participants felt confident in noticing the movement of the watch after setting changes. They weren't surprised by the gradual warming, attributing it to their sense of orientation. The slow progression of the clock cemented these expectations. When the system met expectations, acceptance was rapid, reflecting the effectiveness of the design and in line with research findings (Chapter 2.3).

Interlocking design in "clock" display concept

When confronted with the automatic rotation of the dial due to interconnection, most 'non-expert' participants inferred that it was caused by another occupant's interaction with another thermostat. They often sought confirmation from other household members. Conversely, 'experts' showed surprise and typically investigated autonomously, examining other thermostats or consulting manuals. Their confusion was directed towards understanding the event rather than fearing a malfunction. This design aspect enhanced communication between 'non-experts', encouraging family discussions about system intricacies and adaptation strategies.

When presented with a limited adjustment range of ±0.5 degrees following a recent change by another resident, all participants showed initial confusion but actively sought out the potential adjustment limits. They largely perceived this as a system constraint rather than a malfunction. However, 3 out of 9 participants expressed doubts about the functionality of the thermostat. Non-experts' often re-evaluated their previous interactions and in certain situations, such as approaching bedtime, either sought guidance or chose inaction. Many tended to postpone the issue, especially if they didn't see an immediate effect in the room. Solving problems was often delegated to others or put off until another time. Consultation of the manual was a last resort. In contrast, 'experts' were more analytical, comparing experiences and using manuals for insights.

The interconnected features of the design encouraged engaging experiences, stimulated proactive responses during 'crises' and encouraged family dialogue. This design emphasises the system's capabilities and changes residents' perceptions and understanding.

Bubble design in Feeling Message Board concept

At first glance, participants focused primarily on the textual content, with the design as a secondary feature. Once they interacted, they began to associate colour cues with specific buttons and size dimensions with their records. However, they also reflected that the bubble change was not as eye-catching. Six out of nine participants identified emotional nuances by comparing bubble variations with device feedback. Non-experts often initiated family discussions based on these insights, while experts observed longer before discussing.

Surprisingly, the three 'experts' who couldn't relate bubble variations to family feedback doubted the effectiveness of the product, preferring comprehensive system instructions to vague suggestions. In contrast, the 'non-experts' were keen to interact with the bubbles and reflect on their recorded feelings, showing limited concern for the device's gentle suggestions. One 'non-expert' even expressed scepticism about the device's ability to accurately reflect her family's feelings, believing that her own understanding was superior.

The bubble reset feature introduced uncertainty that could alter participants' initial perceptions and engagement with the system. Two people admitted to random interactions with the device in an attempt to determine the cause of the bubble reset.

8.4 Discussion & Conclusion

Can the dial design and the light design in “clock” display concept convey the real-time system status effectively to improve understanding and inspire experiments?

The dial design and light design roughly reach the expected effect on system expression and occupant’s cognition building. Research shows that occupants generally understand the dial design, with the 'sad face' icon effectively communicating system capabilities and subtly guiding user actions. However, the 'off' setting is ambiguous in the context of a zero-energy house. A clearer distinction between shutting down the heat pump system and turning off the temperature control could improve the user experience by emphasising the multi-functionality of the system, potentially making users more cautious about responding to a 'crisis'.

The design element using different flashing speeds to indicate the intensity of system operation was less effective. User engagement with the dial settings and the attractiveness of the icon interfered with their perception of the change in flashing speed. I am considering simplifying this to a single fast flash and a steady light to indicate major changes or maintaining current temperature.

Although not immediately intuitive, users recognised that icons indicated different system states rather than errors. This encouraged users to seek a deeper understanding through resources such as manuals. However, design improvements can make interpretation more intuitive, like adding instructions next to it.

Can the interlocking design in “clock” display concept highlight heat-pump system features to inspire new response?

The interlocking design effectively stimulates curiosity and encourages user exploration. By offering nuanced interaction, the design emphasises the holistic regulation of the system and highlights the interconnected impact of individual decisions. For 'non-experts', it encourages shared experiences and family discussions, in line with the design goal of inclusive participation. They often link the automatic changes to the interactions of other household members, grasping design intent.

On the other hand, 'experts' engage in more independent exploration, trying to understand the relationship between multiple thermostats. While they may sometimes overlook automated changes, thermostat restrictions following interaction with another thermostat consistently trigger family discussions. Notably, these restrictions shift concerns to the thermostat's functions rather than the heat pump, encouraging patience. This mindset could be instrumental in eliciting adaptive 'crisis' responses. Overall, given the family context, the design elements largely achieve intended goals.

Can the bubble design in Feeling Message Board concept effectively raise user’s awareness on individual difference in perceiving indoor climate to inspire family discussion and tailored family adaptation solution?

The study highlights the potential of the design feature to illuminate individual perceptions of the indoor environment and stimulate family discussions. However, the design hasn't fully achieved its expected impact because the bubble change doesn't attract enough attention. For optimal user experience, the design, particularly bubble attributes such as size and colour, needs to be improved. Initial overshadowing by text has reduced the importance of bubbles as markers of individual feelings about the indoor environment. Subsequent design iterations should emphasise these attributes.

User expertise influenced design reception. Non-experts' easily grasped the bubble shifts, sparking family conversations. Conversely, 'experts' found it difficult to relate bubble changes to family feelings. Once understood, they actually preferred quiet observation to communication. These 'experts', disinterested in bubble interactivity, sought extensive feedback, were confident in their understanding of the system, and adapted for the comfort of their relatives. This suggests that while the bubble approach is effective in increasing awareness and communication for certain users, it may not be appropriate for all.

In addition, the current design of the bubble reset feature introduced ambiguity, inadvertently leading some to question the reliability of the system. This highlights the need for user-centred, intuitive designs. Future versions should prioritise consistency of user experience and reduce elements that cause confusion or doubt. In summary, while the bubble design raises awareness and encourages familiar dialogue, further refinement could increase its effectiveness.

09

REFLECTION & CONCLUSION

This section proposed some recommendation on the future iteration of the design based on the evaluation findings and summarily illustrated how the final design successfully fulfil the design vision: Raise the interest of households to start exploring the 'crises' and the enacted 'interface' to find out tailored adaptations to the new technology. It will also discuss the feasibility and manufacturability of the final design.

9.1 Future Recommendation

"CLOCK" Thermostat

Figure 55: Small instruction next to the thermostat

The inclusion of a light may detract slightly from the 'clock' metaphor, but its utility in communicating real-time system status through distinct patterns is valuable, providing users with tangible insight into system 'crises'. To aid user understanding, a short instructional label next to the thermostat, explaining the meaning of the icons, could be beneficial (Figure 55). This will help occupants to quickly recall unfamiliar icons, thereby mitigating potential concerns. The evaluation sessions revealed a preference for fast flashing to indicate the heat pump is actively trying to change conditions, while a steady light suggests maintaining current state.

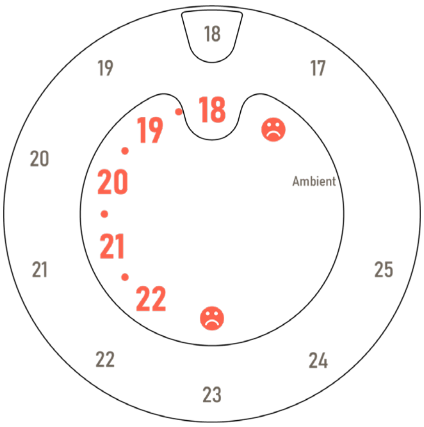


Figure 56: New dial display design

Figure 57: Add knobs to cotrol boiling water & shutdown

The 'off' labelling on the dial was a source of confusion. There needs to be a clearer distinction between the complete shutdown of the heat pump system and the mere deactivation of temperature control. I recommend a change in the design of the dial, with "Ambient" indicating that the heating and cooling functions are switched off, while the hot water supply is maintained (Figure 56). Given the prevalence of two hot water modes in existing systems, an auxiliary knob could be added to the side to further cement the "clock" aesthetic. This would facilitate adjustments related to water boiling and complete heat pump shutdown (Figure 57). Following the current mode design, there will be an 'Eco Water' mode - which activates water boiling at certain times, such as at night, and stores the heated water for use during the day - and a 'Comfort Mode', where the heat pump heats tap water when it senses the tank temperature falls below an ideal threshold. There's also a 'Shutdown' mode for completely shutting down the system. Given that a clock's small knob is usually used to indicate adjustments to its internal workings or major system changes, it's apt for designating the modes associated with boiling water and shutting down, thus neatly distinguishing them from temperature control.

Feeling Message Board

Figure 58: New bubble effect design

Based on feedback from the evaluation session, I intend to refine the bubble feature to enhance interaction, add a playful element, and emphasise the recording of feelings and individual differences (Figure 58). Instead of enlarging an existing bubble when a user documents their feelings, a new colour-corresponding bubble will materialise, providing clearer user feedback. To differentiate between the bubble and subsequent responses, greetings are positioned higher on the interface. After interaction, the display will first highlight the change in the bubble. After a 5-second delay, an appropriate response will appear. Based on context and available reports, this responsive design could be extended to provide richer, contextually relevant information. The response designs outlined in Chapter 6.5 serve as preliminary illustrations that need to be further developed.

Figure 59: Bubble merging when the colour gets full

More like a game, as bubbles of one colour fill the screen, pressing the key to the same colour causes all the previous bubbles to merge into a larger bubble, while also creating an additional standard size bubble. This makes it easier for the user to quickly identify recent recordings (Figure 59). As bubbles of the same colour fill the screen again, the previously recorded bubble at the top will expand (Figure 60). Records are reset each season.

Additionally, how to motivate all the occupants to continue playing with it should also be considered. The relevant service and rewards design might need further development.

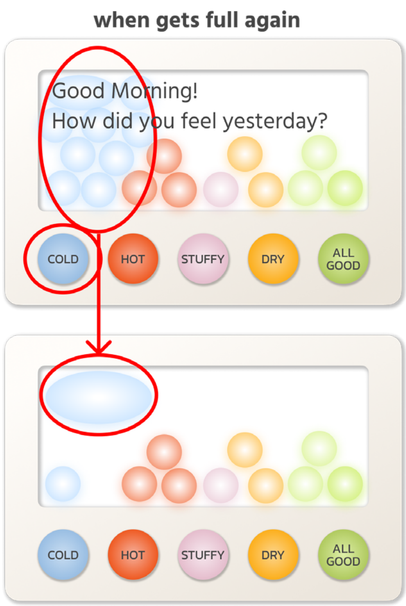


Figure 60: Extend merged bubble when gets full again

9.2 Concept Reflection

"CLOCK" Thermostat

The substantial size and use of the 'clock' metaphor successfully reshapes occupants' perceptions and expectations of the indoor climate system, thus changing the 'crisis' narrative. This also confirms the research findings in section 2.3. It's no longer seen as a tool for active control, but as a display. This leads to a preference for installing a limited number of thermostats in primary rooms, which changes the response to 'crises'. For example, it is easier for them to understand that the heat pump is heating or cooling the whole house together, and they are no longer likely to expect a large difference in temperature between different rooms. The clock metaphor, combined with simplified interactions, dispels the notion of a complicated control panel. It builds trust in a system that works discreetly in the background. In addition, the new features of the 'clock' thermostat encourage occupants to view the thermostat and heat pump as somewhat discrete entities. They have different emotional responses to the thermostat's constraints, which encourages further exploration, elicits different responses to 'crises'.

The interconnected nature of the thermostats and their associated restrictions has proved successful in stimulating curiosity and catalysing family discussions to further decode the 'crises'. The unexpected constraints provide a striking experience and greatly increase curiosity, motivating proactive exploration. Importantly, these design features have a pronounced impact on stimulating household discussions, particularly among 'non-experts', effectively drawing them into a deeper understanding of the system.

The design has much potential for refinement, particularly in the articulation of system status and its operational intensity. The presentation of information should be more intuitive, making it easier for users to understand the manifestations of 'crises' and providing clearer guidance for exploration. While some preliminary suggestions are made in Chapter 9.1, further evaluation is essential to assess their effectiveness.

Feeling Message Board

Rather than being a primary feature, the small box presents itself as a complement to the "clock" thermostat. It blends seamlessly into the daily routine, without working primarily at times of 'crisis'.

The bubble design on the Feeling Message Board has been instrumental in raising awareness of individual differences in indoor comfort. It acts as a catalyst for family discussion, possibly uncovering clues leading up to or during 'crisis' events. This encourages a collective response, with 'non-experts' in particular noticing changes in the bubble and initiating dialogue. One challenge, however, is to maintain sustained interaction. Without consistent input from all family members, the nuances of individual preferences remain underrepresented. Although suggestions are provided in Chapter 9.1, they require further validation.

While the ability of the device to communicate system features remains under-evaluated, initial feedback suggests that it is falling short of design expectations. Particularly for 'experts', the depth and information content of the dialogues needs to be enhanced to promote a holistic understanding of the system. This comprehensive understanding is essential to equip occupants adequately to deal with "crises" and to formulate innovative strategies for them.

9.3 Implementation

“CLOCK” Thermostat

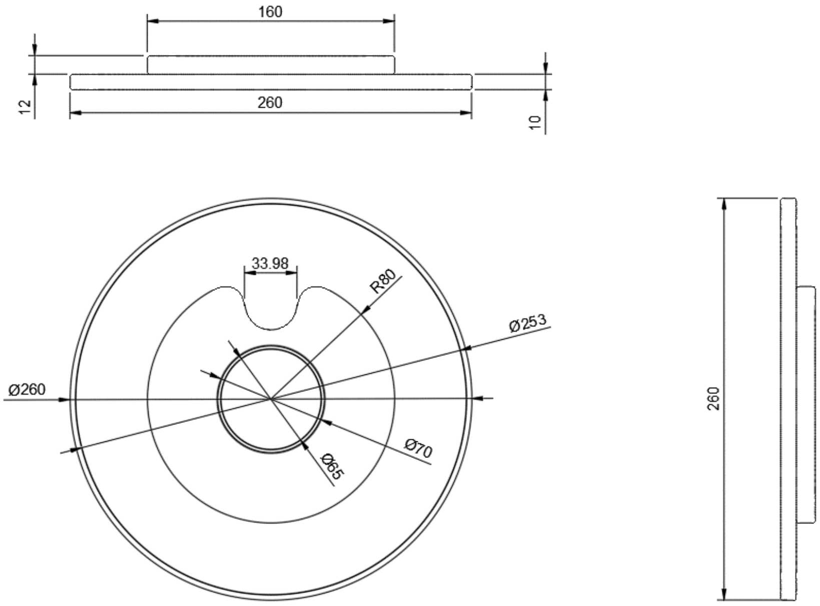


Figure 61: Key dimensions of “clock” thermostat

Figure 62: 1:1 physical prototype of “clock” thermostat

The Clock thermostat has a diameter of 26 cm, similar to a traditional clock (Figure 61). The coloured components are made of ABS with a matt finish, while the transparent components are made of PMMA (Figure 62). The standard shapes of all the components is suitable for the common injection moulding, which is cost-effective. The rotation mechanisms for both the dial and the red pointers are fully developed, ensuring feasibility for mass production.

The light pattern is achieved using a 15x15 pixel matrix, optimising power consumption compared to previous LED displays. Internally, a temperature sensor measures the surrounding air and directs the red pointer to indicate the indoor temperature. An infrared sensor is integrated to activate the light when it detects the approach of an occupant. As a thermostat, it interfaces with the heat pump system and must be installed before occupants move into ZEH.

Feeling Message Board

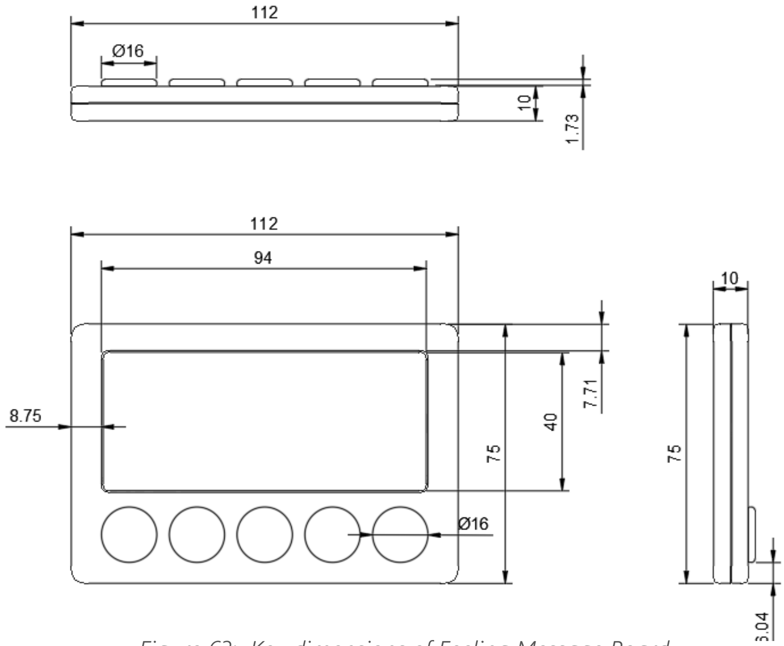


Figure 63: Key dimensions of Feeling Message Board

Figure 64: 1:1 physical prototype of Feeling Message Board

The feeling message board is compact with its LED screen measuring approximately 4x9 cm (Figure 63). All components are made from ABS with a glossy finish (Figure 64). Its simple design and standard assembly line underline its manufacturability and cost-effectiveness. The unit, which includes an internal battery, is portable and can be recharged via a standard type-C port. A built-in light sensor allows the screen to automatically adjust its brightness and enables the screen to automatically turn off and on when someone approaches to interact. Given the maturity of these technologies in the market, implementation should be straightforward. The device connects to the home's Wi-Fi to retrieve weather and time data, as conversations and responses depend on weather change, season changes and time variations.

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APPENDIX

Appendix A: Project Brief
Appendix B: Research elective report
Appendix C: Consent form & HREC approval
Appendix D: Research plan of ethnographic study
Appendix E: Interview notes of ethnographic study
Appendix F: Thematic analysis process
Appendix G: Co-creation Plan
Appendix H: Interview transcripts of co-creation
Appendix I: Evaluation Plan

Appendix A: Project Brief

DESIGN FOR our future

TUDelft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name ____________

initials ______ given name ____________

student number ____________

street & no. ____________

zipcode & city ____________

country ____________

phone ____________

email ____________

Your master programme (only select the options that apply to you):

IDE master(s): ( ) IPD ( ) DfI ( ) SPD

2nd non-IDE master: ____________

individual programme: ___ - ___ - ___ (give date of approval)

honours programme: ( ) Honours Programme Master

specialisation / annotation: ( ) Medisign

( ) Tech. in Sustainable Design

( ) Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair ____________ dept. / section: ____________

** mentor ____________ dept. / section: ____________

2nd mentor ____________

organisation: ____________

city: ____________ country: ____________

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair ________________ date - - ________ signature ________________

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: ________ EC

Of which, taking the conditional requirements into account, can be part of the exam programme ________ EC

List of electives obtained before the third semester without approval of the BoE ________

YES — all 1st year master courses passed

NO — missing 1st year master courses are:

name ________________ date - - ________ signature ________________

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: APPROVED NOT APPROVED

Procedure: APPROVED NOT APPROVED

comments

name ________________ date - - ________ signature ________________

Tailored family living experience in zero-energy housing

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 15 - 02 - 2023 | 28 - 07 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The market of zero energy housing is expected to grow rapidly because it is considered a key role in future energy transitions. This comprises well-isolated and airtight houses in combination with heat pumps for heating and heat recovery systems for ventilation and heating as key elements. In order to maintain optimal indoor climate and minimize energy consumption, it is recommended to keep the windows and other openings of the house closed when the temperature outside differs significantly from the interior temperature. This actually is not aligned with what households used to and requires adaptation. Therefore, the impact of smart housing on energy consumption fundamentally relies on how they are used by occupants. However,living in a smart building can be full of conflicts from the perspective of households, and the performance of the building service system does not always align with what residents feel is appropriate and the expectation of sustainability.

The automated indoor climate system performs based on design assumptions, referring to the average behaviour in the calculation of the energy performance coefficient (EPC), which was based on standardized occupancy and the characteristics of the building envelope and installations. However, the individual has different needs and preference for comfortable indoor climate thus automation cannot always meet users' intentions without friction. In summary, computational models (configurators) typically exclude human diversity for simplicity, leading to the misfit of system.

The sustainable building service system becomes more complex and failure-prone, which increases the learning cost for users to understand the system features and expectations. Secondly, the problem is that automated, smart technologies work in the background to purposefully reduce the required interactions of residents with their homes. The assumption is that automation will perform appropriately in the background, meeting the residents' intentions and actions smoothly. However, this is often not the case. Consequently, residents cannot maintain control over complex and mutually interacting systems through limited touch points when they are not familiar with relevant technologies and zero-energy housing.

Due to the high learning cost and demand for behaviour adaptation, people with little knowledge of technology tend to avoid interaction with the system. Instead, they will use some external devices to adjust to the indoor climate or search for help from other family members. Additionally, even for people with much knowledge with the indoor climate system, the control options are still limited. Therefore, the accessibility of the system is not so open to all users.

Instead of preventing conflicts and reducing interactions, this project will focus on 1) how to facilitate co-performing among the building service system and multiple actors within a family; 2) how to enhance communication among family members on setting a comfortable indoor climate. This project will focus on the renovated zero-energy house due to the client.

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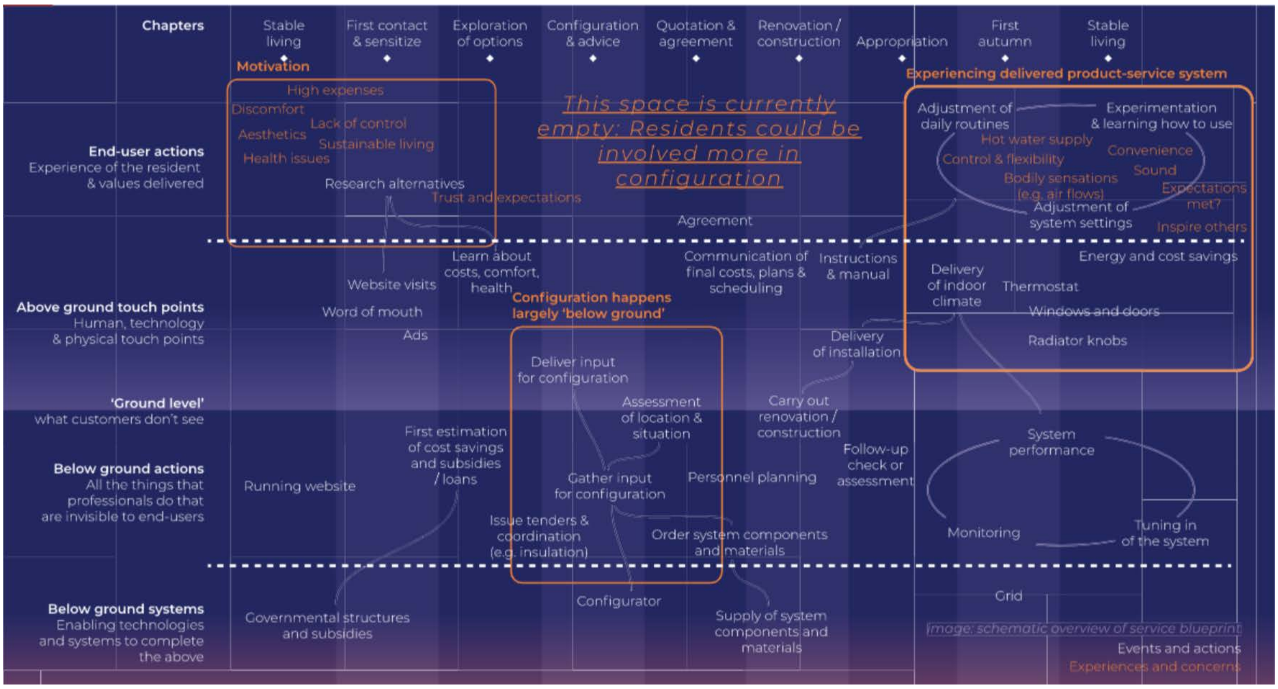


image / figure 1: A product service blueprint for heat pump configuration in zero energy housing (From Evert.v.Beek)

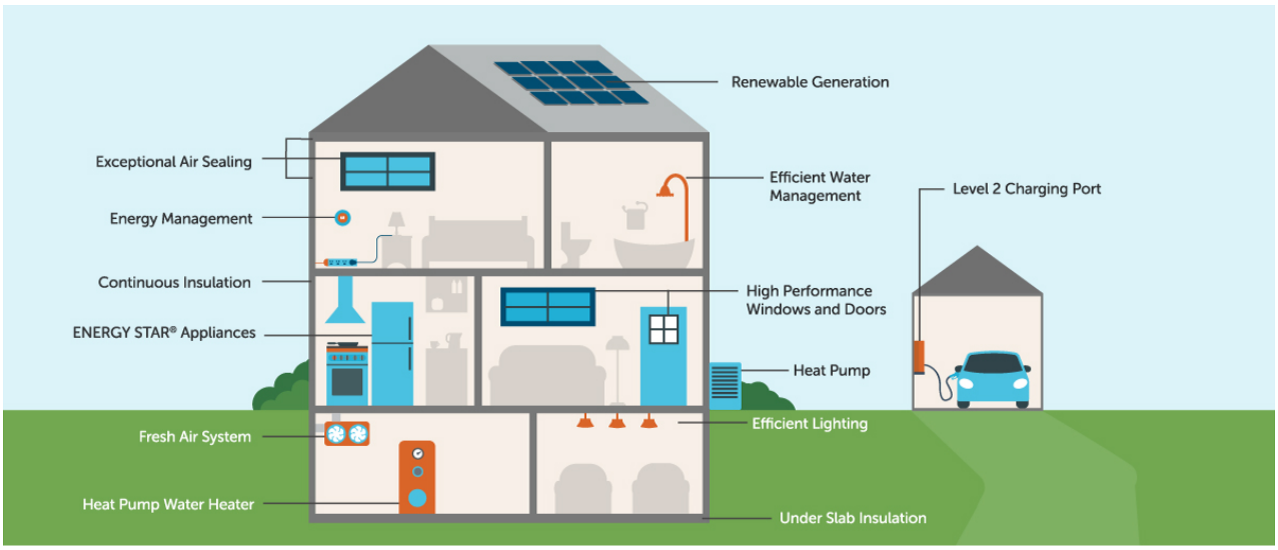


image / figure 2: System scope: building service system in an example zero-energy house

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

This project will focus on 1) how to facilitate co-performing among the building service system and multiple actors within a family; 2) how to enhance communication among family members on setting a comfortable indoor climate.
The scope:
The system scope refers to the building system with the core of in-house heat pump and heat recovery system which can automatically control the indoor climate and reduce energy consumption on an annual basis.
The key stakeholders in this project are the building system and each family members,who have different knowledge levels of technology, living together in a smart zero-energy house. The relevant stakeholders are the maintenance labour, the technicians, the system designers, the renovators, the neighbours.
The solution space:
An experience design for "post-occupancy" tailoring
Issues:
1) Inclusivity: The automated performance of the system depends on design assumptions (average behaviour data), which typically does not accommodate human diversity for simplicity, leading to the misfit of the system.
2) Usability: Limited touch points of interaction and control options make it difficult for residents to maintain control over complex and interdependent systems.
3) Accessibility: Due to the high learning cost and demand for behaviour adaptation, people with little knowledge of technology tend to avoid interaction with the system.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

This project aims to research on the active co-performing between multi-users and the building service system in "post-occupany" phase in a zero energy house. I hope to design to make all family members to actively involved in the cooperation with the system to enhance the bonds between family and the housing and within the family.

This project will focus on 1) how to facilitate co-performing among the building service system and multiple actors within a family; 2) how to enhance communication among family members on setting a comfortable indoor climate.

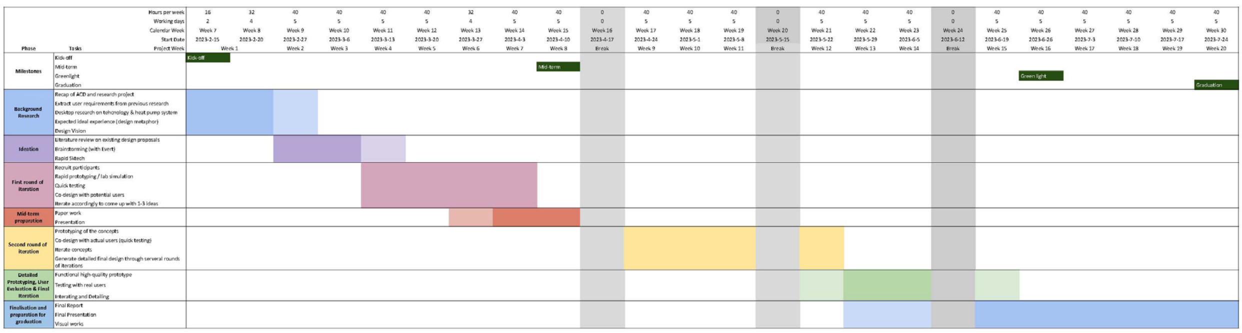
Design the "post-occupancy" tailored experience which can 1)smoothen the transition from renovation to post-occupancy by assisting households and the building service system in learning mutual expectations; 2) help the building service system actively involve multiple actors in co-performance to tailor the comfortable indoor climate.
The design will probably be a mixture but it will work in the "post-occupancy" phase within the house. The period "before renovation finished/ before moving into well-renovated house" will also be taken into consideration due to its strong link and high impact on "post-occupancy" experience.
In my expectation, before moving into the well-renovated house, it could be participatory design or service design to help the family learn about the system features and usage and also help the system to learn the family expectations on comfortable indoor climate in advance. In post-occupancy phase, I expect to do a "constellation" design to demonstrate suitable information in suitable ways for different individuals so that all the family members can be actively involved. Additionally, I also expect to design a "family agency" to work as a middle ground to actively participate in family decision on indoor climate. The output could be interface design or product design.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 15 - 2 - 2023

28 - 7 - 2023 end date



Kick-off meeting: 15/02
week1-2: background research
I will mainly look through all the materials I already have because I already took ACD and a research project on the same topic. I will also have some discussion with my client to learn about his expectations. I will conduct desktop research on technology and system. The output will be user requirements, design vision, my ideal experience, detailed system scope.
week3-4: ideation
I will do the brainstorming together with client and sketch out some rough ideas.
week5-8: first round of iteration
I will develop and iterate my ideas through rapid prototyping, lab study, co-design with actual users...The output will be 1-3 concepts.
Midterm: 10/04-14/04 (week 15 on calendar)
week9-12: Second round of iteration (involve actual users)
week12-16: Detailed Prototyping, User Evaluation & Final Iteration
Greenlight: 26/06-30/06 (Week 26 on calendar)
Gradaution: 24/07-28/07 (Week 30 on calendar)

TU Delft

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

During my bachelor, I first studied architecture and later transferred to industrial design because I found that what I am interested in is not architecture design itself but only the living experience and bond with home. Living in a smart sustainable house is an really attractive topic for me as it is a interdisciplinary design project.

I first worked on this topic during my ACD courses in year 1. I was really interested in discovering problems related to living experience and the interaction with building service system in the zero energy housing. However, due to the time limitation and course structure, I considered my ACD output was halfway to what I expected. Therefore, I decided to dive deep in this topic for my graduation. I also took a research elective in year2 on this topic to discover the effect of households' behaviour on indoor climate change in zero-energy housing, which help figure out some design opportunities for my graduation project.

Since I am a ipd student, I hope I can learn more about interaction and experience design, practicing some relevant skills. I also plan to do a phd later, thus I would like to learn more about the research methods and diverse user testing design. I am also curious about how to use the suitable evaluation tools to help a designer to make decisions rationally. I believe that my competence, such as sketch, prototyping, data analysis, qualitative research, gained from my previous experience, can help me the finish the graduation project perfectly.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Client is the IEBB consortium, https://www.tudelft.nl/urbanenergy/research/projects/iebb
IEBB Project 8.1, heatpump configurator, PhD candidate Evert van Beek.

Appendix B: Research elective report

Effect of residents' behaviour on indoor climate change in zero-energy housing

[ID550X Research Elective]

Name: Yichen Jin (Y.Jin-13@student.tudelft.nl)
Student Number: 5500648
Supervisor: Evert van Beek (E.vanBeek@tudelft.nl), Stella Boess (S.U.Boess@tudelft.nl)

Introduction

The smart home market is expected to grow rapidly because it is considered a key role in future energy transitions (Hargreaves et al., 2017). The impact of smart housing on energy consumption fundamentally relies on how they are used by occupants. However, living in a smart building can be full of conflicts from the perspective of residents, and its performance does not always align with what residents feel is appropriate and the expectation of sustainability (Hargreaves et al., 2017).

The automated indoor climate system performs based on design assumptions, referring to the average behaviour in the calculation of the energy performance coefficient (EPC), which was based on standardised occupancy and the characteristics of the building envelope and installations (Guerra-Santin et al., 2022). Moreover, smart automated technologies are intentionally designed to reduce residents' interaction with their homes (Harper-Slaboszewicz et al., 2012). However, the individual has different needs and preferences for a comfortable indoor climate so that automation cannot always meet users' intentions without friction (Guerra-Santin et al., 2022). Consequently, residents are unable to maintain control over complex and mutually interacting systems through limited touch points of interaction.

Instead of preventing conflicts and reducing interactions, shifting the focus of design to embodied learning in daily practice for both occupants and systems could be another perspective (Kuijer & Giaccardi, 2018). Co-performing with users can help the building service system improve the knowledge of residents and the quality of customised service experiences (Kim & Lim, 2019). Users' co-performing behaviour is found affected by the cognition of the relationship between humans and non-humans, iterative response experience, and the perception of the system's active learning (Kim & Lim, 2019). This research project focuses on how to realise the noticeable mutual response between humans and systems, contributing to Evert van Beek's study on the co-performance between residents and systems when living in a smart zero-energy house.

This research investigates the effect of residents' activities on indoor climate change, as well as potentially understandable ways for communicating indoor climate data with residents. The key aim is to identify design opportunities for enhancing mutual response between humans and systems. The detailed research questions are:1) Can the system notice the resident's daily activities through sensor data change? 2)How to communicate indoor climate change in an understandable way in residents? This paper focuses on the actual living experience in a zero-energy house in the Netherlands and highlights the data analysis of the relationship between occupants' behaviour data and indoor sensor data.

Method

Participating residents (pictures related to tech&pp)

The cases studied were two different sustainable houses in Delft. A single resident lives in case 1 house while a couple lives together in case 2 house. The reasons for dividing them into two different cases are the difference in the existence of independent rooms and housemates which may affect the routines and system performance largely.

Case 1 was a single-dweller resident living in a small studio with an area of 33.72 m^2, which has only one floor. The flat is a studio type, which means there are not any doors to divide the sitting room, kitchen and bedroom. The indoor climate system should be automatic and can be controlled by a portable thermostat. The heating system and the ventilation system were combined in case 1. Heating was realised by the warm airflow from the ventilation outlet on the ceiling. There is only one ventilation outlet in case 1 flat.

Case 2 was a couple living together in one house with an area of 84.8 m^2, which has two floors. The heating system is controlled by a thermostat installed on the ground floor. Heating is realised by radiators and each room has at least one radiator. The ventilation system consists of several ventilation outlets and two extractions in the kitchen and bathroom. All the outlets and exhausts are connected to each other and can be manually controlled by panels or automatically controlled by indoor sensors.

Data resources

All the data were collected by Evert van Beek in March and April 2022. A combination of a video-recorded home tour, including reenactments of interactions and daily routines, and a semi-structured interview were utilized in the collection of qualitative data.

All the indoor climate data was collected via an attachable integrated sensor box. The sensor data includes the temperature (℃), humidity (%), light (lux), motion, CO_2 level (ppm). It detects the environment every 5 minutes. The light is detected by the photosensitive component, referring to the room brightness. The motion data changes when the user passes by the sensor box. The more times the user passes by within 5 minutes, the higher the detected number is. The behaviour data is collected through a QR code reflection system. Users can scan the physical QR code tags attached to key elements, such as thermostats, windows, and ventilation control panels, every time they interact with them, to record their behaviour and report their intentions.

Analysis Approach

1. ***Literature Review:***

   The literature review was conducted to understand the background situation, existing problems and design opportunities related to the living experience in a sustainable smart home.

2. ***Behavioural analysis:***

   An examination of the daily routine, personal habits, and indoor climate preferences of residents were conducted through the integrated analysis of behaviour data, home walkthrough data, and interview data. This was conducted case by case. The consequence is demonstrated in the form of a dynamic floorplan and a corresponding timeline, aiming to straightforwardly provide an overview of the frequency of interaction with different key elements and the habitual time of interaction with some specific devices at home. It is expected to extract meaningful stories through this analysis approach.

3. ***Sensor Data analysis:***

   Data analysis was conducted based on the sensor dataset. The dataset was classified into the “weekday” category and the “weekend” category to figure out how the difference in residents’ activities on weekdays and weekends affected the indoor climate change differently. The analysis focused on the change of a single variable according to time, shown in the form of a data dashboard for the researcher to track details. The comparison between sensor data and external weather was also conducted to figure out how external factors affected indoor climate change.

4. ***Triangulation:***

   Triangulation involves the use of different methods of data collection to analyze the results of the same study. Case-by-case data analysis on the change of sensor data according to the behaviour data was conducted to figure out whether there is any regular relationship between users’ interaction with key elements and the change in indoor temperature, humidity, CO2 level. The change of motion data was also paid attention, to validate whether it can reflect users’ indoor activities or walking paths.

5. ***Follow-up interview:***

   This aims to figure out the intentions behind specific user interactions with each element, trying to explore the potential link between user intentions and sensor data change. All the data visualisation diagrams will be demonstrated to participants to see 1) whether they can understand the information; 2) which kind of information is more interesting to them; 3） how will they respond to them. Additionally, it is for participants to double-check whether their behaviour data is correct, which is collected through QR code scanning.

Result

This section shows the detailed analysis process and objective results case by case. In each case, it demonstrates the resident's behaviour analysis first then the sensor data analysis and in the end the triangulated analysis of these two. The result presented here aims to answer the research questions: 1) Can the system notice the resident's daily activities through sensor data change? How do I collect the data? More focus was put on the first question.

Case 1: single occupants

Behaviour analysis

All the pictures in this section were made through Illustrator. All the behaviour data is reported by the resident who scanned the QR codes attached to different subsystems to record their use.

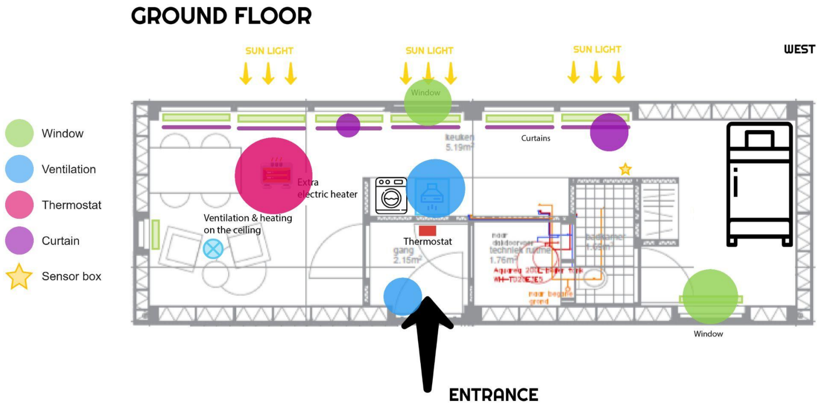


Figure 1: GV1 interaction frequency and location of key elements

Figure 1 shows the overview of the apartment and the locations of key elements in the system in the form of a floor plan. Different colour represents interacting with subsystems and the size of circles represents the frequency of interaction. The resident prefers to open the window in the bedroom over the larger one in the kitchen.

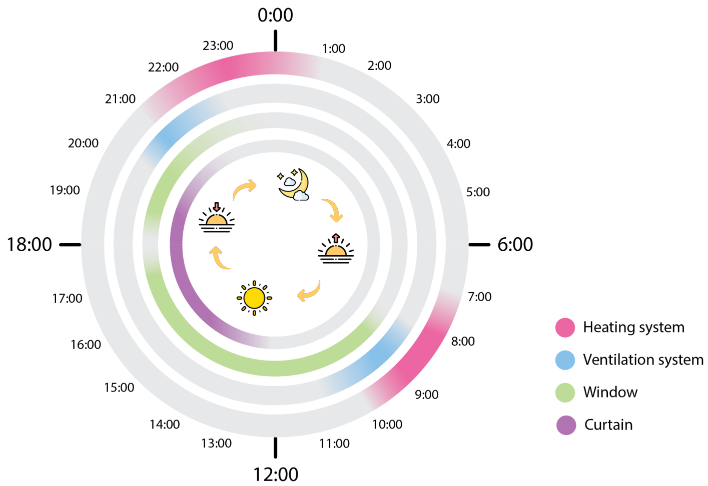


Figure 2: GV1 frequent use period of key elements

Figure 2 demonstrates the period when the key elements are in use. The colourful segments indicate different elements are in the status of "ON" or "OPEN", while the grey segments represent the status of "OFF" or "CLOSED". The gradient indicates the certainty of the status. The more solid the colour is, the more data of "turning on" or "open" was collected.

Through the analysis of behaviour data, collected through QR codes, resident routines and personal living habits are discovered, which are also reflected in interview data. It is found that the resident interacted with the portable electric heater most frequently because the system is not powerful enough to provide a comfortable stable indoor temperature. He believes the system should operate automatically so that he never touched the thermostat. From Figure 2, we can see that GV1 resident has the habit of turning on the heater for around an hour before sleep at night (23:00-00:00) and turning on the heater for around 2 hours after waking up but before leaving the room in the morning (7:30-9:30). Residents mentioned that he normally left the bedroom window open during the daylight when he is not at home. To cool down the room and refresh the air, he usually opened windows in the morning and evening upon returning, sometimes even keeping the door open. The user usually interacts with the ventilation in the kitchen in the morning or at night for cooking. According to the interview and behaviour data, usually, it takes half an hour for cooking breakfast and he didn't have lunch at home on weekdays. The resident reflected that he pulled the curtain up to let more sunlight in considering the health of his plants and prefers the one next to the bed for convenience. According to Figure 2, he usually pulled them up in the afternoon or early evening instead of in the morning. Additionally, Figure 2 indicates the existence of two dense periods of interacting with all elements: 7:30-9:30 in the morning and 21:00-23:00 at night.

Data dashboard

All the figures in this section were generated by the R programme. The data on indoor temperature, humidity, CO2 level, motion and light were collected through the installed sensor box. The behaviour data, which usually is represented by coloured dots, was collected through residents scanning the QR codes and recording their interactions.

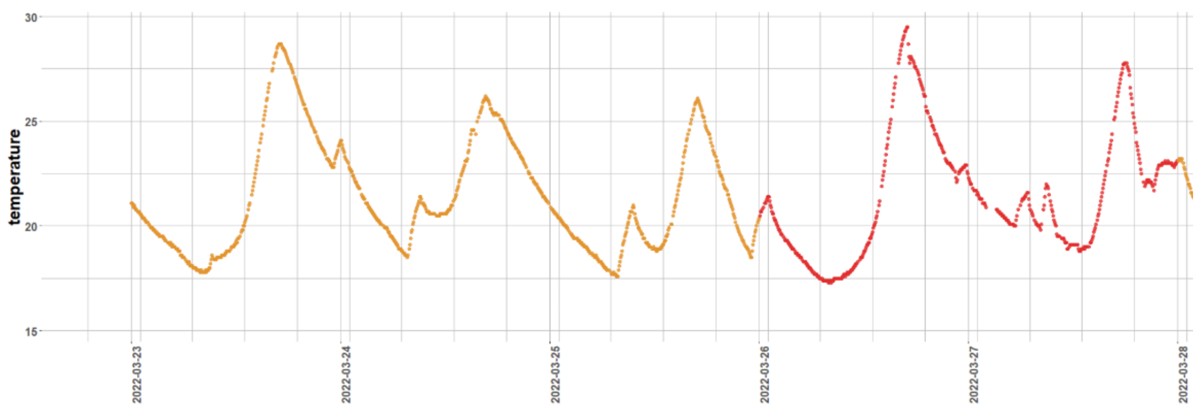


Figure 3: GV1 03/23- 03/27 indoor temperature change

Figure 3 shows the change in indoor temperature according to time. Orange represents the weekday period, while red represents the weekend period. It is reflected that the daily indoor temperature difference is larger than 7 ℃, and the highest temperature difference can reach 12 ℃, indicating that the room cannot keep a stable temperature under the cooperation of the building service system and user behaviour.

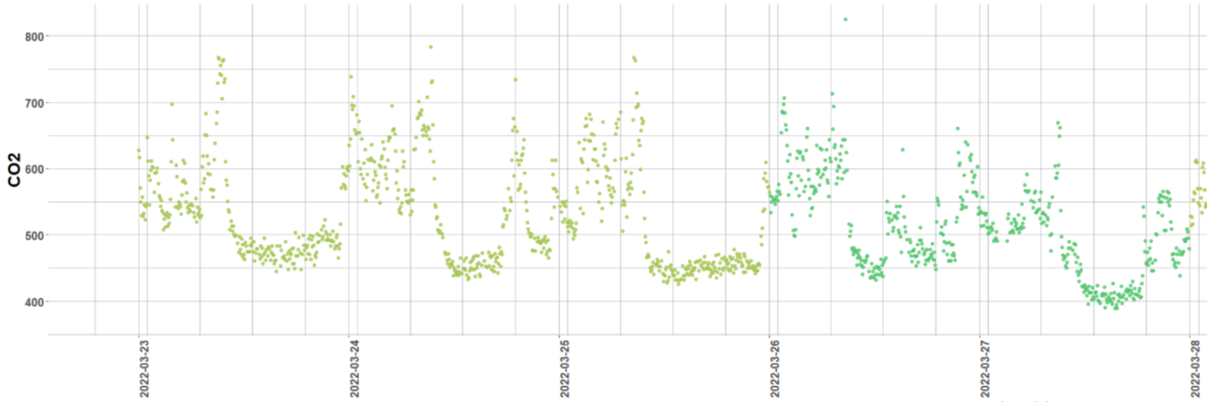


Figure 4: GV1 03/23- 03/27 indoor CO2 level change

Figure 4 shows the change in indoor CO2 level, in which light green represents the weekday period, while dark green represents the weekend period. There exists a repetitive U-shape pattern in daily CO2 level. It usually reaches the peak in the morning after the resident wakes up (8:00-10:00) and then decreases rapidly until the CO2 level gets close to the external environment. The CO2 level gradually increases during the night. This U-shape pattern actually reflects the user behaviour of keeping the window open during daylight well.

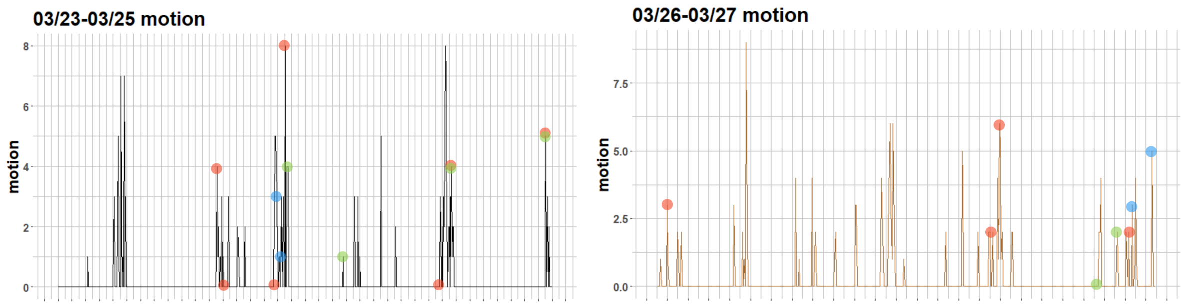


Figure 5: GV1 03/23- 03/27 motion data change

In Figure 5, the value means the times that the user passes by the sensor box within a certain period, which can represent the activeness of the user to some extent. The black represents the weekday period, while the brown represents the weekend period. The different distribution of data during weekdays and weekends can indicate the different indoor activities. The dots in different colours represent interactions with different subsystems which residents themselves recorded through scanning the attached QR codes. Red dots mean interacting with the heating system; blue dots mean interacting with the ventilation system; green dots mean interacting with windows. From the overlap, it is found that motion data can reflect interaction with subsystems well, indicating the capability of the system to detect some indoor activities.

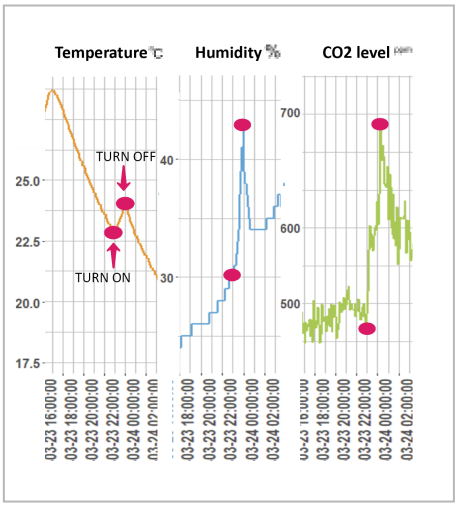


Figure 6: GV1 Effect of using heater

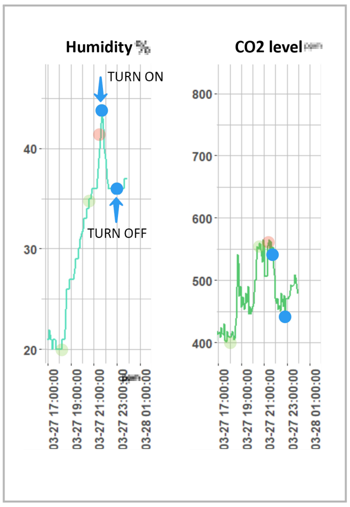


Figure 7: GV1 Effect of using ventilation

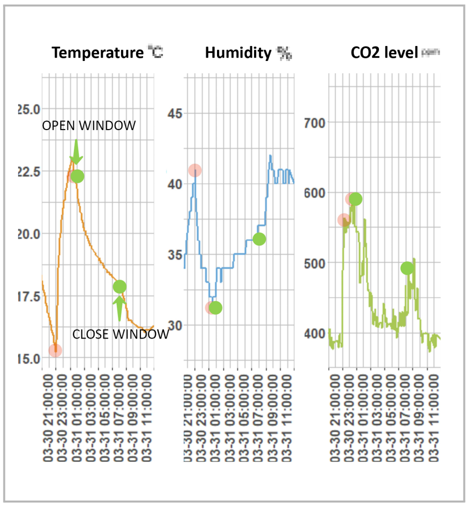


Figure 8: GV1 Effect of opening window

Figure 6,7,8 aim to figure out the capability of the system to notice the resident's indoor activities through triangulated analysis. Figure 6 shows the change in indoor temperature, humidity and CO2 level in the same period respectively caused by the use of the electrical heater. The red dots represent the interactions with the heater which are reported by the resident through scanning the physical QR code attached to the heater. Normally, as reflected in Figure 6, turning on the heater can lead to a rise in room temperature, humidity, and CO2 levels. The increase in humidity is blame to the habits that the resident in case 1 usually hangs on the wet clothes close to the heater. Since the resident stayed at home during that period, the rise in CO2 levels should be caused by the use of the heater. Using the blue dots to represent interaction with the ventilation system, Figure 7 shows the consequent change in indoor humidity and CO2 level in the same period of time. It is found that the use of the ventilation system can lead to a drop in both indoor humidity and the CO2 level. The green dot in Figure 8 indicates the actions of opening or closing the window. Through comparison analysis to outdoor weather change (*Weerstatistieken KNMI - Actuele Weergegevens*, n.d.), when the window was open in March, the room temperature and the indoor CO2 level decreased, while the humidity increased, getting close to the external weather conditions. The outdoor humidity also depends on the outdoor temperature and weather conditions.

Follow-up Interview

The follow-up interview also works as a trial of exploring "how to communicate indoor climate change in an understandable way?". The diagrams of behaviour analysis (Figure 1 and Figure 2) are easy for residents to understand, while the data dashboard with condensed information takes more time to react. When showing all the visuals to the participant, he showed more interest in CO2 data compared with temperature and humidity data, because he cannot feel whether the CO2 level is in a comfortable range. During this interview, the resident reflected that he usually cooks only twice a day, in the morning and in the evening, which corresponds to the use period of ventilation in the kitchen shown in Figure 2. He said that usually he hangs up the clothes on the rack indoors in winter and turns on the heater for a quicker drying process, which is partly reflected by the rise of humidity data when turning on the heater (Figure 6). He mentioned that he prefers the bedroom cooler than the living room, which can be reflected by the relatively far location of the heater (Figure 1) and the preference for opening the bedroom window (Figure 1). Additionally, He mentioned a preference for more fresh air when sleeping, which is another reason for opening the window in the bedroom more often (Figure 1). The resident considered that keeping all the windows closed means no circulation and no fresh air even though he cannot really feel the circulation. Keeping the window open during daylight when he is not at home was considered as a preparation for a comfortable indoor climate when he is back home. Regarding the adjustment of room temperature and humidity, the resident stated that he usually do it depending on his feeling instead of the statistics displayed in the thermostat. That’s one reason for no interaction with the thermostat, which makes thermostats unable to notice the resident behaviour of regulating the temperature in other ways.

Case 2: couple occupants

Behaviour analysis

All the pictures in this section were made through Illustrator. All the behaviour data is reported by the residents who scanned the QR codes attached to different subsystems to record their use. Also, they clarified which family member scanned the QR code by filling in their names. Thus, we can do the analysis of the woman's using habits and the man's using habits separately for comparison.

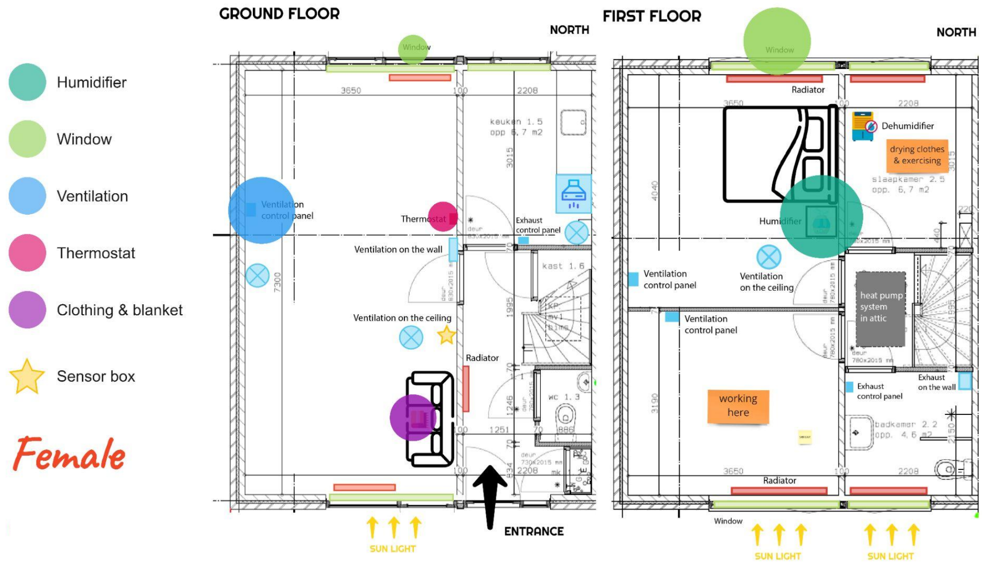


Figure 9: The woman's use of the indoor climate system in the GV2 house

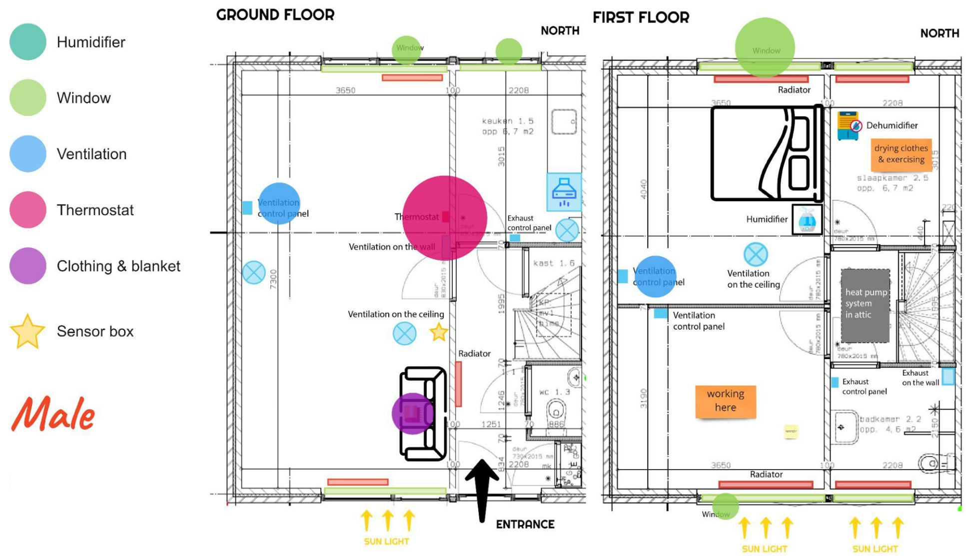


Figure 10: The man's use of the indoor climate system in the GV2 house

Figure 9 and 10 show the overview of the house and the locations of key elements in the system in the form of a floor plan. The difference between Figure 9 and 10 indicates different behaviour patterns between the woman and man who live together in the same house. Different colour represents interacting with different subsystems and the size of circles represents the frequency of interaction.

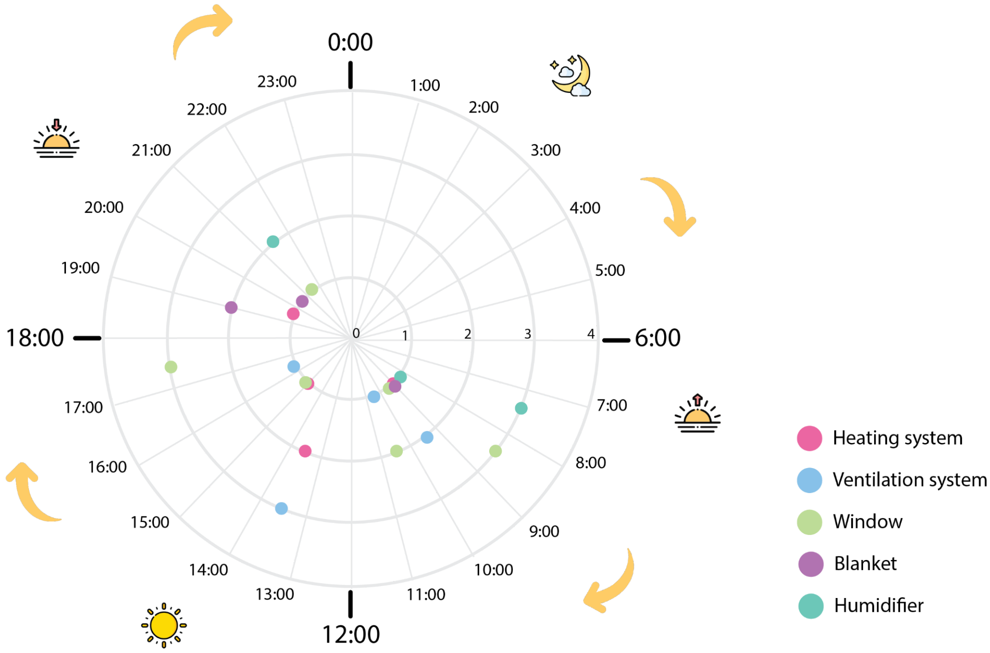


Figure 11: GV2 interaction frequency of key elements

Figure 11 demonstrates the frequency of interacting with different elements at different times. The frequency was reflected by how many times occupants scanned the QR code. The figure here is slightly different from Figure 2 because the occupants in this case did not record whether they are turning on or off the subsystems. Thus it is impossible to mark the working period of each subsystem. However, the interaction recording is also valuable for further analysis. Two residents' behaviour was analysed together here because more focus is put on the human input change for the whole building service system.

Comparing Figure 9 and Figure 10, it is found that the male occupant took the main duty to interact with the thermostat, while the female seldom touched it. Usually, they set the room temperature between 19 ℃ and 21.5℃. From, figure 11, The common periods of interacting with thermostat were in the afternoon (13:00 -15:00). From the interview, it is reflected that the radiators in the bedroom (due to noise), laundry room and bathroom (warm enough) were kept off. The female stated that the radiator on the porch usually is on because they consider the entrance an important place and would like to feel warm once back home. Another point they mentioned in interview was that they used to put on more clothes and set the room temperature to around 18 ℃ in the previous house. Currently, they still have the habit of leaving a blanket on the sofa and they usually use the blanket in the evening (19:00 -21:00) depending on their evening activities (Figure 11).

There existed some communication between husband and wife on ventilation. The male resident would like to play more with it while the female prefers not to use it due to the noise. Usually, he interacted with the ventilation control panel in the bedroom in the morning (9:00-10:00), because he felt stuffy when waking up. Additionally, he stated that he prefers to set the ventilation to the highest operation speed and open the window meanwhile for instant feedback when he feels stuffy. The ventilation in the bathroom and kitchen was seldom used because they experienced that they can cause the air with terrible scent to circulate around the whole house. Apart from interaction with ventilation, both of them have the habit to open the window in the bedroom when waking up

(8:00-9:00), which, for them, indicates the start of a new day and the connection to the outside world. The female sometimes closed the window in the bedroom in the late afternoon (17:00 -18:00). As for humidity control, the female resident took the main duty to control the independent humidifier they bought for the bedroom due to living history in a humid house. From Figure 11, it is found that she usually interacted with the humidifier in the morning (7:00 - 8:00) and at night (21:00 - 22:00). They also bought an independent dehumidifier in the laundry room to make the clothes dry in around 2 hours. As for routine, the male resident also mentioned that he usually works at home at least 3 days a week, which is reflected by more interaction with the system during 13:00-15:00. Figure 11 reflects that the most frequent interaction periods are 8:00 - 10:00 and 19:30 - 21:30.

Data dashboard

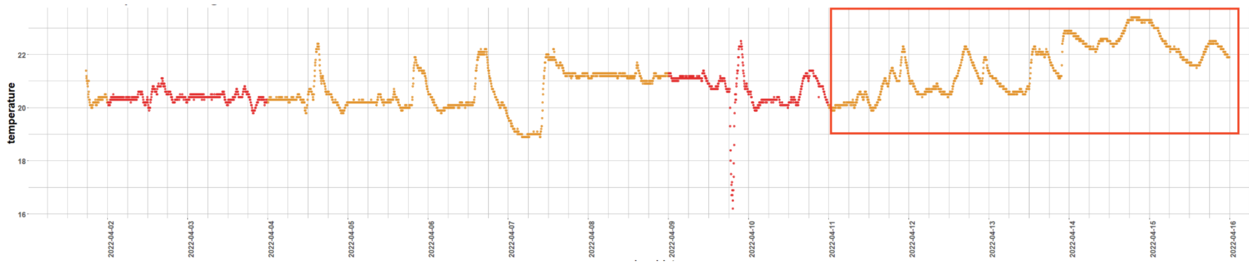


Figure 12: GV2 04/01-04/15 indoor temperature change

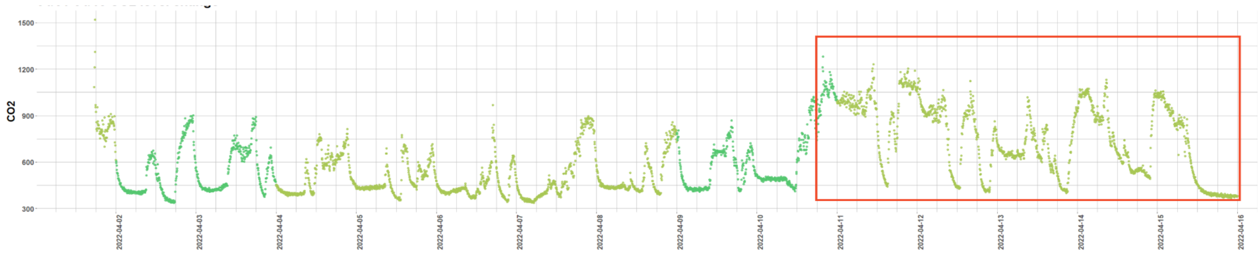


Figure 13: GV2 04/01-04/15 indoor CO2 level change

In Figure 12, the red line shows the room temperature during weekends while the orange line shows that during weekdays. Figure 13 uses dark green and light green to demonstrate the CO2 level during weekends and weekdays respectively. The red box highlights the special period when some guests visited and lived in their living room. It is found that the occurrence of visitors, which means a sudden increase in the number of residents, can lead to an obvious rise in the overall level of CO2 and temperature (Figure 12&13).

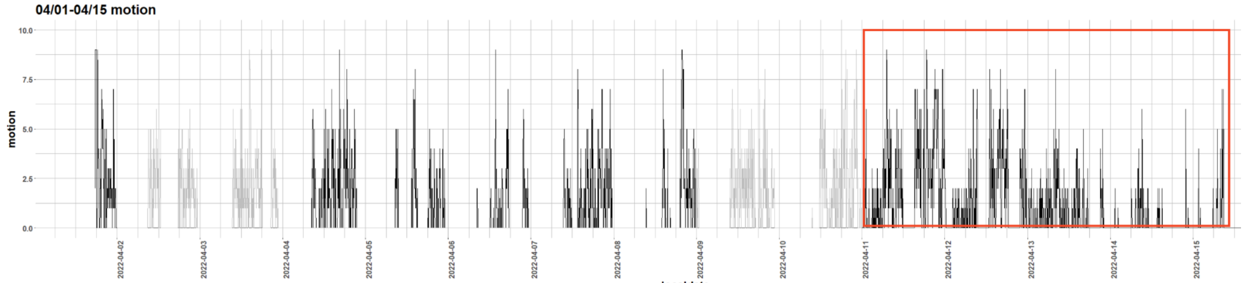


Figure 14: GV2 04/01-04/15 indoor motion data

The high density of motion data indicates that they often work at home (figure 14). The red box emphasizes the period of guest living, which can be reflected by the higher density of motion data.

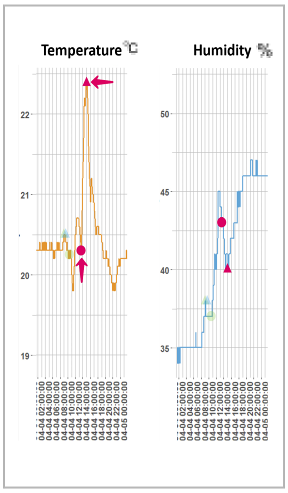


Figure 15: GV2 Effect of thermostat

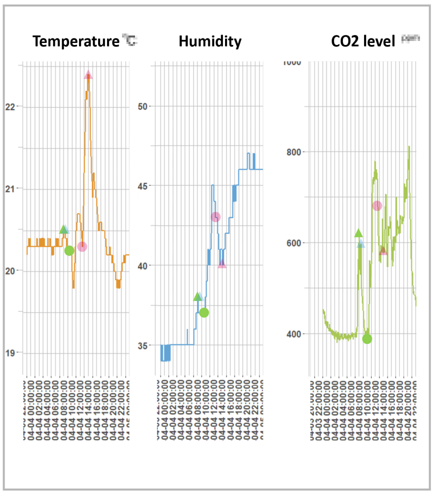


Figure 16: GV2 Effect of window

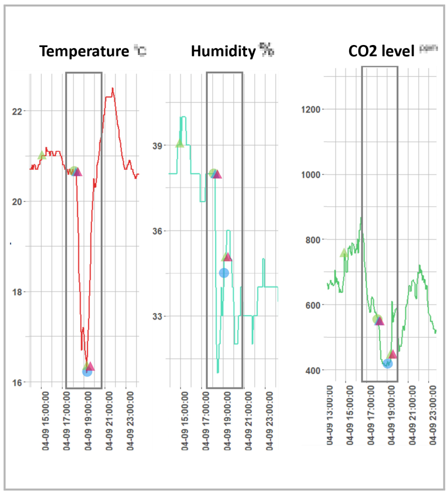


Figure 17: GV2 Effect of shutting down the system

The red dots in Figure 15 indicates the interaction with the thermostat, which can lead to an obvious change in temperature. If the action causes an increase in room temperature, then the humidity will drop correspondingly. Figure 16 shows the change in indoor climate when interacting with the window (green dot). If the temperature grows up after the interaction with the window, the humidity and CO2 level will also increase at the same time. The operation of the ventilation system in case 2 can also be automatically adjusted by the internal sensors within the building service system, which means the specific user interaction with the ventilations cannot be reflected on the change of data collected by researchers. Apart from this, the use of an independent humidifier they bought cannot be reflected on the detected humidity data because the humidifier was in the bedroom on the first floor while the sensor box was installed in the living room on the ground floor. The grey box in Figure 17 highlights the rapid indoor climate change caused by occupants' shutting down all the subsystems because they were going outside with their visitors.

Discussion

The purpose of the research is to investigate the impacts of residents' activities on indoor climate change, as well as the design opportunities for enhancing mutual response between humans and systems. Here we discuss: 1) Can the system notice the resident's daily activities through sensor data change? 2)How to communicate indoor climate in an understandable way to residents?

Key insights

Through data analysis, it is found that the building service system can notice the interactions with key elements, such as the heating system and ventilation system since they can result in obvious changes in sensor data. For example, Figure 7 shows that the use of the ventilation system can lead to a drop in both indoor humidity and CO2 level. Additionally, the system can notice households' regular routines because it can cause repetitive patterns in sensor data change. Via comparison, the system can detect unregular activities, such as turning on the heater at midnight or guest visiting, since these will cause unusual fluctuations in sensor data. The interference of the system's automatic operation, like shutting down the heating and ventilation system (Figure 17), can also be identified through the rapid change in indoor climate data, which is getting close to the external weather.

However, there is no fixed relationship between a single interaction with one subsystem and the sensor data because the change in indoor climate depends on diverse factors. In reality, diverse subsystems, such as heating or ventilation, mutually influence performance, resulting in the change of several parameters of indoor climate at the same time. Therefore, it is hard to tell which fluctuation in sensor data is caused by a specific interaction with one subsystem. Secondly, the difference in personal living habits will also affect the change of indoor climate data under the same interaction with the same subsystem. In case 1, it is found that turning on the heater leads to an increase in humidity while the relationship becomes the opposite in case 2. This is blame to the habit that the resident in case 1 usually hangs on the wet clothes close to the heater. Thirdly, the automation level of the building service system also differs. In case 2, the ventilation system also adjusts itself automatically through sensors within the system installed in each room. Therefore, residents' input cannot be well reflected in the indoor climate data change.

Furthermore, zero-energy housing not only can notice the resident's activities but also can build habits together with users. According to behaviour analysis, the house layout design, including which direction the rooms face, the walking path design and the division of rooms, will affect their interaction time and frequency with different key elements in the zero energy house. In case 1, the resident prefers to pull the curtains up in the afternoon instead of in the morning probably because most windows of his house face west and receive more sunlight in the afternoon. In both cases, the window in the bedroom is the one that residents interact with the most, which could be attributed to its easiest access during the morning routine. The residents' expectation on the indoor climate varies depending on the functions of rooms. Different expectations on indoor climate lead to different interactive hebaviour. In case 1, it is mentioned that the resident prefers a cooler environment and more fresh air for sleep, leading to more interaction with the bedroom window. In case 2, the use of an extra humidifier in the bedroom and the use of an extra dehumidifier in the laundry room could be another indication.

Design opportunities

Build occupants' expectations and intentions together - co-learning

From research, the house layout design and the individual difference build together the resident's intentions and the corresponding interactions. In case 2, it is found that living history affects residents' perception of a comfortable indoor climate. According to Kalmár (2016), living history affects occupants' thermal sensation and satisfaction level of indoor air freshness. Additionally, individual differences, such as body mass index, gender and age also affect the expectations on indoor climate (Fadeyi, 2014). Additionally, personal expectations on the home experience also shape user behaviour. For example, residents in case 2 keep the radiator on the porch on because they would like to feel the warmth once back home. Secondly, it is discovered that the residents' intentions and interactions with the indoor climate system are shaped by the house layout and the functional division of rooms. Additionally, personal expectations on the home experience also shape user behaviour. For example, residents in case 2 keep the radiator on the porch on because they would like to feel the warmth once back home. Therefore, designing channels for the users and the system to express their personal features or habits before or after moving into the new house would be a good opportunity. The residents can learn about the house design and system features while the system can learn the individual expectations on indoor climate and home experience. Thus, they can build the expectation of the comfortable indoor climate together, consequently building user behaviour together.

Information hierarchy design for accessibility - "constellation" metaphor

In case 2, it is reflected that According to the case 1 follow-up interview, it is found that users are only interested in part of the system data, instead of getting access to all the detailed information.

Additionally, the amount of information and the visualisation level of data which are exposed to users, affect the learning cost. Therefore, information hierarchy design, which refers to demonstrating suitable information in suitable ways for different individuals, could be a potential solution to improve the inclusivity of the system. The building service system can be considered a “constellation”, while diverse elements within the system can be considered “stars with a constellation” (Coulton & Lindley, 2019). Each element in a “constellation” works both independently and interdependently. A constellation's appearance varies depending on the observer's perspective (Coulton & Lindley, 2019). In zero-energy housing, people with different culture and technology backgrounds are able to access different scopes of the system and interpret them variably. Consequently, all of them are actively involved in the mutual response between humans and non-humans.

Middle ground design for multi-occupants scenario

In case 2, we noticed that there exists a duty division related to controlling the system due to the knowledge and interest differences in this high-tech, complex system. Additionally, some conflicts sometimes happen within the family caused by different expectations regarding the performance of the systems and the comfortable indoor climate. The family decision-making experience could be a special entry point for improving the co-performing between the system and occupants in the multi-user scenario. Furthermore, it is reported that some people place more importance on the comfort of certain others, such as babies, than on their own comfort and some people are in higher possibility to compromise their comfort when they consider it as a luxury (Huang et al., 2017). Designing a middle ground or a reference “person” could be a solution to facilitate the communication between the system and multi-users and within the family about indoor climate control (Huang et al., 2017).

Limitations

Since the participants may not record all the interactions, the collection process of behaviour data through manually scanning the QR code may not be that reliable. Additionally, they sometimes did not record whether they were turning on or off, which also adds difficulty to the analysis. The fixed location of the sensor box also could be another limitation during data collection. In case 2, the sensor box was on the ground floor but the humidifier was on the first floor, thus we cannot figure out the effect of using the humidifier on the sensor data change. Secondly, it is hard to control variables due to the complexity and interdependency among subsystems. Therefore, we failed to figure out a fixed relationship between a single variable and a specific interaction. Thirdly, the change in external weather will affect the system performance, user expectations and user behaviour. All the data was collected in March and April, which is not the most pressure period for the building service system. The number of interactions and the use of external devices during this period suppose to be lower than those in winter or in summer. In case 1, it is stated that he usually hangs on wet clothes outside in summer, but hangs on them indoors in the winter, which correspondingly affects the user interactions with the system and the indoor climate. Apart from this, the small sample size may affect the reliability of the results.

Conclusion

With this paper, we hope to have contributed to the investigation of the impacts of residents' activities on indoor climate change and design opportunities for enhancing mutual response between humans and systems. The qualitative analysis of two typical cases revealed whether and to what extent the system can notice the resident's daily activities through sensor data change. We have argued some potential design opportunities for enhancing the co-performing between residents and the building service system.

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Appendix C: Consent form & HREC approval

Technische Universiteit Delft would like to do research on your renovated home
Information sheet

We're trying to understand how you use your home, will you participate?

Technische Universiteit Delft, with funding from RVO, is doing research to make your and other people's homes usable, comfortable, healthy and energy efficient.

Do you want to participate? This is what that means:

- We will ask you to give a guided tour of your home to show us how you use your home. We will record this guided tour with a video camera.
- In an interview of about 1-2 hours, we will discuss how you use your home right now and how the family discussions related to indoor climate setting happen.
- You will then participate in a series of small testings which simulates the new system in a zero-energy house. You will then receive several questions and write down your answers without discussion.
- A pair of households needs to be present for these activities.

Important to know:

How do I participate?

- We plan the activities together with you.
- You are not obliged to participate, or to answer all questions.
- You can always withdraw from this research by contacting me (see my details below). You do not have to give any reason. We will then remove the sensors, and erase the data at your request.

What happens to the data from this research?

- We will use the data and information gathered within this research to improve technologies and renovation processes for comfortable and sustainable living.
- We will use this data for:
  - Communication within the research team
  - Academic publications
  - Publications related to the research project
  - Further research
- The data from this research will be stored safely at TU Delft, where nobody but the involved researchers will have access to your personal details.

- We only use your personal details (like name, address, phone number) for staying in contact. These personal details will be erased at the end of the research project. Besides from this, you will not be identified by name or address. Instead you will receive a unique participant number. Data, quotes and images will only be linked to this participant number.
- We will anonymize all data (including photos and videos) by removing personal details, before publication or sharing outside the research team.
- Anonymized data, not containing any personal details, will be stored safely for 10 years at TU Delft for possible further research.
- With your consent, anonymized data will be archived in a public location (*4TU.Research.Data*) for further research.
- As a participant in this research you have the right to request access to, and rectify or erase your personal data.

Questions, comments or complaints?
Yichen Jin
Y.Jin-13@student.tudelft.nl
0682582084

Consent form for research on your renovated home

Please tick the appropriate boxes

Taking part in the study	Yes	No
I have read and understood the information in the information sheet above, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.		
I consent voluntarily to be a participant in this study and I understand that I can refuse to answer questions, and withdraw from the study at any time, without having to give a reason.		
I understand that taking part in the study involves a video-recorded guided tour, a video-recorded interview, the installation of small measuring boxes in my home, recording some insights on leaflets.		
I understand that data about what happens in my home will be collected with the measuring boxes and from the heat pump installation during the research.		
I understand that I can indicate in which rooms in my house, measuring boxes should not be installed.		
I understand that information I provide will be only be used for the purposes stated in the information sheet.		
I understand that personal information collected about me that can identify me, such as pictures of my face, my name or where I live, will not be shared beyond the research team.		
I agree to joint copyright of the information documented on the leaflets to the researcher.		
[Optional] I agree that what I say can be quoted in research outputs.		
[Optional] I give permission for the data that I provide to be archived without personal details in *4TU.Research.Data* so it can be used for future research and learning.		
I understand that the measuring boxes are a property of TU Delft. I will treat them appropriately.		

Signatures

________________________ ________________________ _________

Name of participant [printed] Signature Date

I have witnessed the accurate reading of the consent form with the potential participant and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

________________________ ________________________ _________

Name of witness [printed] Signature Date

Date 26-May-2023
Contact person Grace van Arkel, Policy Advisor
Academic Integrity
E-mail E.G.vanArkel@tudelft.nl

Delft University of Technology

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The Netherlands

Ethics Approval Application: Tailored family living experience in zero-energy housing
Applicant: Jin, Yichen

Dear Yichen Jin,

It is a pleasure to inform you that your application mentioned above has been approved.

Thanks very much for your submission to the HREC which has been conditionally approved. Please note that this approval is subject to your ensuring that the following condition/s is/are fulfilled:
- it should be mentioned more explicitly that photos of a participant's house will be made public

In addition to any specific conditions or notes, the HREC provides the following standard advice to all applicants:

- In light of recent tax changes, we advise that you confirm any proposed remuneration of research subjects with your faculty contract manager before going ahead.
- Please make sure when you carry out your research that you confirm contemporary covid protocols with your faculty HSE advisor, and that ongoing covid risks and precautions are flagged in the informed consent - with particular attention to this where there are physically vulnerable (eg: elderly or with underlying conditions) participants involved.
- Our default advice is not to publish transcripts or transcript summaries, but to retain these privately for specific purposes/checking; and if they are to be made public then only if fully anonymised and the transcript/summary itself approved by participants for specific purpose.
- Where there are collaborating (including funding) partners, appropriate formal agreements including clarity on responsibilities, including data ownership, responsibilities and access, should be in place and that relevant aspects of such agreements (such as access to raw or other data) are clear in the Informed Consent.

Good luck with your research!

Sincerely,

Dr. Ir. U. Pesch
Chair HREC
Faculty of Technology, Policy and Management

Appendix D: Research plan of ethnographic study

Research Plan (qualitative research)

Unstructured interviews + "stimulation recall" in the first part(prompt participants concerning specific events + "simulation response" in the second part (presents hypothetical situations to obtain responses)

https://writing.colostate.edu/guides/guide.cfm?guideid=63

Research Aim & Questions

Key aims

- Identify typical “crisis in routines”
- Figure out how the diversity within the family and the family relationship affect households’ understanding and reaction to the “crisis in routines”.

Research Questions

1. How does each family member perceive/ understand "crisis"?
2. When facing "crisis", how does each family member do/ respond?
3. When having different reactions towards "crisis", how do they communicate and make decisions?

Method

Participants

- couples to take part in the workshop together
- living together in the same house.
- No need to live in a zero-energy house; but live in NL

Stimuli

- go to the participants’ house
- hot water bottle with a cover, a cushion with cover, a box to simulate the effect of old radiator and the effect of new heat pump heating system
- sound from a speaker and the fan to simulate the new ventilation system

A. hot water bottle without a cover: old radiator (itself hotter; radiate the heat quicker)
B. hot water bottle with a cover: new radiator (lower temperature; heat up room slower)

The empty box and the empty cushion cover simulates the current house. (no insulation)

The empty box and the cushion simulates the new house with good insulations.

Putting A or B into the cushion cover and close the box for a while simulates turning on the radiator and heat up the room.
Remove A or B and close the box for a while simulates turning off the radiator and the cooling down the room.

Apparatus

- A camera: to capture images during the tests.
- An interview script

Script Design (Procedure)

Introduce their house and life:

a. current heating system

   i. what's your current heating system? can you show us? any features?

   ii. what's your current room temperature? how do you know that?

   iii. How do you know it is working? (interaction feedback/ operation information/ room status)? the thermostat display? the haptic? the body feeling?

   iv. usually, when will you interact with it? (within a day/week/year) **for what reason to interact?** (humidity/ air quality/ smell) frequency of interaction?

   v. How do you control it? any personal preferences? **why?** -> try to figure out a typical scenario, better for later imagination

   vi. when living together with your girlfriend: who controls it more often? any communication on the temperature setting? different preference on temperature? home wear different?

   vii. if you are living together now and need to pay for the bill euqally: how will you reach an agreement on temperature setting in the shared area? what will you do? just change it and believe others will also change? any communication? any fixed settings?

b. current ventilation system (including window)

   i. what's your current ventilation system? can you show us? (normal & bathroom exhaust & window) any features?

   ii. usually, when will you interact with it? (day/week/year) **for what reason to interact?** (humidity/ air quality/ smell) frequency of interaction?

   iii. How do you control it? any personal preferences?

   iv. How do you know it is working? feeling/ any display? scent? airflow? temperature? dry? sound?

   v. when living together with your girlfriend: who controls it more often? any communication on the setting? different preference? different understanding of the role?

   vi. if you are living together now and need to pay for the bill equally: how will you reach an agreement on ventilation setting in the shared area?

what will you do? just change it and believe others will also change? any communication? any fixed settings? window more? less?

current warm water supply system

vii. what's your current warm water supply system (at home, not student apartment? do you know it?

viii. usually, when will you interact with it? (day/week/year) **why?**

ix. How do you control it? frequency of interaction? any personal preference settings?

x. when living together with your girlfriend: who needs more hot water? who washes the dishes more? shower habits different?

xi. if you are living together now and need to pay for the bill equally: how will you reach an agreement on the use of hot water? what will you do? any communication? any fixed planning?

heating conflicts: imagine roommates

- ask them respectively about what they discover about the difference between A and B. How do they understand it? why? (ask them to write down respectively)
    1. what do you feel (individual)? (discover difference)
    2. imagine it is the actual living room…
    3. How do they understand the difference? it represents what? why do you think like this?
    4. compare your answer, how to come to an agreement?
- imagine under a typical scenario they mentioned before, if they now live in a zero-energy house with such a heating system, how will they respond to different system features? why? (write down respectively)
    5. what participants found challenging about living with these technologies?
    6. how will they respond to it? why?
    7. will you keep your habits? will you buy new stuff? will you change your behaviour? how to solve/ adapt to the new style?
- compare their understanding and response, if there is a difference, ask them to discuss and make a family decision (observe the process) and why they finally get this agreement.

ventilation conflicts:

i. ask them respectively about what they feel, what they discover and how they understand it and why (ask them to write down respectively)

   1. what do you feel/hear?
   2. imagine in the actual living room….
   3. can you notice it is working? will you keep it on?
   4. what do you think about this and the window? (the role for you)
   5. compare your answer, how to come to an agreement?

ii. imagine under a typical scenario they mentioned before, if they now live in a zero-energy house with such a ventilation system, how will they respond? differently? why? (write down respectively)

   1. what participants found challenging about living with these technologies?
   2. how will they react? why?
   3. will you keep your habits? will you buy new stuff? will you change your behaviour? will you tend to use windows more or less? how to solve/ adapt to the new style?

iii. compare their understanding and response, if there is a difference, ask them to discuss and make a family decision (observe the process) and why they finally get this agreement.

hot water conflicts:

i. tell them to imagine when turning on the warm water tap, you can immediately get warm water; (current: cold water comes out first and need to wait for a while) how will they respond? differently? why?

ii. tell them to imagine what if you are doing a shower halfway and the hot water runs out; (because the hot water is stored in the tank and could run out and then need to wait for the heating) how will they respond next time? differently? why? - will you make a plan/ discussion because of the new situation?

iii. if you own the house/ if you rent the house

Appendix E: Interview notes of ethnographic study

CASE 1

couple: master students (ME) living in student accomadation
No working experience/ No renting house experience

current home:

tradition radiator (only one)

knob control

1-5 level: 1-3 cannot feel working; but 4-5 hot immediately and can feel it

4-5 level super hot

heat up immediately

gril can feel 3 but boy cannot feel it is warm when 3

turn to 4-5 level first, after the room is heated up; change back to 2-3

learn from conflicts: new "interface"

no thermostat; no idea about indoor temperature

based on own feeling; will not check temperature

may forget to turn off and then feel hot

when feel hot, first check radiator because the window is not that effective for cooling down

no fully open window: hopper casement window

start to use radiator in December (afraid of extra energy bill)

but they don't know the exact energy consumption, so careful about heater use

always turn off heaters when not at home (worried about bill)

usually turn on at night, turn off before sleep

it will get too dry (uncomfortable) , if turn on during sleep

girl prefers turning on it before shower at night and turn off after shower

boy prefers turnig on when working at night

girl have a warm slip at home; no specific home wear (just a fleece sweater)

if feel cold, the girl will heat up a hand warmer first (use microwave)

then tell her boyfriend her feeling and turn on the heater (because she still need to turn off it before sleep)

usually boy will not feel cold

small outlet in bathroom

weak extractor in kitchen

buy an additional fan

hopper casement window with ventilation grid on the top

close the bathroom after shower; rely on the outlet there to dry the room

close the bathroom after shower because the light relies on IR sensor

light may turn off when showering halfway, have to pull up the curtain and wave hands to turn on the light

extractor: weak (1-3 level); but once put tissue under the outlets to check whether it is working

current productive crisis

family respond example

can hear a little bit sound (think it is airflow)

just tell other he/she will open the window, if the other feel uncomfortable they will close it.

girl: window for ventilation and cool down; low demand on opening window

boy: window just for ventilation and have the habits of keeping open when he is not at home

boy: feel safe because their window faces the parking area

girl: always close window when not at home, rely on the grid on the top of the window (think it is enough)

they have own areas, and take responsible for the windows in their own areas

rainy day, will not open window

shower: one for temperature; one for changing the flow

no need for preheating

for shower temp, have figured out the comfortable temperature and then never change it. just turn on to the largest flow

boy for dish washing, a bit cool water

single tap for kitchen sink

no idea about warm water temperature; no display

girl: at parents house, set max warm water temp to 60-80 ℃, depending on season (gas)

because many people need to shower

always warm water for showering

learn from conflicts: new "interface"

boy: at parents house, have heat pump for floor heating and warm water

boy:it is too complex and everything is connected, no idea about max water temperature

how to understand the simulations: heating

Girl

heat up evenly

the air seems to be similarly warm

cool down evenly

can notice the insulation for keeping the heat

the wall/ the floor can help transfer the heat to make the whole house warm

pillow: insulation + special material to help transfer the heat around the house

Boy

heat up unevenly and slowly (two side of pillow)

cool down slowly

need more time for heating up/ need pre-heating

the distribution of radiators matters

can notice the insulation for keeping the heat

think more suitable for the elderly, who stay at time for longer time

pillow: different between two side, indicating the different distance to the radiator

how will they respond: heating

Girl

- try to discover first: to figure out the regularity
- may prefer to have some schedule function/ remote control/ season mode
- may prefer: turn on automactically when detect the room temp is lower
- would like to see the energy consumption information or the bill
- can accept to keep it on for 24h,depending on experiments and introduction

Boy

- may need to pre-heating/ add schedule function
- check the weather forecast more often
- not sensitive to the energy use amount; but would like to have access to energy consumption situation at home
- if the bill is crazy; then will track energy use
- comfortable first; but will also balance the energy fee

- may purchase extra heaters depending on the experiment/ discovery process
- prefer stable bedroom temperature; will seldom open the window
- in kitchen: keep the same habits of opening window
- window use depends on room/ area
- would like to have some window use tips/ advice (stick somewhere at home)

- may refuse the heat pump but add insulation to their house
- doubt whether it is real energy saving, because may have to keep it on for longer time
- will use home wear to adapt to new system first
- but will purchase some other stuff for winter and summer
- may not turn off the heaters when not at home; because it takes long time to heat up

how to understand / respond: ventilation

Girl

- a bit noisy; will turn off it when listening to music, watching movies, playing games
- if no quick ventilation demand, will use it; otherwise open the window
- will use it more in summer and winter; believe it could help keep temperature stable compared with window
- will reduce the use of window but will not fully rely on the ventilation system
- filtration advertisement: not important

Boy

- a bit noisy but think belongs to white noise so acceptable
- will try the new ventilation first; if not enough, open window when needed
- window: means the connection to outside world not only for ventilation
- will use the ventilation system and keep my window habits
- will not turn on it when sleep

Girl

- will turn on it when working at home
- will not turn on it when sleep
- prefer to keep it on in sitting room or laundary room
- don't expect it to remove the smell, window deserves more trust for smell removing
- but may turn on in advance if I know I will eat something with srtrong scent later

Boy

- no need for timer function
- filtration: not important
- always keep it on except in bedroom

how to understand / respond: hot water

Girl

- check the current tank temperature/ how much water left in the tank
- will have family plan: especially when to wash hair
- will leave longer intervals between two people's shower
- try to discover the regularity
- have little knowledge of where all different hot water is from (one/ two tank)

Boy

- pre-heat it/ set higher heat pump temperature
- no need for weekly plan
- will leave longer intervals between two people's shower
- half an hour interval: acceptable

- temperature: boy has wider range of accpetable temperature
- usually girl finds uncomfortable and start the conversation
- girls tends to self-adaptation first, then communicate to turn on the heater

---

- used to live in a similar house: heat pump to realise floor heating and warm water supply
- mother prefers to turn on the heat pump when use, but turn off it when not use it
- father prefers to keep it on, because he believes frequent turning on/off consumes more energy
- mother won the debate by checking the energy bill

- no one cares about the ventilation status; not important; so no communication on this part

CASE 2

couple: master design students living in student accomadation
have renting house experience for working; live in the USA for 4 years

current home:

- knob control
- keep turning on (based on season)
- always set to the max, because it is not hot
- put socks on the radiator for drying clothes
- can satisfy the need roughly
- girl: cannot feel the difference between different levels
- boy: 0-3 level no difference; 4-5 can feel it is working
- girl: take responsible for turning off the heater
- because she is easier to feel hot
- no idea about indoor temperature, and think not important
- rely on body feeling
- comfortable zone for girl and boy is different
- put up/down clothes first
- then try to change some device

- strange ventilation control
- there is one physical button
- and also a panel which has flash orange light when it is working (automatically)
- guess it detects whether there is someone at home
- feel useless because cannot feel the airflow, cannot hear it
- not sure whether it is working
- boy: turn on it before sleep
- because opening window at that moment will make room too cold for sleep
- girl: when feel stuffy, may turn on it
- use window for ventilation more
- window in bedroom: open widely
- window beside tables: open a little, because opening widely disturb working on the table
- the window opening also aims to guide the airflow, so that people sitting on sofa will not feel so cold
- boy: take main responsible for ventilation system and window
- boy: when wake up: open the window in bedroom widely;
- boy:later close the window half; fully close it before sleep
- each one is responsible for one window beside their own table.
- when feel cold, close the window in bedroom
- light rain, always keep the window next to table open a little
- not at home: keep window open
- window: for removing the scent
- never notice there is an outlet in bathroom (passive one)
- gril: does not care about the steam after shower
- boy: will open bathroom's door to let the steam out
- boy: but will not turn on the ventilation in sitting room (useless)
- boy: NL is dry enough
- girl: feel dry; from face and leg; use body lotion
- boy: used to dry environment

- need to wait 30s-60s for warm water coming out
- bridge tap
- boy: responsible for dish washing, always use warm water
- girl: has the habit of use toilet first and then take shower
- thus get super hot water in the beginning
- she feels confused and does not know the reason
- but boy knows the reason: because the cold water for toilet and shower are shared.
- girl: take cool shower in summer; warm shower in winter
- boy: always warm shower

how to understand the simulations: heating

Girl

- cannot feel working hard
- expect to be hotter, a feeling of lovely home
- feedback not enough
- prefer hot radiator- means safety
- room temperature- prefer not too warm and evenly heated

Boy

- love the radiator to be super hot; can dry the clothes
- hot- means safety and multi-task
- cool down slowly
- even distribution: feeling of floor heating
- love the floor to be warm; love the slight temperature difference.
- pillow: remind him of blanket

how to understand / respond: hot water

Girl

- continuous warm water supply is the necessary
- refuse the system
- super disappointing
- then would like to separate the heating and warm water system
- constant temperature for shower- important
- shower means relaxation: must high standard

Boy

- large consumption of warm water, continuous warm water supply is necessary
- install another new system
- wash dishes - use warm water flow
- constant temperature for shower- important

how will they respond: heating

Girl
- need time to adapt, will try first
- set to the max first, if not suitable, will change
- if the radiator is not that warm, may think it is broken
- keep the heater always on in winter
- not much idea about the energy bill

Boy
- need time to adapt, will try first to figure out the suitable setting
- keep the heater always on in winter
- if the energy bill is acceptable, keep it on (in the USA do the same)
- if the bill is unaffordable, will keep the radiators in the some rooms on, where most activities happen
- study room, bedroom should be warm; sitting room not that important

Girl
- may put on some clothes first
- only when think the system is useless,then will buy extra heater
- sleep should be warm- most important
- would like to set for the whole house
- active area: warmer; no one is there: cooler not turn off

Boy
- may put on some clothes first
- may consider buy a electric blanket, because sleep it the most important thing

how to understand / respond: ventilation

Girl
- will not notice the noise
- result is the key thing; noise doesn't mean it works hard
- sound and airflow makes her feel it is working
- need a clear button to show the status; because it is not that noticeable
- prefer automatic/ smart adjustment (for slight change)

Boy
- will not notice the noise, even not louder than his laptop's fan
- usually set in middle level and then keep it
- or set to higher level in the beginning and later set to lower level (just like window)
- filtration: could then use more, depends outside environment

Girl
- filtration: "clean and healthy air" - fraud
- would like to keep the whole house same (ventilation level)
- family decision based on the bill
- would like to track energy consumption details at home
- like APPLE SCREENTIME

Boy
- active area: need ventilation; other area- doesn't care about it
- would like to know daily energy consumption details at home
- will reflect on their routine based on it (experience in the USA)

- temperature: girl prefers cooler than boy
- boy secretly add one more duvet in the same cover
- boy: responsible for laundary
- boy: warm feet necessary; girl: cover the stomach
- girl: terrrible sleep experience and then complain to the boy
- sometimes boy need two duvets, while girl only need one
- boy: then admit what he did; and later remove the extra duvet
- boy: in the end, only he uses two duvets

CASE 3

roommates: master design students living in student accomadation
have renting house experience for working; have lived together with their grilfriends before
have good technology knowledge and interests in IOT

current home:

- always on; keep it to the max
- because it can detect whether you are at home, but not trustworthy
- sometimes when you are at home. it detect that you leave home, and stop the heater
- think based on movement (shang)
- think based on CO2 (dino)
- did some experiments, heard from EE student
- have to manully set the status back, and then need some time to preheat the radiator
- sometimes turn off automatically during midnight, feel cold
- the heating is not enough in winter
- summer, turn to the cool level (radiator)
- summer super hot; face west
- 5-10 min preheat, can hear the water flooring and noise
- A/C for cooling/ heating when lived together with girlfriend
- keep it on until sleep./ set timing because girlfriend easy to feel cold
- think frequent turn on and off waste more energy
- boy: easy to feel hot
- remote controller
- APP control at own home, integrated control for all the room
- summer A/C: set at 26 (shang), without any t-shirt at own room
- summer A/C: set at 16 (dino), but set the direction of fan up, so no direct wind
- dino: prefer heavy duvet in summer and set A/C at 16
- in public area: similar preference, not much conflict on this

- ventilation: can hear the sound from neighbourhood
- dino: no sound; shang: have sound
- no cooking (dino)
- open window after cooking (shang)
- will not open window in the morning, because will leave soon
- if the room air qulity is good then think ventilation is done. (has a display on the air filtration on the device) (dino)
- whether open the window for ventilation depends on the outside situations
- have air filtration device at home. when turn on it, will not open the window (dino)
- at least 30-60 min, open the window every day, then turn on the air filtration (shang)
- the grid not useful for ventilation (shang)
- shang: not trust the numbers on air purification device
- dino: will track and trust the numbers on air purification device
- dino:girlfriend takes more responsibility for ventilation, 10 min window use then air purification
- because outside is too noisy, usually turn on purification before sleep
- shang: everyday must open window for a while, girlfriend and I: half and half
- shang take full responsible for ventilation
- shang has high requirements for air quality
- at least 30 min open window, just habits
- dino: not really care about air quality and window use

- keep window close when not at home (safety reason)
- sometimes will open the grid on the top of the window (shang)
- always open the grid on the top of the window (dino)
- shang: has the habit of opening the bathroom to let steam get out after showering
- shang:prefer the whole room to be more huimid
- privacy consideration (the window face the corridor, can see people pass by (dino)
- clips to close the curtains -> more difficult to open the window, so seldom do that (dino)
- a bit noisy, lazy to close it (dino)
- dino: will not open bathroom after showering
- dino: don't want to the whole room to be too humid
- dino: the outlet in bathroom can remove it, wait for 30min
- shang:depends on the feeling when back home

- warm water for washing dish
- turn on the hot water to the max, wait for super hot water come out, then set smaller flow and turn on the cold one a bit, to adjust to a suitable temperature (shang)
- dino: has already remeber how much to rotate the tap to get comfortable temperature, will turn on hot and cold taps together and then wait and adjust a bit.
- shang: need to wait for a bit long time 10-20s, annoyed
- dino: shower need to wait for longer time to get warm water (30s)

- dino:has water tank in Ireland
- press the switch to heat up the water
- heat certain amount of water
- if not use it immediately, it may cool down
- the hot water will run out

- shang: will collect and use the cold water to wash small clothes -> don't want to waste water
- shang:10 min shower
- dino:40 min shower
- dino:only wash quick when live together with girlfriend, because need to pay the bill by themselves
- different routine, no problem with sharing the bathroom
- shang: take responsible for dish washing

- sometimes just do cold showering
- 2 person: normally enough hot water
- shang: when live with girlfriend,preheat the water, always turn off the water heater when showering.
- shang:(concern about the ground connection problem/ safety reason)
- shang:turn off the hot water system when not at home (daily)
- shang:have idea of water amount: 30L normally enough for two people showering.

how to understand the simulations: heating

Shang

- evenly heat up the room
- feeling of warm home
- like floor heating
- more comfortable feeling
- prefer the new one
- large contact area - like floor heating
- like to stand on the floor wihtout socks if have floor heating

Dino

- feel the insulation
- cool down slowly (safe feeling)
- feel like floorheating
- generally the room is warmer
- the old feel fragile and unreliable
- the hotter radiator: then sit close to it
- prefer the new one
- can even sleep on the floor if have floor heating

how to understand / respond: hot water

Shang

- depend on the capacity of the tank
- need to discover
- if experience one time that the hot water runs out when doing shower, next time will leave some intervals between two person
- would like to buy a new one, too inconvenient

Dino

- have idea of the water consumption, 40L should be enough for two people
- if experience one time that the hot water runs out when doing shower, next time will leave some intervals between two person
- change to a larger tank

how will they respond: heating

Shang

- may need schedule mode
- in winter, prefer to turn on it before back to home
- will turn off the system earlier before leave home
- may have concerns about window use, because think the heat is losing
- feeling of collection heat, working hard, finally get it, don't want to lose it

Dino

- prefer IOT or schedule mode
- phone control and remote control
- would like to have more sensors, more automatic
- hope the system can better adapt to user habits
- not worry about data privacy, think these kind of data
- the fridge is super hot
- curious about the bill
- think more during renovation
- have the habit to check the calculation of energy bill
- pay attention to enery bill, and in the end, find the fridge is broken, it consumes too much energy
- proud of that
- machine learning, may be worried a little bit
- not care much about the bill, normally will not change my behaviour
- would like to have the service feeling, enjoy DIY & add sensors by himself
- normally trust sensors, if I know the mechanism
- camera at home, detect whether someone get in

how to understand / respond: ventilation

Shang

- a bit noisy, would like to have some different modes
- better to adjust the power
- more convenient - new system
- window behaviour also depends on outside weather

Dino

- normally acceptable, but for sleep a bit noisy
- would like to have sleep mode
- prefer new ventilation system, privacy protection + active ventilation
- can track indoor climate, curious about data visualisation
- depends on the trails
- water A/C filter before the summer
- integrated to phone, better
- I am in sitting room, can use phone the turn on it in advance

Shang

- care about maintenance: frequency, cost,time
- how long to clean the tube/ change the filter....
- how to ensure the heat not lose too much
- prefer the each room has a ventilation

Dino

- would like to DIY
- have idea of humidity, prefer 60-70%
- in own home, have sensor to detect indoor temperature
- when the temperature gets lower, it will heat up the room a bit automactically

Shang

- lazy to get into bedroom to turn on it and then leave
- if already lay in bed, no need to turn on it anymore. (the experience of goro bed but before fall asleep matters)
- kitchen must stand alone
- prefer position of the outlet can follow my routine/ walking path.
- rainy outside, may open window because I love the smell of rains
- prefer whole house ventilation instead one by one room

Dino

- try to keep at a stable temperature when I am at home
- sunny outside, may open window
- prefer whole house ventilation instead one by one room
- kitchen must stand alone

CASE 4

couple: master design students living in student accomadation; live in netherland for already 4 years (bachelor + master); no working experience

current home:

- floor heating
- the whole building connected
- NOV-FEB turn on
- good insulation
- march; can feel the heat from neighbours
- unclear mark
- need to first turn to the max level; to let the water fill in the floor
- then the system knows you will start to use floor heating
- then they can set heating levels
- normally, 1/4 level; super cold (JAN) -> set to 1/2 level
- technician told them 1/4 level = 22-23 degrees
- if turn to 1/4 level at the first time; not working
- tought it is broken
- ask technicians to check
- no temperature display
- technician says keep it on saves more energy, they also believe that, so not much interacion
- has an APP to see the daily bill
- 130-140 euro for heating and hot water per month in winter
- can see the hot water consumption & heating consumption
- boy: turn on the floor heating (easier to feel cold)
- girl: turn off the floor heating because she pays the bill
- girl: usually not feel cold
- only turn on it one time before the winter and turn off it when spring comes
- thus to save energy (from technician)
- becasue filling the floor with warm water consumes most energy
- this way : save most money
- just follow the instruction; never try to turn on and off frequently
- after having idea of the bill, will not check it frequently
- 1/4 level -> the lowest level, if set lower than it, the system will shut down
- feel the floor is hot (1/2 level); 1/4 level - feel room warm but not feel the floor is quite hot
- prefer floor heating
- takes half an hour to get ready (when first time using floor heating)
- can hear the water is flowing
- the floor is super hot when turn to the max level
- summer: 40-50 euro energy bill
- electric heater in the bathroom, turn on it and open the door in winter to get the whole room winter
- because the electricity bill is covered, but need to pay for the heating bill by themselves

- three outlets
- rely on window for ventilation
- no sound; no air flow; cannot feel it is working
- a passive ventilation in toilet
- have level1-3, but can feel nothing
- seldom touch the controls
- boy: feel quite cold, girl: feel good, boy gets onto the bed
- girl: not want to open the window, but indeed really stuffy, agree to open the window widely
- window: can be widely opened or slightly opened
- before leaving/ cooking, open widely
- stay at home, open windows a little bit (noisy outside)
- close the window when sleep (consider noise)
- extractor in kitchen
- don't know where the smoke is extracted to
- noisy but roughly useful
- not enough when cooking, will also open the window
- no work from home
- have a study room downstairs
- quite regular routine/ to office or downstaris
- 8 am get up, 9 am leave home to office
- boy leaves early; company far away
- thus girl responsible for opening window more
- open the bathroom's door to get rid of the steam/ humidity
- always keep the window on a little bit

- immediate get hot water
- shower: one control temperature (lowest 38 degrees) one controls water flow
- there is no cold water for showering always warm water
- has a 40 degree mark
- now will not change the temperature setting now; will keep it
- temperature settings- sensitive, easy to get hot
- boy: warm water to wash dishes
- summer too hot, boy: use cool water
- when they would like to fill the mop bucket using the shower head
- can only get warm water for mopping; think it wastes energy

how to understand the simulations: heating

Girl	heat up slowly	feel warm, not that hot as the previous one	cool down slowly	suitable for the whole year	prefer the new one
Boy	low temperature heating, close to the body temperature	hot- means safety and multi-task	cool down slowly		

how will they respond: heating

Girl
- always keep it on, even when not at home
- think it takes long time to heat up
- prefer dispaly to see the temperature
- need several trials to find the most comfortable setting
- slow heating up is acceptable
- would like to see the progress (the temperature is getting up), have an estimated time of heating up is good
- know the temperature will affect my perception, if I can see it is growing, I will trust the system more

Boy
- slow heating up is acceptable
- would like to know what temperature it can reach
- if keeping it on can save the bill, then will keep it on
- need more feedback after changing the setting. (same to the girl)

how to understand / respond: ventilation

Girl
- prefer able to turn off it, when sleep (need silence)
- prefer silent when working at home
- ventilation is not that trustworthy, window is necessary
- sound indicates it is working, good

Boy
- prefer it in the bathroom
- may keep it on at medium level
- in winter, may close the window and turn on ventilation, since it is cold
- prefer a powerful ventilation in bathroom

Girl
- don't think it will affect window behaviour
- depends on the bill, may keep it on or turn off it
- mechanical ones -> keep it on
- still prefer opening window when not at home, even when the energy bill rises a little bit

Boy
- clean energy/ air circulating -> keep it on, but low level

sleep: if girl feel hot, just removes the duvet; the boy will keep himself covered

how to understand / respond: hot water

Girl
- prefer to always have warm water
- if have more fixed routine + know the consumption -> can adapt
- if save the bill -> can adapt
- need time to learn it
- wait for a while is fine

Boy
- no
- install a new one
- don't want to wait, not enough for family use
- if go back at similar time, tired and sleepy, don't want any member to wait

small family debate

- if I can know the bill/ energy consumption, I can learn the resctrictions
- some restrictions, make me more conscious about my hot water consumption
- I may not use the hot water for some unnecessary activities
- boy: sustainability relaetd to what kind of energy used to support the operation of the system; nothing related to the style of hot water supply system

Appendix F: Thematic analysis process

indication of progress (system working hard)

- sound of water flow
- temperature of the radiator -> indication of system operation
- sensitivity of the hands
- temperature of the radiator in level 3 -> indication of system operation in level 3
- sound and lack of air flow
- expect sound/ air flow when it is working

Professional advisor involved

- profession reference (knoweldge)
- instruction on the system use
- knowledge of the system

Access to testable advice

- advice on how to live together with the system
- advice on how to live together with the system

limitations of adjustment

- the restriction of the knob control, cannot rotate more when reach "level 5" mark (physical stop experience)
- stop experience (turn the hot water tap to max)

supporter involvement

- doubts on previous judgement
- repeated experiment
- different sensitivity of the hands
- eligible for decision making
- access to plenty of experience
- previous experience
- other's experience

indication of successful action input

- can rotate to ideal level and knob stay at that position
- indication of successful input
- indication of successful input (flow change)
- hint of successful input (the switch can be pressed)
- change of the water flow -> indication of the effective control input

link between control and acuator

- clear link between the controls and the floor heating
- No indication on the link between the control and the system (no tag & location)

feeling of capability of control

- capability of rotating the knob
- capability of rotating the knob
- capability of controlling water temperature
- access to ventilation control
- lack of normal direct controls (not align with common sense)
- capability of detecting movements

indication of setting status

- marks on the controls
- marks on the knob
- marks on the tap
- lack of indication on input status -> the switch

Number of human actor

- the single human actor in the "crisis"
- multiple human actor

hint of the final effect of system working

- individual body feeling
- expect to feel the air flow and smell removed
- indication of system effect (bright/dark room)
- instantly access to the effect caused by different interactions

Affordance

- access to profession reference
- not reachable (outlet)
- obvious position of the outlets
- the position of sensor is reachable
- inconspicuous position of the sensor
- room arrangement (curtain block)
- fixed position of the sensor

Mysterious message

- random/ irregular signals (from a sensor)
- abstract signal (flashing light from a sensor)
- assume there is some error message to indicate what to do in next step

Indication of automation

- indication of automation

regularity in system performance

- regularity in system performance

Access to trackable evidence

- easy access to evidence
- trackable information to verify the experiments

Appendix G: Co-creation Plan

CO-CREATION PLAN

https://miro.com/app/board/uXjVP_QaOUk=/

Research Aim & Questions

Key Aims

To evaluate current design concepts and determine which design features inspire the creation of their own "interface" for the system to deal with the "crises". Currently, it is considered that 1) households' learning of conflicts between the system and them, 2) the involvement of supporters can facilitate the creation of their own "interface".

interface: It exists between the resident and the automatic housing system, operating as a new connection between humans and the system within the daily use case. It refers to residents' own way to live together with the system, improving the matching process.
"crises": The unsatisfied effect caused by the conflicts between the system and households occuring in everyday life due to the misjudgement of the system in the background.
supporter: who takes the role of a bystander when a "crisis" happens and brings more possibility and inspiration for an actor to discover the system more.

Research Questions

- How to use design features to affect households' interest and willingness to learn about the conflicts behind "crises"?
- How to use design features to involve supporters (e.g. other family members) in the learning, exploration and creation process?
- What are other possible elements or methods that may have a positive effect on promoting the creation of their own "interface" to deal with the "crises"?

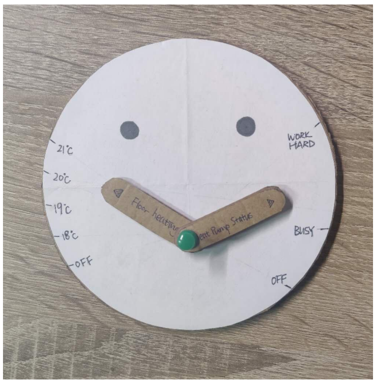
Method

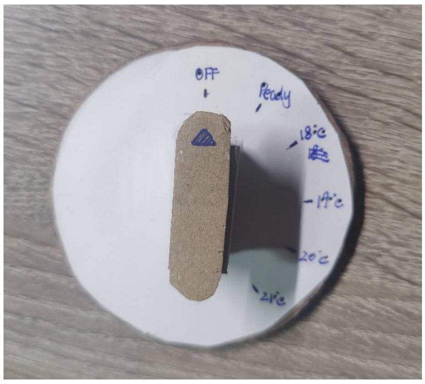
Participants

- Adults who live in a zero-energy house now (preferably living together with family)

Stimuli

- Go to the participants' house
- Paper prototypes to demonstrate my concepts ("system state")
- Sketches to demonstrate my concepts ("supporter involvement")





Apparatus

- A camera: to capture images and videos during the tests.
- A script

Procedure

1. Sign the informed consent and explain my project a little bit

PART A: SMALL INTERVIEW（~20min)

*no need to go through every questions, may select depending on the real situation

2. General talk about their home and family:
    - When do you move in?
    - Who do you now live together with?
    - Why select/purchase this house?
3. **Would you mind showing me around the house? especially controls & subsystems**
    - The features of your heating/ventilation/window/hot water supply/heat pump?
    - How do you control them?
    - who interact with the system most at home? why? Do you ever have any discussion/ conflicts on indoor climate settings/ system use?
    - Any personal using habits according to your routine? (daily/weekly/seasonal)
    - How do you feel about living in this house now? (especially the indoor climate and energy saving) satisfied? why or why not?
    - Any different feelings in the beginning and now? why?
    - Any impressive story happen when they first time use heating/cooling? can you share it? how do you deal with it?
    - Have you done any adaptation/ adjustments to the system by yourself? why? (any add-on?)
4. About neighbourhood/ community:
    - Have you ever discussed the indoor climate system (heat pump) with your neighbours before? why? can you share the story?

- Do you know/ join in any community for similar house?

PART B: EXPLORE AND EVALUATE MY CONCEPTS (~40min)

*10 min for each concept; randomizing the order in which you present the prototypes to reduce potential bias.
*think about a protocol/script/scenario for how you present the prototypes (e.g., you could set the arms on the first prototype to a specific position)
*you can use the feedback on existing concepts and discussion to produce new concepts or combinations of concepts.

5. Present the sketch and paper prototype of each concept within context **one by one**:
    - Stick the paper prototypes at their home and introduce the designed product's context, scenario, interaction (with the help of sketch)
    - Participants were given time to explore freely and observe its features.
        - observe participants interest and behaviour and choice; can have some small talk depends on the situation
    - Ask for feedback on concept: (version A: if related to "system state")
        - How do you understand the concept itself (goal/function/..)?
        - How do you understand your heat pump system now? Do you realize any specific system features? Will it change your cognition of system?
        - how will you use/react to it? **(immediately & in long time scale)**
        - How do you feel about the concept? why? (emotion side)
        - Do you think it fits in your house/ real scenario? why or why not?
    - Ask for feedback on concept: (version B: if related to supporter involvement)
        - How do you understand the concept itself (goal/function/..)?
        - How do you understand what is happening in your house? How do you understand your heat pump system now?
        - How will you react to it? **(immediately & in long time scale)**
        - How do you feel about the concept? (emotion side)
        - Do you think it fits in your house/ real scenario? why or why not?
    - Brainstorm and design: discuss together how to improve the design to fit in your house/ your situation

Appendix H:
Interview transcripts of co-creation

LB 66

almost 4 years
select the house due to the energy efficiency, used to live in a heat pump apartment for 10 years, really looking for this area and energy efficiency house, won the lottery.
The smaller and cheaper house in this area/street
already knows the heat pump and the system and is satisfied with it.
This one is combined with solar panel, which is new to them
They are quite aware of how the thermostat works, all the system working
many things not new to they, some small features are new to them
choose to add small controls/thermostats on the third floor

the central control panel in the sitting: for ground floor temperature and the bathroom; always set to 22 around the year. The bedroom on the first floor should also get 22.
But they notice that because the big window/door in the living room, the temperature in the ground floor in summer gets higher than other rooms. But the thermostat will detect the temperature here, the bathroom on the north upstairs gets a bit cool/cold.
The shown temperature is what they set but they also believe the real indoor temperature is close to it, they believe the system is reaching the set temperature.

when they show me the heat pump, not sure if it is for both warm water supply and floor heating (wife) or it is only for the warm water (husband) but reached agreement in the end, it is only for warm water. the one for floor heating is underground and will remain at 16 degrees. so when using floor heating, it only needs to heat up to 22.

warm water: boil only at night around 11 pm (60 degrees) ECO MODE, when more people comes to house, need to change the mode. (it will work when the temperature is lower than a certain temperature - don't know the temperature constrians; start to work early COMFORT MODE) can switch off when on holiday
Read the manual (~10p) and rely on previous experience to learn all these stuff

should not touch it too much, always keep it. it takes several days for the system to change the room temperature.

buy a separate electric heater, can programme it, seldom use it.

have simple thermostat upstairs; you can set different temperature for different rooms, but actually you are interacting with the whole system, either cooling/heating up the house. it is not possible to get one room 28, another 21. But they think they can do one room 21, another room 22. when you set at 21 on the first floor, the temperature in the second floor may gets a little bit higher.

you can interact with the thermostat in every room, but need to think about the whole house, either cooling/heating up. the whole house will change together. They always set the temperature in each room similar.

You need to wait for a couple of days for the change. They already knows the features, so for them it is not the problem. So they set the temperature same for the whole year. They learnt a bit before and also learnt here.

Have some strange noise in the valves, don't know why; but when it happen, the thermostat downstairs will display "error", Ask for checking; technicians also don't know, don't solve it.

full of solar panel on the south of the roof, only two rows on the north, two solar energy box

ventilation system: one inlet, one out let, has filters, every room is connected. have three levels. when showering/cooking - level 3; normal - level 1. Two filters for internal and external, need to change every three months and it is expensive. there is also heat exchange there, so warm/cool air comes into the rooms, save energy. ventilation is always on. but possible to switch off.
"I think it should work as it is designed and we are happy about it." Reduce the bill a lot, only pay 10 euro/ month, so they are super satisfied with the system and the insulation. Summer is also good, also keeps 22. External weather does not matter for them.

should close the window and follow the rule. She missed opening the window,but also mentioned that we can open the window for half an hour, it is okay. The recommendation is to keep the house closed. the ventilation can get air into the house and manage the temperature of the air and the filter helps with preventing the flies to get in.

think the combination of solar panel and heat pump is perfect. knew heat pump before and both engineers and work more or less related to it, so they know the basic mechanism and have trust on it so they are willing to learn more about the system and now understand it well.

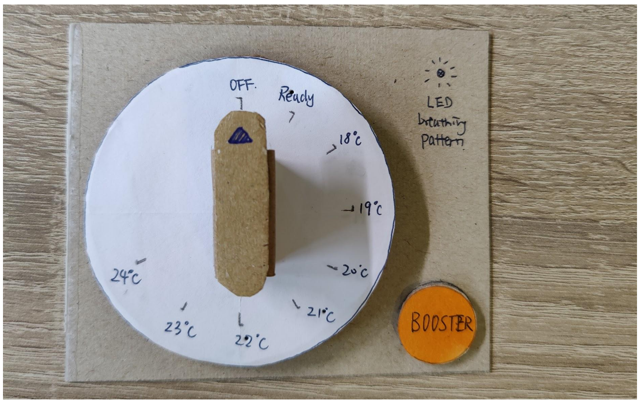
Their house is customized: have some solar panels on the north side, have thermostats on the second floor. (standard: only on ground floor and first floor)

still not understand the timer icon on the ventilation control in the kitchen. If they forget to switch to lower level, they can notice it due to the noise.

they may not notice the floor in the living room is warm because it is low-temperature heating. But you can feel it in the bathroom and the pipes is warm (for distributing floor heating)

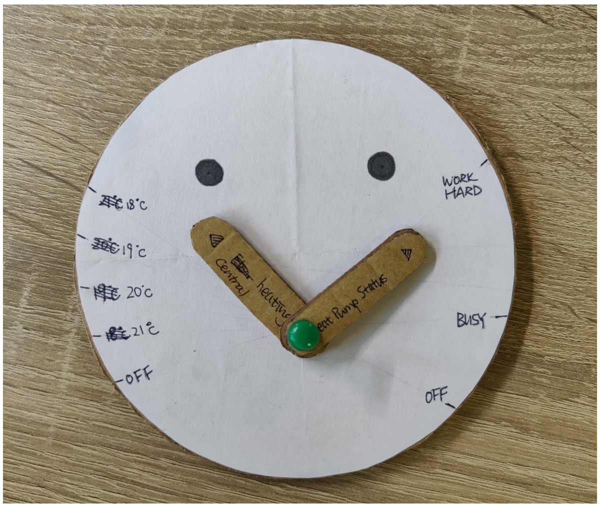
have some communication with neighbours, someone complains, but they think because they don't understand it. Need to wait 1-2 days for the change. Misunderstanding of different thermostats on different floors. noise of ventilation, someone complains but they get used to it. There is one facebook group and whatsapp group for six neighbours but she is not interested in facebook. Other people will post issues there. No regular maintenance. Advice from technician: once a year: clean all the outlets. But according to friends and colleagues thinking, it is way too much. So they did not do it.

the aim of the bubbles? a little bit confused
you teach the system how you would like the house to be
maybe useful but prefer to directly set the system
may get used to using it
but it is probably good for adaptation, but then afterwards?
not really get the idea
good for family living
they have discussion about indoor climate
winter- too dry (through skin; from kids)- have discussion
but did not solve it yet but know some neighbours instore extra units for their ventilation system to regulate the humidity. (like a humidity)
so currently- have a small humidifier for their son and sometimes open the window to get more humid.



we always have the same temperature, only change 0.5 or 1 degrees, so the range seems too wide for them.
don't know the limitation of the system (temperature setting)
think will not work for their house, because it cannot change that fast. maybe it is more suitable for the radiator in the bathroom.
does not really apply to their system. They feel it is super stable.
think they get more troubles/ confusion in understanding the system. the counting down is too slow, so it feels quite strange.

They have an orientation night (house rules) which tell them all the features and also they get to know them from their previous experience. They had a similar system before.
The ventilation is exhausting the air and there are small outlets on the top of the window. you can open it to keep them on to balance the air pressure.



interesting idea - curious and fun
help you become more conscious about whether you are using more energy
when you set the temperature, you can see how much is caused the system to reach that
help saving energy - nice concept
children will definitely like it - chase for happy face
can be simple controls
busy? work hard? - confused
their system same: when busy with boiling water, cannot working hard to heat up the house
There is more information, and more aware of system working, know some condition the system working on other things. should be helpful for getting to know more system features.
they like it
with colour to indicate the system mood/ LED behind
make you aware how hard the system is working to get to your expectations

pick the third one, hesitate about the first, the second - not fit

LB 68

live longer than 3 years
past: live with my son and her girlfriend
current: live alone
divorce - have to move; funda-get the information; then find this house; not intend to look for a sustainable house; but in the end pick it
satisfy with the house; especially with the energy crisis
the nice environment here; “won the lottery”; even the house is more expensive (including the panels on the roof) kitchen is included but can be customized; bathroom - friend did it; insulation is already down.
think can open the “heat pump” but never try to open it. maintenance: call/email them
she knows which is the tank.
they have a website- that shows all the detailed information for residents
they also have a Facebook group for neighbourhood
only floor heating/cooling system; no convector on the wall; have a small thermostat in every room to change the temperature setting for the whole house. 21 downstairs, then upstairs get 24, so usually don’t use the thermostat upstairs. because when you set it to 21, actually downstairs is 21, but the room is 24.
the solar panel control on the top floor: she does nothing with it. sometimes the technicians will come and check the settings.

the ventilation filter is on the top floor: have three levels (1 for normal life; 3 for shower); you have to change the filters by yourself - have lots of types (consider the allergy)
have a portable control in the bathroom; normally set level 1; press”30 min” then set to level 3 for 30 min.

also have a portable one in the kitchen, this can just change the levels but not set the temperature. the extractor works well and use it when cooking. you can see the smoke is getting there.

She knows that you have to keep the window closed for this system. She used to keep the window open when sleeping. but it will affect circulation and the ventilation has filters which can make air of good quality. it is better than opening windows. because of the insulation, the whole system works well, the indoor air can stay cool when outside is warm. Sometimes she will open it just for fresh air (but it is “fresh” in your mind)
upstairs may be a bit warm, and her son sometimes will open the window at night.

they will tell you the rules, and have an information evening to tell you everything.
also know from neighbours, have lots of discussions on the Facebook group. Someone is quite technical and can help to solve the problems.
There is a daycare nearby and neighbours will have communication there when picking up their children. different groups for different types of houses.

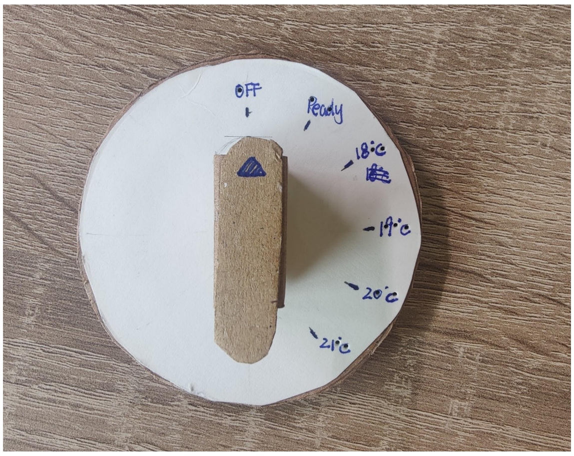
when showering - will set to level 3; it is always on level 1, no choice to turn it off
floor heating/cooling: always on; I am not turning on a heater/AC, I am setting room temperature.

not used to sleep with my window closed, but now adapt to it. In the beginning, not believe it. Also, feel it is too warm to sleep. (23 degrees) Thus, she just chooses a less warm duvet.

Satisfied with the room temperature range, but indeed it needs adaptation. She finds that the system seems can only change once within 24 hours. so now seldom interact with the controls.

ventilations all over the house + big gap beneath the door- because if one room is blowing, another room is exhausting; then there is a danger to get vacuumed. thus they leave some space beneath the door for circulation.

there is an APP to see the result of the system, energy from the sun, energy bill, electricity use (eneco app)

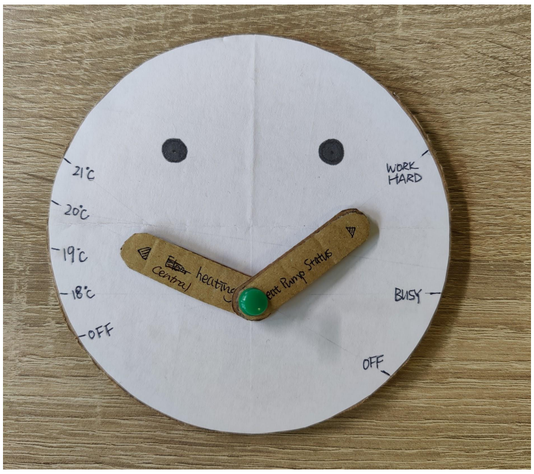


easy to understand it
I don't interact with the system that much; so not sure about the effectiveness
but should fit in the room upstairs

the central control panel in the living room:
currently, have showering with lots of people, "booster" mode - works quicker
currently, icons to show the status, always need the booklet to interact with it, booklet is useful (central control panel in the living room is more complex and state more information)

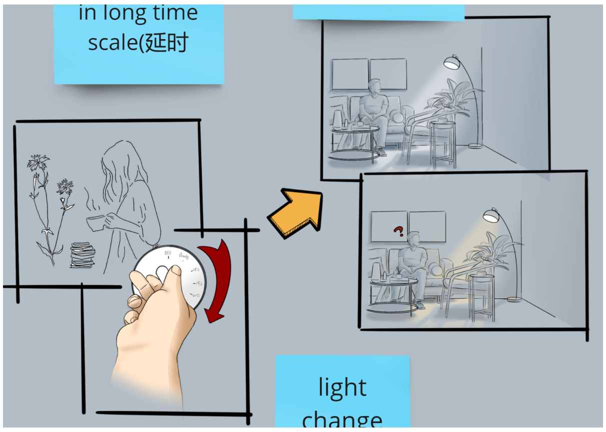
understand: a conversation with the system (answers from the system)
She think it works; and if do it every day, the system can recognize my preference better (learn my preference); the answer makes her feel then she don't need to do anything herself. and willing to interact with it every day. I can see the comfort.

but may not fit in her house, because the current system is always the same.(change once in 24 hours) it is not that regulated and long lagging. sometimes experience the conflict but now she just leave the system alone. this house has low humidity. she bought two humidity meters. because lots of neighbours complains about the low humidity, she gets curious and she also experiences it. higher than 40%- shows a smile on the small screen.
mentioned that the central panel was designed in kitchen but later change to living room because usually kitchen has a higher temperature, affecting their understanding on set temperature.



favourite among "system state"
can see multiple things happen
nice to know what is happening (heat pump)
especially in this house, you would like to use energy when sunny, so it is good to know if it is sunny (remind) because she does not have a battery so not store the solar energy in the house.
you don't have to consider it is a "smile"

setting the temperature higher- bigger smile; but in reality it means consume more energy; so may be better to change the orders. the lower temperature you set, bigger smile you get.



confused a little bit; the light has to be on?
if have children at home, may get crazy and would like to get rid of it
can be disturbing, depending on housemates
she will ask “What are you doing?” when living with your husband and children
if it is a good temperature and then someone else change it, annoying, but the feeling is subjective
I don’t want something affect the whole house.
personal colour- indicate who is changing the setting; this is better but then it has to get some identical info

favourite among “supporter involvement”
this can help if live with more people together. If central organized, can see other people’s advice, and can be put within the house. can be combined with the porch one.
in a bigger building, know other’s feelings, if you change the setting, and the next day receive lots of red dots
people may not be at home during the same time slot.

LB 70

move here one year before
live with his wife and two sons

old house: insulation problem + energy crisis
look for the house: good insulation + **energy efficient**+ close to the center
it is close to the day care and older son’s school
sustainability is the most important thing.
lucky not to experience the energy crisis in the old house because it is summer
used to 100 euro/month, later become 300 euro/month, too expensive
for current house, because it produces lots of energy- from solar panels, so get money back instead
previous owner: get 500 euro back/year
have 16 solar panels- produce lots of energy if it is sunny-able to supply the whole family living for 4-5 days
not have a battery but connected to the grid- so produce energy that others can use and get money from it.
have two meters: one for consumption; and one for the energy sent to the grid
so advanced

two valves: one for floor heating and one for hot water
once a year regular maintenance - 10 years guarantees

ususally set to 21; if outside is warm, change to 20 but may not work
in winter set to 21.5/22, because his son born

it is the set temperature and also it detects the temperature around it
of course, in the winter, if close to the window, temperature will be lower - unavoidable

icon-flame-heating
icon-fan/another-heat pump not working (think cooling caused by insulation + refrigeration in the pipe cooler)
Summer - inside so cool - satisfy

temperature in the boiler (display on the screen)
never adjust the hot water mode
the supply is enough for the family

if one uses the water in the kitchen, the one upstairs who is showering feels cold due to the system design (distribution)

think advanced ventilation system
and can hear the sound- very powerful
forget how to set the timer (in the kitchen)

ventilation connected for all the rooms

but not feel the smell spread around the whole house

solar panel system: can see how much it produces today
have a thermostat in each room and can control the temperature for each room

turn it off during night- noisy
but keep the window closed during night- do not think it is a problem
they believe it cannot be super insulated so should be fine
sometimes open the window to refresh the air, (open a little bit)
keep the habits

the temperature - the actual indoor temperature- it changes quickly
when turn it, can see what temperature you are setting
currently, the whole system is off
downstairs: display the temperature you choose

love it and are satisfied - this is what they want

neighbours nice and more suitable - used to have old neighbours - here his son has lots of friends
community - good

know that should keep the window closed
follow it during winter and summer and also prevent insects

during spring and autumn- turn off the system, so no need to turning on the heating.

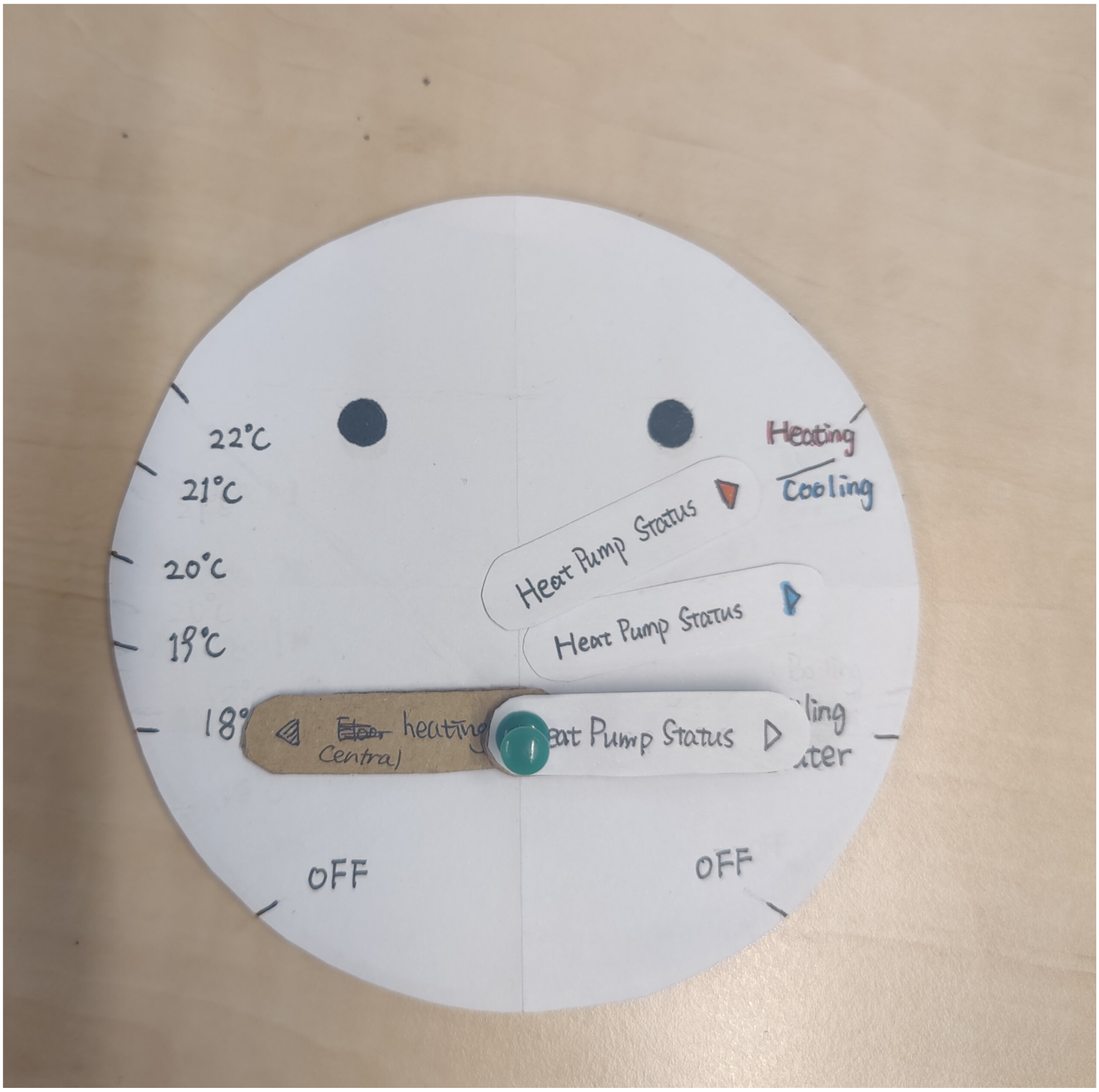
closed system - not mixed with other

boiler still makes them hot, and supplies hot water, but not delivering hot refrigeration to different rooms for heating.

experience the leakage - just fixed it

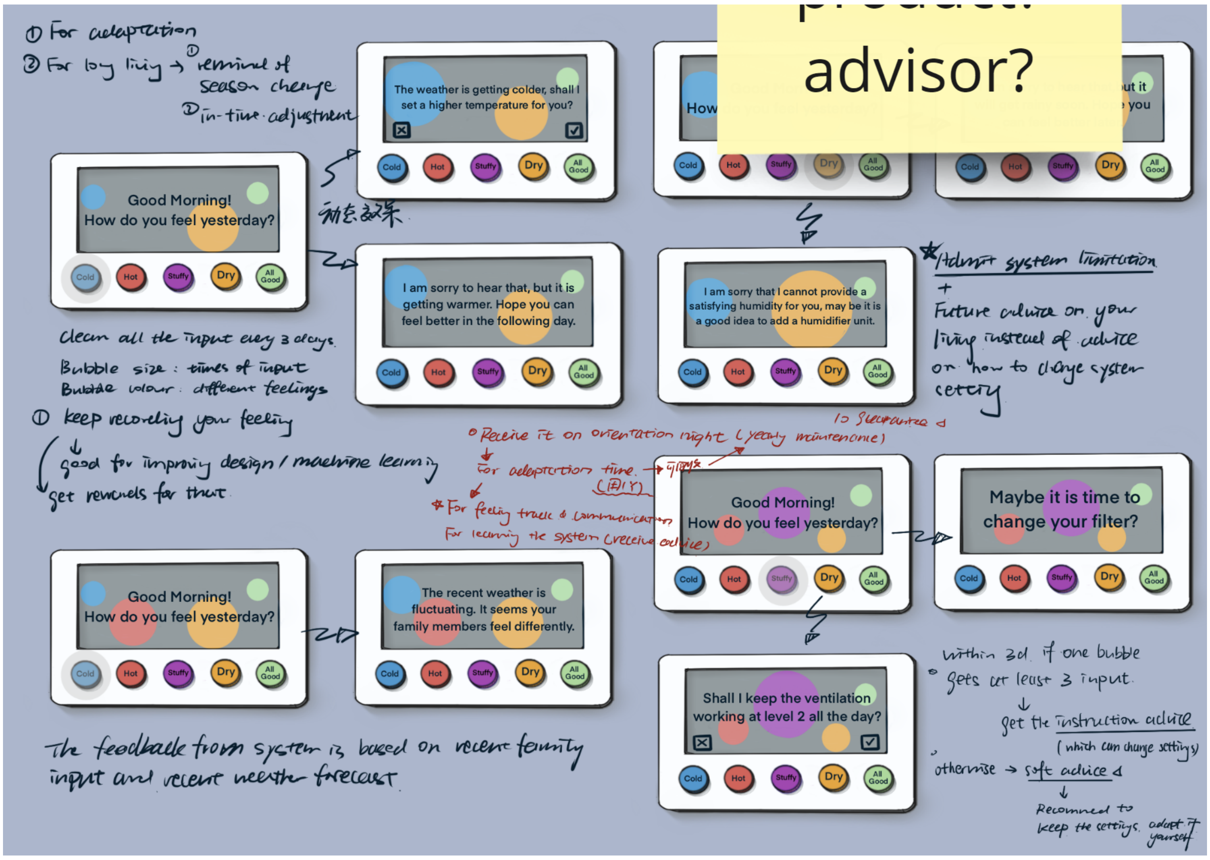
feel dry living in this house but they come from a dry area, so it is fine for them to adapt.
don't think their neighbour knows how it works
problem with CV (pressure and hot water supply), and contact technicians, but poor service takes a long time (5-7 d) to fix it
they have lots of departments and pass to different departments
everyone just says it is not their responsibility

Facebook group page - very nice community
WhatsApp group



a bit confused- maybe because I put heating and cooling together - so it looks like two positions but super close to each other
depends on temperature gradients
it is a good explanation of the system with the help of my explanation (but when he just experience it by himself, he is a bit confused, due to the poor quality of the prototypes)
for him - not difficult to understand
“big smile” - important for them, better to show the most sustainable choice
maybe make it a seasonal display
guiding on sustainable choice - good to have
if understandable and simple - not funny
they don’t know how the system work actually - good to provide more information on it

confused- putting “heating” and “cooling” at the same place



if their sons get older, happy to have it, because they can also play with it (but children are the priority)
currently not fit, only my wife and me interact with it
I already know her preference and would like her to be in the most comfortable indoor climate. I like cold but can tolerate hot. (a bit sacrifice)
might be unpleasant for them to record and have the system - does not work

just record feelings and give recommendations - better; not just change the system
when he first experience it, feel it will be a controller (normally a screen installed at home should be functional)

should be fine for a family to show individual feelings

Appendix I: Evaluation Plan

EVALUATION PLAN

Research Aim & Questions

Key aims

To evaluate whether the concepts can effectively raise households' interest in learning the conflicts behind "crises" and discovering their own response.

Research Questions

1. Can the dial design and the light design in *“clock” display concept* convey the real-time system status effectively to improve understanding and inspire experiments?
2. Can the interlocking design in *“clock” display concept* highlight heat-pump system features to inspire new response?
3. Can the bubble design in *Feeling Message Board concept* effectively raise user’s awareness on individual difference in perceiving indoor climate to inspire family discussion and tailored family adaptation?

Method

Participants

- living together with his/her family in the same house.
- have the willingness to move into a ZEH or already live in a ZEH

Stimuli

- **Digital Prototypes** that can simulate the interactions and response
- **Digital Prototypes Download:** https://drive.google.com/file/d/1eh_9nt2TQ8IpsQ3tZ6TqjB2K3_gDcBs7/view?usp=drive_link

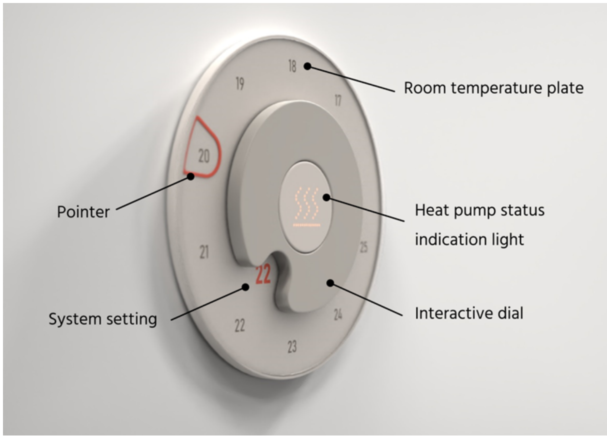
Script/ procedure

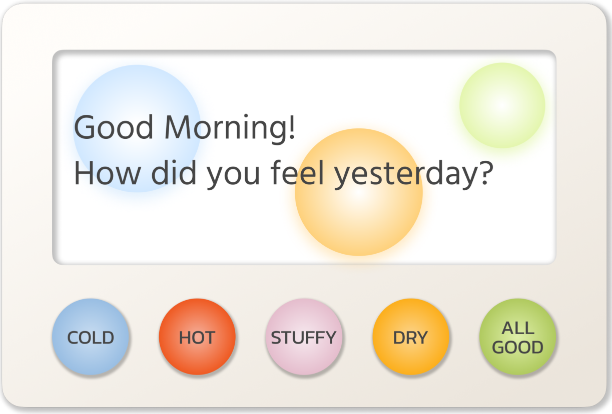
Details:
https://docs.google.com/forms/d/e/1FAIpQLSe82pcbKo8gF53_4XhmZzF3o1iJI6Q-Lgtp9wJ4YBtSAg_X9Q/viewform?usp=sf_link

This project is about adapting to the new indoor climate system in the zero-energy house which is based on a heat pump. The new system has some unique features that are not aligned with users' previous cognition thus some conflicts ("crises") between the tech and residents happen. The test aims to validate the effectiveness of my design in raising households' interest in learning the reason and discovering their response. The test will last around 40 min in the form of an interview.

NOW: Imagine you with your family move into this renovated house in September. The technicians told you the new heat pump system here can help you largely save the energy bill and keep the indoor climate constant which can ensure comfort and healthy. It is for both domestic warm water supply and indoor temperature regulation. However, you should prevent frequent turning on/off and opening the window.

You have the thermostat in every room. (Introduce the basic function of the "clock" concept) and you received a small device from technicians which helps for adaptation. You can report your feeling here, see all the family members' records, and receive some advice on living with the new system. (Introduce the functions of the feeling message board)





Scenario A: dial design

- It is November, the first winter you have in this house. Recently, the weather suddenly drops (a big fluctuation is happening) and the indoor climate gets uncomfortable and unsatisfying.
- Can you describe what will you do then normally (in the current context)? (Walk around the house; describe their action)
- You now interact with the thermostat, imagine changing from 19 to 21. (experience the video of light shining heating pattern change):
    - how do you understand it? What system features do you learn about?
- During interaction, rotating to show all the possible settings: how do you understand it? What system feature do you learn about?
- you are watching TV with your family in the living room (living room picture+clock moving). Suddenly, you hear a strange noise. You feel confused and go to the thermostat to check the system status (defrost shining): How do you understand it? What system feature do you learn about? What will you do then?
- Later at night, in the living room (living room picture+clock moving): How do you understand? What system feature do you learn about? What will you do?

Scenario B: interlock design

- After showering, you are lying on the bed, scrolling your phone, feeling warm and satisfied. and your family are still downstairs. Suddenly, the dial rotates and the light is on. (GIF): How do you understand it? What will you do then?

- But You are satisfied before, so would like to adjust back a little bit. (experience auto returning back): how do you understand the response? What will you do?

- Later at night, You would like to change the settings for better sleep environment, experience boiling water shing + auto returning back, How do you understand? What system feature do you learn about? What will you do?

Scenario C: bubble design

- It is now morning, you still feel a bit cold last night. You are having your breakfast now. You picked up the device and report your feeling. (the bubble and the greeting page; beginning and in the end) How do you understand the bubble change?
- It is now evening, you have been back home for hours but you still feel a bit cold. You pick up the device and notice the bubble is different now (digit prototype): How do you understand the bubble? And what will you do then? After your feeling input, a new response: How do you understand it? What will you do then?
- The second day. You feel warm, even a bit hot. You picked up the device and report your feeling. (interact with the digit prototype): How do you understand the bubble (have previous recording)? What will you do then?
- The third day,...
- The forth day, bubble clean up: How do you understand it?

Analysis Approach:

- “How do you understand the system/design?”: indicate the effectiveness of the hypothesis.
- “What will you do?” - observe their reaction and exploration process; indicate whether motivates active exploration/ stimulate family communication.

THANK YOU