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In Control or Being Controlled? Investigating the Control of Space Heating in Smart Homes

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Abstract: Low-carbon scenarios for enabling heat demand flexibility in district heating networks include smart home technology (SHT), which can automate control of heating by responding to utility signals while considering household preferences. This study empirically explores how control of space heating using SHT is performed in heating practices by occupants. The study is based on in-depth interviews and home tours with occupants living in smart homes in Denmark. The results suggest that (1) practical knowledge, (2) notions of being in control, and (3) temporal aspects of everyday life are of specific importance for how occupants perform control of space heating using SHT. Furthermore, results show how occupants act when feeling out of control. The data illustrate that control of space heating using SHT is performed in a variety of different ways, displaying the dynamic relationships between the materiality of the home, the importance of practical knowledge that occupants draw upon, and the meaning they ascribe to 'homely' practices. As SHT limits people's active engagement in controlling space heating by relying on automated features, the findings presented in this paper highlight how control of space heating is more than the ability to control but concerns the dynamics of social practices performed within and outside of the home. Based on the results, the paper recommends four specific design and policy implications for future SHT solutions.

Keywords: smart home technology; demand-side management; energy demand; energy flexibility; control; everyday life

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1. Introduction

Danish heating utilities must increase the level of renewable energy sources (RES) in their energy mix [1] to meet the milestones on the Danish decarbonization roadmap, which aims for full independence from fossil fuels in the overall energy system in 2050 [2]. In Danish residential households, 84.2% of the final energy consumption is used for space and domestic hot water heating [3], and it is therefore an area of energy consumption that plays a key role in low-carbon transition scenarios. Domestic heating sources differ (according to building type and geographical areas), but as 64% of all Danish households are connected to a district heating network, the network remains an important focal point for future interventions. District heating networks (consisting of more than 400 utilities) have not yet been fully electrified, and as of today, most of the energy production relies on biomass [3]. Political visions for the future include transition scenarios for electrifying the district heating network [2,4], and energy demand flexibility is thus an emerging issue in this context.

In Denmark, short-term peak demand primarily occurs during the heating season (October to April), when energy is used for both space heating and domestic hot water. Short-term peak heating demand occurs in the morning because many people shower before going to work or school [5], and in the afternoon because most people return to their homes (although it is a smaller peak).

As the amount of intermittent RES increases on the generation side, the demand side must become more flexible and ready to adjust demand relatively quickly. Technical solutions have been broadly investigated and include solutions that are based on storing energy in the thermal mass of a building or domestic hot water tanks [6,7]. On the energy demand side, that means shifting the heating baseload to times of the day when energy production is in surplus and avoiding peak demand [6,7].

Visions of enabling energy demand flexibility in the district heating network include using connected technologies, often referred to as smart home technology (SHT), that can automate control of heating, respond to utility signals, and consider household preferences [8,9]. One scenario is to apply a preheating strategy, load-shifting the critical morning peak (and the afternoon peak) to other times of the day [7]. SHT is expected to conduct such load shifts automatically, either with basic prescheduling or with more advanced machine learning features (e.g., model predictive control) [8]. Included in many of these visions is also the idea that occupants should not notice a change in their thermal comfort due to load-shifting activities [10,11]. While some studies show the potential of enabling heating demand flexibility in low-energy buildings without a loss of comfort for occupants [12], other studies have highlighted the need for understanding energy consumption as the outcome of everyday practices and the implications of conflicting visions embedded in SHT [13–16].

As SHT for the control of space heating has become increasingly automated and scripted with algorithms that allow the technology to operate space heating 'by itself' and only with limited involvement from the occupants, it becomes important to critically examine the meaning of control and how control is performed by the occupants themselves. Contrary to expectations, SHT for controlling space heating does not always deliver the energy savings or demand flexibility that it promises [17]. The reasons for this performance gap are often ascribed to the technology itself (e.g., inter-operationality or user friendliness), and the relationship between the occupants and SHT has received less attention. The few social scientific studies into occupants' use and engagement with SHT have shown that occupants often create workarounds or interfere with the technology in other ways, e.g., [18–20]. In this paper, a workaround is understood as a way of maintaining certain ways of performing practices by rearranging certain elements of a set of practices. This includes using technologies or materials in different ways than before or rearranging the notions that one ascribes to comfort or control. Workarounds also include innovations in other practices, such as airing the home in a different way, to maintain a meaningful space heating practice. Workarounds can therefore not be limited to rearranging elements of one specific practice alone.

This paper approaches heat demand flexibility and the use of SHT through the lens of social practice theory, setting out to empirically investigate how control of space heating using SHT is performed in heating practices carried out by the occupants. The purpose of the paper is to understand how using SHT to control space heating unfolds depending on both the characteristics of the technology and the occupant's abilities. The paper contributes specifically to how control can be performed in different ways, resulting in heating practice reconfigurations, and delivers a definition of control as an outcome of practices imbedded in both technology and occupant abilities. Following these contributions, specific recommendations for policy and technology designers include making SHT more familiar and designed for homely practices, increasing the role of intermediaries, and providing clarity on the occupant's role in delivering flexibility.

2. Related Work

Hargreaves and Wilson conducted a literature review on the concept of SHT control (in general) and identified three different approaches: artefactual, perceptional, and relational [13]. Artefactual control concerns the technology itself, relating to the occupants' ability to control SHT physically and to (cognitively) understand how control is performed. Perceptional control concerns the occupant's perceptions or notions of being in or out of

control. The third concept of control, relational control, is somewhat different from the two other concepts of control because it refers to the relationship between technology and people and concerns how control influences people's everyday lives [13]. As noted by Hargreaves and Wilson, the majority of the literature on SHT has approached the subject with a focus on the technology itself (i.e., artefactual control) [13]. Similarly, when assessing the influence of SHT on energy demand, most research has been conducted based on simulations or in experimental settings [21], focusing on the technical capabilities of enabling energy demand flexibility.

Fewer studies have explored the control of SHT as a relational concept in real-life settings [13]. While the amount of social scientific and humanistic studies on SHT has increased in recent years [22], little is still known about how SHT control changes how occupants perform space heating practices and alters the implications for heating demand. With studies focusing on artefactual control as the central unit of analysis for how SHT control can play a role in low-carbon transitions, these studies also tend to view heat demand as the outcome of technical capabilities or as an attribute of the energy system. The risk of such a focus is to neglect or overlook important aspects of how occupants perform everyday heating practices, perceiving heat demand as the outcome of social practices.

Nuancing the Perceived Benefits and Drawbacks of Smart Home Technology Control

In the literature on SHT, it is possible to identify both the benefits and drawbacks of outsourcing control to SHT. In this section, some of the perceived benefits and drawbacks of SHT control (with a special focus on space heating) are highlighted. Although the distinction between the benefits and drawbacks of SHT control is simplistic, the following section aims to bring awareness to common narratives of SHT control as either positive and convenient or negative and inconvenient. This section aims to provide insight into certain contradictions in SHT control, although it is not a comprehensive literature review.

In visions represented by the industry [23] or in policy [24] for the implementation of SHT in residential buildings, the 'smart element' (i.e., internet-connected devices) often plays an important part in providing occupants with a convenient way to accomplish energy savings. Based on a media content analysis and interviews with industry professionals, Strengers and Nicholls [23] found that SHT industry visions are characterized by a narrative of convenience, marketing SHT solutions as a way to a better life while generating energy savings. Likewise, in policy scenarios, such as the European Directives on Energy Building Performance [24], the criteria for SHT in buildings (specifically, the Smart Readiness Indicator) include both convenience and comfort while providing energy demand management, i.e., savings and flexibility. The argument for SHT control of energy demand, either by users, utilities, or algorithms, is that the technology can provide energy and cost savings [13,25] (e.g., by shutting off space heating, automated and remotely, when occupants are not within the home). Specifically, regarding the control of space heating, research on the influence of implementing smart thermostats on energy demand has shown that these technologies may deliver demand flexibility; however, it is also argued that potential gains vary greatly among households [17].

Based on a systematic review of the literature, Wilson et al. [26] argued that more research on occupants' engagement with SHT is needed to understand the potential influence on energy demand when implementing SHT in residential buildings. Socio-technical studies on the use of SHT have found that occupants, contrary to expectations, seldom use the technologies as they are designed. Exploring the long-term use of SHT, Hargreaves et al. [18] argued that SHT is disruptive, prompting occupants to adopt multiple strategies to cope. Similarly, Mennicken and Huang [27] found that occupants are challenged in using and fitting SHT into their everyday lives.

In another study of 23 occupants and their use of a smart thermostat, Yang and Newman [20] presented how occupants conduct workarounds when faced with challenges in using the system. As these and other studies show [28], a risk exists that occupants feel out of control despite the technological design aimed at providing *occupants with more*

convenient control of energy consumption and related chores. Some occupants perceive SHT as intrusive because it 'acts back' on everyday life (e.g., by prompting unwanted changes in daily routines) [16]. When delegating control to SHT, occupants deploy different strategies to cope with these new technologies and either change their everyday routines to cope with what the technology prompts or they might de-script the technology to continue performing their practices in a meaningful manner [29].

In discussing the meaning of home and the integration of SHT, Gram-Hanssen and Darby [30] argued that, as occupants' notions of home are about actively engaging with the materiality of the home, automating practices that occupants usually perform themselves is not always convenient to occupants. This is because the meanings that occupants ascribe to these practices might be meaningful, despite being more inconvenient [30]. Promoting visions of SHT control as a convenient technology that provides control of energy demand and everyday life may not be as convenient as envisioned. One reason for this contradiction may be that SHT relies on underlying assumptions about human behavior that are not reflected in everyday life situations. Strengers argued that SHT visions rely on assumptions about people as so-called 'end-use programmers' [16]. In these, the occupant is assumed to be a technologically able user who can easily configure (e.g., monitor, program, and schedule space heating closely) the technology so that it relates to their preferences, such as specific temperatures in different rooms [16]. Following this discussion on interest and programming capabilities in households, it is important to note that there are also gender differences in the engagement with having, programming, and using SHT [31].

Table 1 highlights some peer-reviewed (empirical and review) studies that have explored the influence of SHT on energy demand and everyday life. Concerning energy demand, a review of the literature by Peffer et al. [32] finds that, while some large-scale studies show that programmable thermostats can provide energy savings (10% or less), other studies have found that they do not generate any savings, and some studies have even indicated that energy demand increases. Regarding more advanced SHT for space heating control, such as GPS-controlled thermostats [33] or smart thermostats [34], the effect on energy demand is also unclear; findings both show potential [35] and a lack of potential [36] for energy savings.

In addition, in the literature on the potential benefits of SHT on the everyday lives of occupants, there does not seem to be any clear narrative. In a comprehensive literature review, Wilson et al. [26] identified a dominant research theme, labeled the functional view, that argues that SHT can help occupants perform everyday practices, among others related to energy management. Similarly, Sovacool et al. [25] identified that increased management of energy demand is perceived as one of the main potential benefits of SHT. A recent study of households' use of an app that combined consumption data feedback and the possibilities of controlling appliances concluded that some savings were achieved but also confirmed several of the limitations for enabling flexibility that previous studies have found [37]. In addressing demand response initiatives using the data of surveys, interviews, and focus groups, Darby [38] also found that some occupants especially liked SHT for being able to have control in a 'better' way and thereby achieve their desired level of comfort, while others found it difficult to control their comfort digitally. Besides delivering a service of comfort, in another study of 20 families living in smart homes, Woodruff et al. [39] found that SHT supports a specific religious lifestyle, promoting the goals of the Jewish tradition of Sabbath.

In contrast, several studies have shown that SHT also involves drawbacks concerning the occupants' everyday lives. As previously mentioned, in a qualitative study, Mennicken and Huang [27] found that occupants felt a loss of control with the increase in automation. A similar result was reported by Balta-Ozkan et al. [40], in which SHT control (and occupants' notion of being out of control) is considered a possible barrier for the adoption of SHT. Other risks include that occupants could increase their use of ad hoc temperature adjustments to their heating demand after having SHT installed, as argued by Miu et al. [41], or that SHT lacks personalization and aesthetic identification for occupants, limiting their notion of

being in control of SHT and their lives, as argued by Takayama et al. [42]. Another study also showed that SHT lacks familiarity and flexibility in the everyday lives of people, as argued by Davidoff et al. [28], meaning that SHT design should become better at accommodating changing routines and plans.

Table 1. Peer-reviewed studies related to the perceived benefits and drawbacks of SHT control.

Benefits	Drawbacks
Energy savings • Programmable thermostats [32] • GPS-controlled thermostats [33] • Algorithmic control [34] • Smart thermostats [35,36]	No energy savings • Programmable thermostats [32] • Smart thermostats [17]
Convenience and comfort • Increased controllability of everyday life [18,25,26,37] • Supporting lifestyles [39]	Inconvenience and discomfort • Loss of control [27,38,40] • Increase in ad hoc temperature adjustments [41] • Technologies need more familiarity in the home [42] • Control of lives, not of devices [28] • Conducting workarounds [20]

Table 1 illustrates that the effect of SHT on energy demand and everyday life is unclear and that competing and contradicting scenarios and narratives are at play. This paper does not evaluate whether the implementation of SHT and the new modes of control have led to increased heating demand flexibility or energy savings in general. Instead, it addresses how SHT control is performed by the occupants when SHT becomes part of the existing space heating practices.

While a body of research has focused on SHT in energy-consuming practices, this research has primarily concerned electricity consumption, and less research has explored how SHT for control of space heating has been performed in practice by occupants. This is especially relevant in the case of Denmark, where the district heating system holds great potential for enabling energy demand flexibility by including residential buildings in the energy system. A Danish study on time-based district heating consumption data for space and water heating shows that different groups of residents have slightly different patterns of consumption [43]. It is seen how pensioners tend to have less peaking consumption, whereas high-income households and households with children show slightly higher morning peaks compared to others. In general, however, all households follow a societal rhythm with a larger morning and a smaller evening peak for heat demand, and therefore it is relevant to study how different types of residents interact with SHT in demand shifting and control of heat consumption.

3. Methodology—Studying Heat Consumption in Households

The study was conducted during the heating season (October to April) in 2018/2019. The study involved 16 household interviews and home tours with occupants in their own homes during the morning or late afternoon. Interviews were conducted during district heating peak periods (5–9 a.m. and 5–8 p.m.). The participants were residents from four different residential areas, consisting of both apartments and terraced houses, all in the Greater Copenhagen region, Denmark. Interviews and home tours were conducted with 1 to 2 adult occupants (18 years or older), but in some interviews, other members of the household were present (mostly young children). Table 2 shows an overview of the interview participants. The participants were recruited using email and flyers (both physical and electronic) with help from residential boards and organizations (e.g., social housing associations) that already had contact with the households. The sample included a 50–50 representation of both female and male occupants, and households varied in size (1

to 5) and age (21 to 58, excluding children). The sample consists of 3/4 (12) owner-occupied houses, and the remaining 1/4 consists of youth housing. Owner-occupied houses were classified as medium-to-high-income households, with asking prices ranging from 300,000 to 1,400,000 euros. In contrast, youth apartments ranged from 500 to 800 euros per month in rent. All households in the sample had district heating as their primary heating source, but varying SHT was installed. In order to account for the different SHT setups in the home and relate that to how control of space heating was performed, is it useful to differentiate between 3 different SHT characteristics, as shown in Table 3.

Table 2. Overview of participants (pseudonyms).

Pseudonym and Age	Occupation	Household Size	Smart Home Setup
Peter (21)	College student	1	Smart home setup A
Anne (25)	College student	1	Smart home setup A
Carina (25)	College student	2	Smart home setup A
Simon (51)	Civil engineer; public official	2	Smart home setup C
Kirsten (23)	College student	1	Smart home setup A
Jan (45) and Carla (43)	Researcher; physiotherapist	3	Smart home setup A
Noah (35)	Political adviser	3	Smart home setup A
Alexander (58)	Researcher	5	Smart home setup C
William (23) and Emma (21)	College students	2	Smart home setup B
Jacob (37)	Financial consultant	4	Smart home setup B
Charlotte (52) and Mia (45)	Consultant; consultant	3	Smart home setup B
Benjamin (45)	Public official	5	Smart home setup C
Liam (58) and Olivia (55)	Politician; consultant	3	Smart home setup C
Sophia (36) and Ethan (41)	Public official; CEO	4	Smart home setup C
Andrew (56)	CEO	1	Smart home setup A
Elizabeth (38)	Public official	4	Smart home setup A

Table 3. Overview of 3 different SHT characteristics which were included in the study.

Smart Home Setup	Control Devices Available for Occupants	Possibilities of Control and Communication	Who Can Control
A	In-home display (IHD), smart phone, wall-mounted thermostats	Control of heat by zoning and scheduling using Wi-Fi two-way communication with thermostats, smart phones, and sensors, but no consumption feedback	Occupants
B	In-home display (IHD), smart phone, wall-mounted thermostats	Control of ventilation and heat by zoning and schedules using WI-FI two-way communication with thermostats, smart phones, and sensors, and including feedback on indoor climate	Occupants or system operator in a test period
C	Wall-mounted thermostats	Automation based on a fuel-shift solution between district heating and electricity with signals from smart meters and the production of RES in the system, including feedback on consumption	Occupants and system operator

All interviews were between 1 and 2 h in length and were conducted in a semi-structured manner, following qualitative approaches as developed by Kvale and Brinkmann [44]. The following topics were included in the interview protocol: daily and weekly routines (in and out of the home), heating practices performed during peak periods, notions of comfort, negotiation of everyday routines and practices, engagement and management of energy use (including smart home setup), experiences with (and strategies for) energy flexibility, and experiences with connected technologies. During the interview, a home tour was conducted where the occupants held a 'show and tell' tour,

explaining routines and practices carried out in each room of the house. The interviews were all voice-recorded and transcribed in full length. The transcripts were eventually coded using abductive reasoning for analysis [44].

4. Findings—Empirical Investigations of Control in the Smart Home

This section presents the results of the qualitative home tours and interviews. The following four themes were identified: (1) how SHT changes the practical knowledge needed to control space heating in everyday practices; (2) how SHT reconfigures the notion of what it means to be in control; (3) how SHT needs to accommodate the flexibility of homely practices; and (4) how occupants stay in control when feeling out of control. These four themes all shed light on how occupants understand (and express) the new SHT control of space heating and how they handle and act accordingly.

4.1. Smart Home Technology Changes the Practical Knowledge Needed to Control Space Heating

The first theme that emerged was related to the occupants' ability to control their space heating using their SHT devices. This includes their understanding of how the technology works and their ability to engage with the technical features (e.g., scheduling and pause mode).

Asked about her direct engagement with the SHT, Anne, a 25-year-old college student, expressed interest and expertise in understanding the features of the technology and how it worked and explained that, after installing SHT in her home, controlling space heating had become more convenient and easier for her to understand:

> *I started using the system* [SHT] *more or less right away, and then I started using the screen* [in-home display] *or the app. Because it's a little bit easier than having to stand there* [by the radiator]. *Also, because it's not the same as the old ones* [manual thermostats], *where you had to turn it using your hands. Now there are more buttons, and I think it's easier to just sit like that—well, OK, that degree.* (Anne)

Anne was primarily using her smartphone as the control interface and found it very convenient because the phone was already an important device in her everyday life. She usually had it to hand and used it regularly throughout the day for many different things (calling, texting, social media, organizing work and school activities, etc.). In addition, it seemed that Anne liked the finer-grained control that SHT allowed her to perform instead of the more traditional manual control of operating the thermostat. In general, Anne was very familiar with connected technologies, and although she did not have any experience with control of space heating using SHT, she found it easy to learn and was quick to adopt this new method of control. Her experience with related technologies from other practices had, so to speak, transcended into her space heating practice, making it easy to control space heating using SHT. In specific, she liked that control of space heating became an embedded part of a technology that she already used and trusted (i.e., her smartphone). The only downside Anne described regarding engaging with the new technology was technical, namely if the Wi-Fi connection was disrupted:

> *I think it's easy [to control]. The only thing that can make it annoying is if my internet disconnects. Because the screen [in-home display] is out there [in the kitchen], and it is connected to the internet, which makes sure that I can use my phone in here [in the living room], and then if the internet doesn't work properly, I can't use it to check it the same way. So, then I would have to go out there [in the kitchen].* (Anne)

In contrast to Anne's experiences, Andrew, a 56-year-old chief executive officer (CEO) from a medium-sized company, expressed that the SHT challenged his way of controlling his space heating because he lacked the ability to understand and engage with the technical features of his new devices.

> *Interviewer: Do you use the scheduling feature of the technology?*
>
> *Andrew: What scheduling?*

> *Interview: The one that allows you to schedule when it should be warm during the day . . .*
>
> *Andrew: I don't use that.*
>
> *Interviewer: You don't use that?*
>
> *Andrew: That's what I'm saying. Now it is winter, and you should probably . . . Now I am going to Kenya next week, and I was also traveling last week. Then, you should probably put it* [the temperature] *down a bit. I don't use it. And I don't use it because I don't know how to do it. So, it's very simple.* (Andrew)

The challenges of engaging with the technology, as presented by Andrew, are related to a lack of familiarity and experience with connected technologies in general. Andrew uses a computer for work, but in general, he described himself as a non-technically savvy person. Unsurprisingly, experience and familiarity with similar technologies seem to be related to how the occupants perform space heating practices and how they reconfigure practices when new SHT become part of controlling space heating in their home.

When occupants control their space heating, they draw (often unconsciously) upon a form of practical knowledge (defined as bodily habits that people have learned through exposure and experience [45]), a way of 'doing' space heating, that they are used to and have experience with. When confronted with new technology and a new way of controlling their space heating, occupants have different prerequisites for engaging with it, which influence the use of the new modes of control embedded in SHT.

4.2. Automation Reconfigures the Notion of Being in Control

As SHT becomes increasingly complex (handling large amounts of data and increasing possibilities for control), it comes to rely more on automated features and levels of machine learning, limiting the occupants' engagement to preference inputs [25]. As control of space heating is increasingly left to technology, it seems just as important to explore how occupants' notions of being in control reconfigure and what that means for their way of controlling space heating using SHT.

In the data, several of the interviewed participants expressed that the increased use of SHT for control of space heating influenced their notion of being in control. In one case, smart home setup B, the occupants' space heating was controlled from the outside by researchers in a series of experimental tests. This was done to investigate the possibilities of enabling energy demand flexibility in the thermal mass without engaging the occupants directly (not advising them about when control was performed) while maintaining their notions of comfort. The technological setup removed the possibility of controlling space heating from the occupants, who could not control their space heating system during specific hours (peak periods). The occupants seemed to dislike this approach because they felt controlled without an opportunity to override the system. At first, Jacob, a 37-year-old financial consultant, was unsure about why the temperature settings suddenly changed in his apartment:

> *When they* [the research unit] *first tinkered with it, we wondered why it was suddenly too low or too high all the way around. So, I am a little unsure what to think about it, because if you do not notice a difference, it is fine, then it makes very good sense that you use less energy in the system at 8 a.m. when everyone wants it. However, again, if our apartment had been a little colder, then it could be that I had thought it was annoying, that they* [research unit] *could do it that day.* (Jacob)

While the research unit, based on calculations of the thermal inertia, had lowered the temperature (during peak demand periods) so that the actual indoor temperature would remain the same as usual, the interview with Jacob showed how his notion of control changed, although the indoor thermal conditions did not. As Jacob realized that the set-points in the apartment had changed, he felt a loss of control and started reflecting on his preferences. Occupants are seldom aware of their temperature preferences, and increasing

automation of space heating might change occupants' preferences. Another risk is that if occupants feel out of control of their space heating (despite having the practical knowledge needed), they might want to conduct activities that ensure that they once again feel in control. That could include working around the technology, limiting it, or disrupting the actual effect that such technology is expected to have.

The notion of feeling out of control was not only related to occupants who had a highly automated system. Elizabeth, a 38-year-old public official who had a smart home setup allowing her to control space heating herself using her IHD or smart phone, also expressed that her notion of control of space heating had changed after installing the SHT in her home. Elizabeth acknowledged that increased automated control of space heating could work, but that the technologies should feature a manual override as well:

> *Interviewer: Would you prefer complete automation, so that the system was operating solely on its own?*
>
> *Elizabeth: I guess yes, I mean . . . It's a difficult question now because it depends on how efficient that system is, right. I also like to be able to control maybe manually sometimes my room system, although we don't do it that much, but to have the option of—if the bathroom gets too hot, then maybe putting it down, or . . . but, I mean again, we don't do that so much. Yeah, I don't know, it's a good question, maybe—if it worked, the system, yes. The problem is often I see that it doesn't work. We have that in our workplace, that's like a smart city, so everything is automated. When the sun comes out, the blinds go down automatically, there's nothing to pull the blinds up or down, right. And often you're sitting there with the blinds going up and down because there's clouds . . . I would say there are certain pluses to an automated system, but I think there are negatives as well. And that manual sensation of being able to control your environment kind of gets a little bit skewed, right.* (Elizabeth)

Elizabeth expressed concern about the actual efficiency of the SHT and related her experience to another smart system at her workplace, which did not accommodate the practices taking place (blinds going up and down). The notion of control in Elizabeth's case seems related to a manual sensation of being able to control and, thus, to a lack of trust in the rationale behind the technology.

A similar concern was expressed by Benjamin, a 45-year-old public official who had a different smart home setup than Elizabeth and Jacob. Benjamin explained how the increased level of automation in his home also changed his notion of being in control. Instead of being responsible for conducting control of space heating himself, he now felt overwhelmed and out of control: *'I feel like it's so automated here* [at home] *that we really can't control anything. I can feel that. However, the question is how much I would do it if I could'* (Benjamin). While Benjamin acknowledged that increased automation has led to a notion of control loss, he also recognized that the use of automation could perform tasks that he might not perform himself.

> *Interviewer: Would you like to have a system that was more automated?*
>
> *Benjamin: Yes, I could easily imagine that, and I could easily imagine a system that could connect to appliances more easily and where it became easier to regulate these things, so you might set your washing machine to start when the electricity is cheap, so I don't have to keep an eye on it. I would think that was ideal. Or that you could get messages about how prices and power supply were at certain times and days, e.g., that you can advantageously start your dishwasher at. 23:00 instead of 9.00. It wouldn't make any difference to me. However, it is because I do not know and do not bother to spend time getting into it. And then I could turn it* [the dishwasher] *on automatically, instead of when it's full no matter the time.* (Benjamin)

Both Elizabeth and Benjamin could see potential benefits in terms of the convenience of daily chores and the economic savings that automatic control of energy demand could generate. They were also concerned about the lack of possibilities for override (which

seemed important for the notion of control) and generally expressed a lack of trust in the automation of space heating. While Jacob had experience having his space heating controlled from outside of the home, Elizabeth and Benjamin did not. A similarity was that all three expressed that increased automation of space heating could potentially lead to a notion of feeling out of control (and in Jacob's case, this was a lived experience).

4.3. Smart Home Technology Control Needs to Accommodate Flexibility of Homely Practices

Control of space heating has a temporal aspect, which is also recognized in demand side management initiatives, such as preheating. In addition, SHT involves features that allow occupants to set up a schedule for heating (when it should be turned on) and an opportunity for occupants to override it. Many of the interviewees used the scheduling feature of their SHT, which was typically set up in the initial period after installing the technology. Those who used the feature set a schedule that was intended to reflect their daily rhythms, typically heating while they were in the home and turning off the heating when they were not. Contrary to their expectations, occupants who engaged with the SHT (and set up a schedule) found themselves making many ad hoc adjustments to the scheduling, which is a result also reported by Miu et al. [41], although this might not be as problematic in relation to energy savings as previously assumed as reported by Huchuk et al. [46] and Stopps and Touchie [47].

In this study, ad hoc adjustments were made because occupants did not feel that the schedule reflected their everyday rhythms, which was less routine than they initially thought. Using her smartphone, Kirsten set a schedule for space heating and used the possibility to remotely control and monitor the temperature in her home while not present. Kirsten explained how she used the remote control:

> *I only use the feature 'vacation mode' if I need to get out the door. In fact, I can also set it for certain dates that I know I'm going on vacation. I sometimes carry that* [iPad] *around. For example, if I am at my parents' place and I decide to stay there an extra day, then I like that I can pause* [the schedule] *it from Friday night to Sunday*. (Kirsten)

While Kirsten used the schedule, she also revealed how she used the SHT to accommodate flexibility in day-to-day life, which was often characterized by more irregularities and unforeseen activities than suggested by her space heating schedule. This meant that Kirsten often used her smartphone to remotely control the space heating and override the schedule. Kirsten also used the 'vacation mode' of the technology (i.e., shutting off the system until the occupant returns home and presses the button again) when going out the door. Despite finding the scheduling feature useful and taking time to carefully schedule her space heating, Kirsten was actually making more ad hoc adjustments to the system than before.

Similarly, other occupants found the possibilities of remote control meaningful, but despite their initial intentions to use it, they failed to continue to do so. Noah, a 35-year-old political adviser, explained as follows:

> *Noah: Just when we moved in, I was excited about the new system, so I tried to get into it with a very open mind, and then I also downloaded this app, and then I think there was something interesting in being able to put it in a holiday mode, where it then turned down the heat. Because there are both some climate considerations, but there is also an economic consideration. And I probably did that the first 2–3 holidays and then I must admit that I stopped doing it and have not really done anything since.*
>
> *Interviewer: And how fast has that transformation happened?*
>
> *Noah: Well it happened after 6 months. The first half year, I think it was interesting to 'geek' a little because you can put it on that holiday mode for example. However, then after half a year, I stopped. It was kind of a bit of a combination of that, then we could also have some friends who came by the apartment, or my dad came by and things like that. And then I thought that if you wanted to lend it to some friends, it would be cold. Or I do not know. It is not just that I haven't consciously thought that now I have stopped using*

> *it. I could easily do it again tomorrow if we were to leave for a week. I really think the primary reason is just that you forget it.* (Noah)

While Noah was initially interested in and actively engaged with the system, he explained how he eventually stopped doing so. This was a rather unconscious decision, but Noah explained the importance of space heating accommodating a certain amount of flexibility in everyday life. Noah mentioned that the possibility of having guests at his apartment restrained him from using 'vacation mode.' This was even though Noah did not have guests at his apartment very often, but the scheduling and control of space heating using SHT were considered inflexible in that case. To Noah, control of space heating was also about being able to handle future and unforeseen events (which might not occur).

Another participant, Liam, also expressed concern regarding the SHT control of space heating due to the irregularities in his everyday life:

> *Interviewer: And would you like to be in control or to have it done more automatically?*
>
> *Liam: No, it would not make sense for us to have something that was too automatic because we have so much. Our usage pattern of the house simply fluctuates so much. So, there is no such thing as us leaving home every day at eight o'clock and every day being home at five o'clock.* (Liam)

The concern expressed by Liam was that automation of space heating would complicate the coordination of space heating with the activities that unfold at a certain place and time and would lead to him being out of control.

An important element in the vision of enabling energy demand flexibility using SHT is the preheating of buildings without generating discomfort for the occupants. The interviewees expressed concern that SHT could complicate the coordination between their activities and space heating, which is a result that was also reported by Hanmer [48]. A concern with the preheating strategy is that it could challenge occupants' sleeping routines (and preferences for sleeping in a cold bedroom). As this analysis has suggested, occupants expressed concerns related to the coordination of activities with SHT control of space heating, which were that they were generally too simple in their representation of daily rhythms.

How Occupants Coordinate Control of Space Heating Using Smart Home Technology

Space heating and airing (understood as a practice that occupants perform to manage airflow in their home related to cooling rooms and aspects of smell and fresh air) are closely related and coordinated practices, and some interviewees also mentioned that their way of airing their homes had changed since the integration of SHT. These occupants explained that they had become better at adjusting their space heating when airing the apartment due to the new control modes that made it possible to shut off the entire heating system with one push of a button. In contrast, other participants reported that their coordination between heating and airing had not changed and that the new modes of control led to more instances of not adjusting the heating while airing their homes.

In coordinating airing and heating practices, occupants seemed to take stock of the different materialities in their homes, such as the type of floor and insulation, and evaluated the interplay between such materialities. Noah explained as follows:

> *Noah: The floor heating is controlled with a thermostat, just like radiators, but since the floor must first be heated or cooled, the regulation is much slower than ordinary radiators. In other words, it takes longer to heat or cool a room with underfloor heating than with radiators, as the hoses are slightly cast into concrete. And I have been told by the entrepreneur when I bought this* [house] *that it can take a minimum of 24 h to make any temperature difference, so therefore we will never be able to use this to say something like 'No, it's a bit cold tonight, we turn up the heat a bit'. Forget about it.*
>
> *Interviewer: So, therefore, it must stand on the same set-point all the time?*

> *Noah: At least that's my opinion. Well then, it may be that if we think it's hot or cold, then we can adjust it up and see if it's better tomorrow night. That's the perspective one should have. And with holidays, there is also something to it, but, for example, for a weekend trip, it does not make sense to put it in holiday mode, in my head at least, because it does not have time to turn down before it must turn up again. And in fact, that way it might use more energy, instead of just having it stable. So, we must go travel a week before I think it makes sense.*

As SHT becomes a part of occupants' homes, it is also becoming part of an assemblage of different things and technologies already in place. Therefore, SHT is entangled in an interplay between different materialities and how occupants use and understand control of space heating by taking stock of the different materialities and the connectedness between them. In the case of Noah, he does not find the interplay between SHT and the underfloor heating compelling and does not believe that it can enable energy demand flexibility while maintaining his comfort.

Familiarity with certain technologies and how that is produced and reproduced as a routine way of doing things was also reflected in the interview with Noah:

> *In relation to putting it on holiday mode, yes, we probably do not turn down so much because you forget it. When you had the radiators on the wall, you had like some check rules. You would walk around and turn off the lights and check the doors and empty the refrigerator and turn down the radiators. And we haven't really incorporated a rule with . . . and that's really stupid because it only takes just two seconds to press it in, so it should be the easiest in the whole world, but we do not have that* [routine]. *So, there is probably something there where you just need to get better at it. However, again, it is also because when it is a thing as such* [underfloor heating] *it disappears a little. So that you do not have those physical devices hanging on the wall, then you feel it, so you do not feel it in the same way. So, there is some satisfaction in that you go on holiday and then you feel it, and then you come home and feel that they are cold, and then you have such a good feeling that 'well yes, they have been cold the whole holiday'. But, like, when you go on holiday now here and you never see those heaters, you do not think about . . . Then, you think about that it is something that is standing and running. And you cannot physically feel if they have been cold or if they have not been cold. So, when you have such a system that you half believe in, you think a bit 'how much does it really matter?' and 'how much does it really matter in the big accounts?'.* (Noah)

In his old home, Noah perceived control of space heating equipment (i.e., manual thermostats) as an integrated part of the home's assemblage of technologies, and he expressed a specific set of rules (e.g., when going on vacation). This has now changed, and Noah does not turn off the heating when going on vacation, despite 'less work' going into doing so. A second takeaway from the above quote is the sensory knowledge that Noah expressed concerning how he uses and understands the control of space heating. Noah found satisfaction in feeling cold radiators and drew on this specific sensory knowledge when controlling his space heating. With the new technologies in place in his home, he lacks this sensory feeling and, thus, refrains from adjusting it.

4.4. How Occupants Stay in Control When Feeling out of Control

Another interesting theme that emerged when interviewing the participants was how the occupants handled and acted in situations in which they felt out of control. The following section highlights some of these strategies and their causes. In the interview with Elizabeth, she explained some of the challenges of controlling space heating using SHT while maintaining her routine of airing her apartment (especially in the morning):

> *Elizabeth: Yeah, I usually air out in the morning. However, I mean, that was one of the things we were told by the manufacturer* [of the smart home technology], *not to open the doors for too long because that's what the ventilation is supposed to do. And then if we open the doors for too long, that's what kind of screws up the heating system, it*

> *gets confused because suddenly it's cold. And then you have these monitors in each room that measure the temperature. So as soon as it feels cold air, it will kick up the heating even more. So, you air out, close, and then the heating is gone up and it's even warmer than before.*
>
> *Interviewer: Has that affected your practices of opening windows?*
>
> *Elizabeth: No, what we've done is just to take down the heating devices instead, so that it doesn't kick in. I mean, in the bedrooms, I don't think we had the heating on during the winter really.* (Elizabeth)

Despite receiving information about the SHT from the manufacturer, Elizabeth explained how she maintained her practice of airing and created a workaround to disrupt the automatic functionality of the SHT. As Elizabeth took down the temperature sensors connected to the SHT, she was able to maintain a meaningful practice of both airing and heating. Nevertheless, this workaround meant that Elizabeth's heating was partly limited in terms of automation (not being able to react to temperature sensors); therefore, Elizabeth had to adjust the temperature more directly (e.g., when opening and airing her apartment).

Other interviewees also explained how they changed their space heating practices, including 're-scripting' the SHT. As with Elizabeth, they did so to maintain what they considered to be meaningful homely practices. The strategies the occupants applied were different, and while some did so to maintain specific airing practices, others did so for aesthetic reasons. This was reflected in the interview with Jacob:

> *However, they* [control interfaces] *are twice as big as the standard Danish power outlet. It also means something. The electrician has also made some 'fun' choices by just putting them up at full height. It's nice enough that they are there, but we might not have wanted them, knowing that they are so big. It is about aesthetic, but it also means something in relation to these systems. Instead, I would rather have some sensors in the ceiling and an app. I do not need to be able to read the temperature.* (Jacob)

Jacob explained that the reason for not engaging in a daily manner with the SHT was a matter of aesthetics and that he perceived the new technological devices as too aesthetically disruptive in his home. He chose to 'hide' the technology in a closet, which generated the problem that he had to open the closet when he wanted to access and control the space heating: *'However, you have to remember to open the closet* [to access the technology]. *So, we may have to put it somewhere else, so that's another thing with these modern things; they are insanely ugly'* (Jacob). To Jacob, the design of the technology lacked familiarity in his home, which resulted in less engagement (because he hid it away).

The above section suggests how occupants have different strategies for dealing with a sense of feeling out of control; however, it also reflects how SHT is situated in a myriad of practices performed in the home and the interconnectedness between them. To the occupants, control of space heating is more than a matter of having the ability to control SHT; their considerations are also related to aesthetics and comfort. Thus, control in space heating practices is about controlling the homely environment by keeping it aesthetically pleasing and comfortable.

5. Discussion

Conceptualizing control of space heating as a social practice in a theoretical sense facilitates a multifaceted understanding of control as relating to competencies (knowing how to control), meanings (notions of being in control), and materiality (embedded control features). Instead of conceptualizing control in relation to different and often singular elements that are entailed in the dynamics of a practice, this paper proposes the following definition of control:

> *Rather than being a competence, a feature of technology, or a notion, control is the outcome of practices performed in everyday life. Control is produced and reproduced through the*

performance of everyday practices and reconfigures who (agency) performs them and when (temporality) they do so.

The proposed definition of control implies that control is produced (and reproduced) in a myriad of different practices—those performed in the home but also those performed in the design process of SHT. Through the performance of these different practices, control and how it is understood become increasingly interlocked. As the findings presented in this paper show, features of control embedded in smart home technology setups matter. In the sample, occupants had different modes for enacting control of their space heating, which to some extent could explain different possibilities and abilities to control space heating. However, control was also related to notions of feeling in control (of homely environments). Occupants expressed that living with a fully automated system increased their notion of being out of control. This underlines that smart home technology for controlling space heating needs to embed features that at least let occupants have the possibility of overriding the automated control. However, in the case of energy demand flexibility, technical solutions often rely on a narrowly defined concept of control. This involves perceiving control as something that only concerns technical capabilities. As reported in the literature and this study, control is performed and understood by occupants in the context of their everyday practices. The design of SHT must broaden the concept of how control is performed and acknowledge that technical solutions cannot stand alone. While SHT is an important element in transition scenarios and might contribute to increased energy demand flexibility (as seen with energy efficiency), it can only be part of the solution. If control is the outcome of practices, then transition scenarios also need to consider how to change practices, as new and more flexible control of space heating (which is needed if we are to sustain the current energy demand patterns) can only be achieved through a reconfiguration of such practices. This means understanding control as something that does not only concern the technical features (e.g., allowing for overriding and preference input), but also as a concept that is closely related to notions of home, comfort and convenience. This implies that despite users having the ability and possibility to enact control of space heating by using smart home technology, their notion of home might not match the embedded features of automated systems. The findings presented in this paper show that embedded features of control influence how space heating is performed. However, it also shows that focusing on the embedded features for control is not enough. Initiatives towards enabling heat demand flexibility using SHT need to include a more holistic perspective of what it means to be in control of homely environments, alongside looking at the abilities for engaging with smart home technologies.

6. Limitations

The findings in this study are based on a relatively small sample of occupants, and the aim is not to deliver generalizable results on how different smart home setups are driving certain perceptions of control or space heating practices. Instead, the aim has been to broaden the understanding of control by conceptualizing it in relation to abilities, notions and the interlinkage between practices being performed in everyday life. A limitation of the study is thus that it does not provide insights into in what way different kinds of technological installations (e.g., fully automated systems) drive a certain difference in how control is perceived or enacted. Instead, it highlights that control is both something embedded in technology and in the occupants' ability to control. Furthermore, control is a notion. Control is therefore not only enacted through engagement with SHT but also implies ways of thinking about what home and comfort mean to occupants.

A second limitation is that the sample used in the study is not representative of other contexts. Social, cultural and material/natural characteristics shape how space heating practices are performed. The specificity of the Danish district heating system may not be comparable to other ways of doing heating, and notions of control as well as the ability to control might be different in other countries or regions. Instead, the findings put forward

in this paper serve to illustrate that control of space heating is a multifaceted concept and not only a matter of embedded features or occupants' ability to control it.

7. Conclusions and Implications

First, the paper empirically illustrates how SHT reconfigures the practical knowledge needed to control space heating. This highlights the practical knowledge that occupants draw (often subconsciously) upon when doing space heating. When different occupants with different levels of practical knowledge are confronted with new technology and a new way of controlling their space heating, their existing knowledge plays a key role in how they perform space heating practices using this new technology.

Second, the paper illustrates how space heating control using SHT is influenced by the notions that occupants ascribe to their homes and everyday lives. With increasing levels of automation, SHT might change the notions and preferences that occupants already have, resulting in a demand for higher levels of comfort and convenience. Additionally, the data suggest that some occupants express a lack of trust in SHT and its ability to accommodate their existing notions and preferences.

Third, this paper suggests that control is also a relational concept influencing the temporal aspects of the everyday lives of the occupants. While SHT encourages occupants to make fewer ad hoc adjustments, the interviews indicated how the occupants used the SHT to accommodate flexibility in their homely practices rather than energy demand flexibility. This was reflected by a perception of everyday life as irregular and a concern that control of space heating using SHT could not accommodate that. This shows how SHT becomes an integral part of occupants' perceptions of technologies already in the home and how occupants take stock of the interplay between such technologies.

Fourth, the paper showed how occupants conduct workarounds when feeling out of control to maintain meaningful practices. The reasons for conducting such workarounds were manifold and were more than a matter of achieving a comfortable temperature.

Occupants understand SHT as both disruptive and convenient, and their use of SHT to control their space heating differs in many ways. Thus, it is not an easy task to design universal devices and policy interventions that can be successfully adapted by occupants and enable much-needed energy demand flexibility. This paper argues that a start is to consider control to be a multifaceted concept produced and reproduced in a myriad of everyday practices. Following the themes highlighted in this paper, the following implications could be considered in design and policy for SHT to enable energy demand flexibility and increase occupant engagement.

(1) Design for flexible homely practices: While the technologies are designed to enable energy demand flexibility, less focus has been on how technology can accommodate flexibility in everyday practices. Occupants expressed that their use of SHT was hindered because their everyday lives were characterized by irregularities. They did not feel that the SHT was able to reflect such irregularities, which resulted in more ad hoc adjustments. An option already embedded in many SHT devices for controlling space heating is the override feature, which allows occupants to deviate from the schedule. This was broadly well received and should have more focus. Furthermore, increased inter-operationality with other technologies and materialities in the home could be preferred, so that space heating can accommodate specific practices undertaken in the home.
(2) Make SHT more familiar: While a certain amount of personalization is already embedded in many SHT devices (e.g., the option to define rooms in the home), there seems to be a need for further personalization of the technology. Current SHT lacks familiarity to occupants (both in the hardware and software), and occupants might refrain from using it for aesthetic reasons or due to a lack of interplay with other materialities in the home.
(3) Increase the role of intermediaries: As presented in the data, some occupants possess practical knowledge that is more suited for the control of space heating using

SHT, whereas others do not. Throughout many of the interviews, occupants expressed a lack of experience and knowledge for engaging with these technologies and, hence, sought more guidance from intermediaries (installers, etc.). Such knowledge must be transferred through exposure and experience with the SHT. Simply handing out information might not be enough, and intermediaries might therefore play an important role.

(4) Consider the vision of SHT for enabling flexibility: In defining low-carbon transition scenarios and the role of SHT in enabling energy demand flexibility, policymakers could play a role in distinguishing between the often contradictory visions for SHT. Although the technology aims to enable energy flexibility and provide occupants with increased comfort and convenience, the role of the occupant is still unclear. If the occupant is limited to a passive user who is only concerned about comfort preferences, SHT might risk a lack of engagement from the occupant.

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