Mind the gap!
The role of ICT in office heating & comfort

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Abstract—**One of the largest single uses of energy, and in most countries therefore oil and gas, is the heating and cooling of buildings. Much of the built environment we need to decarbonise by 2050 is already built. Adapting this infrastructure is going to be disruptive and expensive, and take time we arguably do not have. The main current approach to limiting this consumption is to try to tightly control the indoor conditions to a given setpoint temperature. But, is there another approach? We have conducted a year-long study of the actual thermal performance of a large non-domestic building. We find that there are three significant socio-technical gaps between the buildings systems' perception of how the building performs and the temperatures experienced by building users which affect peoples' comfort and waste energy. In contrast with traditional approaches, we argue for more flexibility and adaptivity in both the policy and and how the building is controlled to address this. We believe that mitigating these gaps and avoiding the wasted energy and associated indirect emissions is a significant opportunity for future ICT for sustainability systems.**

Keywords: non-domestic building, energy reduction, adaptive thermal comfort, energy management, building policy

I. INTRODUCTION

Heating and cooling non-domestic buildings make up 11% of energy-related emissions globally, with the largest share originating from space heating and cooling [1]. 60% of this globally is met by fossil fuels. Active cooling demand has tripled since 1990 [1]. There is no question that huge proportions of the existing built environment need significant improvements to reduce this energy burden and help us decarbonise our heating and cooling. The very changing climate itself will likely significantly increase, rather than reduce, this demand further—since energy is normally needed to bring high temperatures down and low temperatures up to meet social expectations and standards for comfort worldwide. More extremes of temperature outdoors will lead to less temperature stability indoors unless it is controlled in some way—conventionally by adding more heating or cooling!

To keep these temperature adjustments in check and be able to respond to the constantly changing conditions, the intuitive and traditional technological response is to add more sensors and control equipment to address comfort issues. This is partially motivated by a facilities managers' desire to have increased coverage and more data to inform their organisational strategy, and to more precisely automate heating and cooling through granular control of when and where heating and cooling is applied and of set point temperatures within buildings. If automation leads to a more consistently controlled building, it might be argued, there should be fewer complaints from its users to contend with!

Yet, as we report in this paper, in our experience it has become clear that often the building occupants are neither particularly comfortable nor have sufficient agency or user-facing controls to address this. Further, complaints, once raised, seemingly also have led to little actual effect in resolving the underlying problems. Substantial parts of the building seemed to be significantly overheated, even when sparsely occupied, and not just on those rare sunny days in our part of the world[1]. What is causing this overheating, even within a fairly recent Northern European building? Not least, this represents a significant waste of energy and associated GHG emissions due to unnecessary space heating.

As a case study, we set out to instrument our environment more systematically, we were specifically interested in where and when overheating was occurring, whether there was substance to the complaints, and what, if any, effect radiant heat from the sun and other weather related factors was having on the ambient temperatures experienced. We created and deployed a simple data logging infrastructure in 17 individual single-occupant offices for almost a year. Drawing upon Fanger's seminal thermal comfort framework as a lens to analyse the results [2]. The findings support our initial assumptions that there are significant issues which *are not captured* by the existing pre-installed building management sensors—or require further nuanced contextualisation in the building to be properly understood.

This paper is not intended to present a complete analysis of these data (this will be found elsewhere) nor the occupants' comfort; rather, our intention is to highlight opportunities that are available to our community as developers of possible technical solutions to help address this significant and energy intensive challenge. Our analysis uncovers *three key gaps* in relation to building energy management and thermal comfort, and we discuss how ICT can have a role in bridging these gaps that are potentially more cost and carbon-effective than business-as-usual approaches. If widely deployed, this could offer significant potential for saving energy and related emissions savings in similar buildings worldwide.

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[1] Northern UK, Western Europe.

II. BACKGROUND AND RELATED WORK

A. ICT4S, Thermal Comfort and Overheating

We are not the first to discuss non-domestic energy-related topics at ICT4S. Work has featured sensor networks and architectures for intelligent building monitoring [3], [4]; utilising building management data for energy system diagnostics and transitions [5], [6]; office interventions, co-operative games, and co-working for energy reduction [7], [8], [9]; ICT potential for decarbonising buildings [10], [11]; and organisational decision-making and stakeholder attitudes [12], [13].

Regarding thermal comfort and overheating more specifically, ICT4S has considered both domestic and non-domestic settings, for example proposing using heat from supercomputers to warm cities [14]; studied energy managers and the impact of a thermal comfort lens in managed apartments [15]; indoor temperature awareness using ambient displays [16]; and, of heat pumps in domestic settings [17], [18], [19]—including identifying when they malfunction [20].

Work in domestic thermal comfort in HCI and Ubicomp more generally has tended to focus on optimisation of heating and cooling *on behalf of* users. i.e., where control systems and digital interventions try and more efficiently achieve a set point temperature such as 21°C. For example, more optimal preheating of domestic buildings when they are predicted to be occupied [21], improving heat models that consider the thermal transfer between rooms and floors [22], or using thermal cameras to explore the temperature of spaces [23].

Our work aligns more closely with the holistic approach of Clear et al., who explored domestic thermal comfort broadly, considering how individuals can improve their own comfort by adopting adaptive behaviours such as changing clothing, opening windows and doors [24], [25]. Critically, individuals are called to adapt by *working with* their environment, to achieve comfort and also reduce energy consumption for heating. In later work situated in offices, occupants were shown to prefer spaces where they feel more comfortable, and were offered an interface for finding desks that better match their thermal experiences and preferences [26]. An individual's thermal comfort has been connected to their productivity [27] and health [28]. Recasting the terminology 'to hot desk', 'Cool Desking' [29], [30] speaks to the needs of those who are specifically looking to find cooler and more comfortable spaces to work in as they need to.

B. Thermal Comfort

Thermal comfort is subjective but also has been characterised through experimentation and embedded in standards which govern the indoor environment of buildings. When someone is thermally comfortable, they are said to be in a state of mind where they express satisfaction with their thermal condition [31]. This is a subjective judgement, and relates to a thermal strain based on dynamic heat transfer between the person's body and their environment. It thus relates very much to each individual and what they individually experience. Being thermally comfortable is an important concept as it affects an individual's overall well-being, productivity and health—but central to our argument, maintaining 'a comfortable temperature' for everyone can consume vast amounts of energy [27], [32]. It should be clear that to do so is always at best a compromise, where the least number of people are dissatisfied.

Thermal comfort is often crudely associated with ambient air temperature, and indeed, we are conditioned to do so via thermostats and ambient temperature displays. Standards suggest non-domestic building management systems should generally maintain a temperature at 21°C in UK [33]. But thermal comfort is thought to be more than this: in the 1970s, Povl Ole Fanger's foundational work [2] explored several possible additional parameters of thermal comfort, arriving at his well known six-parameter model: air temperature, radiant temperature (reflected heat, e.g., from the sun, walls and surfaces), air humidity, and air speed. Plus two further parameters relating to the individual: clothing level and metabolic rate. The 21°C set point temperature enshrined in building standards is believed to originate from assumptions following from these studies. 21°C was thought to be comfortable for those studied at the time. Later critics have pointed out that these studies lack in participant diversity and do not reflect the modern workplace; being with predominantly of seated white middle-aged men in 1970s business attire [29], [34], [35].

Humans are found to readily adapt and *find* "comfort" within an eight-degree range over a day, with some actively seeking the *thermal delight* from a more dynamic and changing thermal environment (known as 'Alliesthesia') [36], [37]. It may be that rapid changes in operative temperature[2] more directly govern perception of "comfort", than a specific ambient temperatures [38]—despite commonly held 'folk associations' of comfort with particular and specific temperatures [39].

Studies have shown that people can and do make themselves comfortable within the range of conditions they commonly experience [40]. Naturally, these conditions vary significantly around the world. Expectations of what comfort is are in fact societally defined [41], and there is no single shared expectation of this that would please everyone. In fact, what is clear from the literature, is that people have different personal experiences and interpretations of comfort depending on age, gender, underlying health conditions, geography and cultural experiences—all of which intersect and compound their expectations [29]. Even per individual, what is comfortable now may well not be soon after activity, recent meals, adjusting clothing, and so on.

Despite a body of work focusing on thermal comfort in the home, the workplace is less well studied. Workplaces are more complex in that they are often shared, with different expectations about the degree to which building users are expected to be able to influence their comfort, and the controls available for them to do so. Lack of control compounds an individual's lack of agency and perceived responsibility

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[2] Operative temperature is a single factor that combines ambient and radiant temperatures, sometimes with an air flow and humidity factor.

over their own thermal comfort; increasing reliance on the building infrastructures, and consequently, energy [42], [43]. A common default response by building managers is to simply increase the target temperature until the level of complaints is reduced to a manageable level [44]. From a sustainability point of view, such practice is clearly not ideal, but from the view of an occupant, it is not ideal either!

C. *Overheating*

Overheating of buildings (or overcooling!), can be clearly linked to energy waste [45]. To understand this further, we borrow from the CIBSE TM52 standard definition, since this is widely accepted in the UK [46].

Before 2006, when a building reached a simple threshold of 28°C it was considered to be overheating. TM52 in contrast currently defines overheating based on an a more sophisticated approach known as 'Adaptive Thermal Comfort'. A 'band of comfort' is defined in terms of the four environmental thermal comfort parameters (Section II-B), within which it is expected that the majority of people can achieve comfort by controlling the two personal thermal comfort parameters by taking simple actions like adding or removing a layer of clothing, changing position, exercising, or consuming hot or cold beverages. The 'band of comfort' is also not static, but rather calculated from the running mean of the outdoor ambient temperature. A building is considered to be overheating when it fails three tests relating to a 4°K window around the calculated 'comfort temperature'. We discuss these tests and how we applied them to our data further in Section IV-C.

III. METHODS AND DATA

A. *Long-term sensor deployment*

In our work, we contribute a novel analysis of three gaps found between automated control of an existing building and the temperatures actually experienced in single occupancy offices. We set out to explore this 'in-situ' using a living-lab approach to explore how energy waste and overheating might be caused in practice.

Custom sensors (see Figure 1) were installed in 17 single-person offices in a non-domestic office building in the North-west of the UK from 21st April 2021 to 24th April 2022. Due to minor access issues and equipment failures with the building Building Management System (BMS), the data is only fully complete from 25th June 2021 to 22nd March 2022. We refer to this period as *the full study period* for the purposes of this paper. In total we gathered 6,504 hours of study-specific data, 5,231.7 hours of BMS indoor ambient temperature data, and 5,920.8 hours of BMS outdoor ambient temperature data. The study was subject to ethics board approval, and office occupants had to explicitly opt in to the study.

Each logging unit comprised multiple reference quality sensors (see Table I). These were identical in all rooms and recently manufacturer calibrated. We designed the unit to be wall-mounted, and installed at the same height and position in each room, see 'X's in Figure 2. Radiator temperature sensors (see Figure 1 and Table I) were installed on the radiator flow (supply) pipework in each room, see 'Y's in Figure 2.

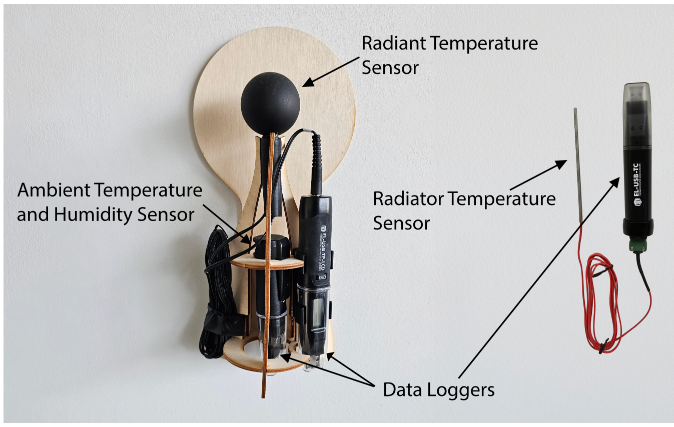

Fig. 1. Sensing devices

TABLE I
DETAILS OF THE SENSORS USED IN THE STUDY

Sensor Model	Measurement	Resolution	Freq.
Lascar EL-USB-2+	Ambient temperature	0.5 ° C	5 mins
Lascar EL-USB-2+	Relative humidity	0.5 % RH	5 mins
EL-USB-TP-LCD+	Radiant temperature	0.1 °C	2 mins
Lascar EL-USB-TC	Radiator temperature	0.5 °C	2 mins
Trend BMS TB/TS	Ambient temperature	0.037 °C	10 mins
Trend BMS TB/TO	Outdoor amb. temp.	0.037 °C	10 mins

The data collected included air temperature, radiant temperature, relative humidity, and radiator (space heating) temperature. These parameters were chosen as they form three of the four standard thermal comfort parameters [2]. Air speed was not measured due to its highly localised nature and the challenge of sensing this unobtrusively for long periods [47]. We consider the heating system on when the radiator temperature was measured to be above 45°C. We attempted to capture door and window opening events, as well as occupant presence; however, these data points were not of sufficient reliability to be included in our analysis.

Ambient temperature data for the same period was collected from the BMS. The BMS temperature sensor is industrial grade and permanently installed, but of unknown calibration status. This was located on floor 0, in a large open-plan, North-facing room with few windows (little radiant heating effect). We also included the BMS's outdoor air temperature (single-sensor externally mounted at floor 0 level).

B. *The spaces and rooms*

All the rooms were single-person academic offices of near identical layout ˜11m^2 selected to cover the main axes of the building (three adjoining rooms wide, by three floors high, by two rooms deep). Note, one room occupant did not wish their office to be included and withdrew from the study, hence the resulting 17 offices. See Figure 2.

Each room features a single large openable window, two permanently open passive air vents (directly to the outdoors), a steel panel radiator fitted with an occupant-controllable thermostatic radiator valve (TRV)[3] and a single entry/exit door to a common hallway. There is no building-integrated mechanical ventilation in the individual offices, although some of our participants employed personal fans. The central hallway area on each floor (approx. 47.3m^2) was monitored for air temperature, radiant temperature, and relative humidity using our sensors. These areas are heated and ventilated using a BMS-controlled ventilation system. Eight of the seventeen rooms face South, while the remaining nine face North. The study started during the COVID-19 lockdown (restrictions were gradually lifted on April 12, May 17, and July 18 2021), resulting in periods where rooms were unoccupied. The study concluded on 22nd March 2022, where most rooms were again back in regular use.

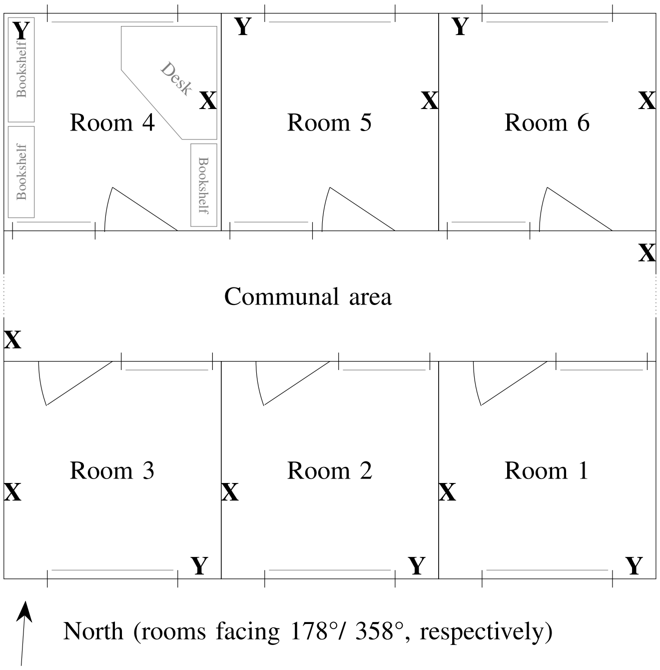

Fig. 2. Layout of office spaces. Room 4 shows a typical layout of furniture (all office occupants have arranged their furniture slightly differently). 'X' indicates the location of installed wall sensor (ambient temperature, radiant temperature and humidity) at a height of 1.3m (approximate head height for a person when sat down), 'Y' the location of (radiator temperature sensors). Room 4 on the 2nd floor was not part of the study. Elevation of floors is 52m/55.5m/58m, and floor area is ˜11.3m^2 (offices) and 47.3m^2 (communal).

C. Estimating heat

The water flow rate and temperature difference across each radiator were not measured as part of the study. We therefore estimate the energy output to each room for illustration purposes by extrapolating a spot heat flow rate measurement of 0.14kW across all periods of the study where the rooms heating was operating—calculated using equation 1, a spot measurement of flow rate (0.0348m^3 per hour), flow temperature of 62°C and temperature difference ΔT of 3.5°K, all taken on a relatively mild day in March, with a measured ambient temperature of 21°C in the room, and the TRV set to a low-medium setting of 3.

$$h = q * c_p * \rho * \Delta T \tag{1}$$

where h is the heat flow rate in kW, q is the volumetric flow rate in m^3 per hour, c_p is the specifc heat capacity of the water in kWh per kg.K, ρ is the density of the water in kg per m^3 and ΔT is the temperature difference between the flow and return pipework in °K.

There will be periods during the study where the actual flow rate and temperature difference in a room will be both lower and higher than the spot measurement. Overall, this estimation method is expected to be conservative but suitable to serve for illustration purposes.

D. Secondary data collection

Beyond the logged data, we rely on anonymous casual reports from facilities managers and occupants as co-researchers, plus our own informal knowledge of inhabiting the building and of the office occupants who are all longstanding colleagues. We did not formally interview the participants nor ask them to log their comfort, so any reflections of how comfortable they might be are based on our assumptions. The research team has been closely engaged with facilities on these topics for over a decade, including part-time roles in the energy management team. These reports and knowledge help contextualise our data and inform some of our speculative assumptions, but are not a substantial part of this paper nor our analysis.

E. Limitations

One participant opted not to take part in our study, resulting in 17 rather than the intended 18 rooms. Participants were otherwise cooperative, and there was no further attrition from the study. Selecting 17 rooms as a specific focus represents a subset of all of the of the possible offices. This was a pragmatic choice in part informed by the cost of the bespoke hardware we built and, in part, the practicalities of installing and maintaining the sensor deployment for an entire year with the available resources.

While our own data loggers proved highly reliable throughout the study, with the exception of the motion sensors and reed switches on windows and doors, the BMS data for this period was not complete. Centralised (BMS) indoor ambient temperature data was not available from: 21st April 2021 until 08th July 2021; and indoor and outdoor ambient temperature were not available from 25th Dec 2021 until 5th Jan 2022 and 22nd Jan 2022 until 3rd Feb 2022. There are a small number of shorter periods of missing data. These have all been discounted from our analysis as they do not

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[3] A thermostatic radiator valve or TRV is a mechanical actuator that can automatically adjust the output of a hydraulic radiator, by adjusting the flow rate of water passing through a valve, based on the ambient temperature of the room. The user can adjust the target ambient temperature the valve is regulating to, usually on a arbitrary scale from 0 to 5 - with 5 being full open (room is uncontrolled), and 0 either off or the minimum to prevent freezing. The mid-point (3) normally accords to 21°C. Specifics of the scale and the equivalent ambient setpoints do vary between manufacturers.

significantly change the results. It is conceivable that some offices elsewhere in the building are more extreme or divergent than those we observed. However, we took pains to cover the core of the building with both aspects (North, South) and vertical inclination (coverage of three floors).

Monthly data downloads and periodic battery changes gave us an informal way to observe the offices and talk with the occupants, but we did not take formal field notes on what we found during this process. The data was collected during periods of no, partial and full COVID-19 lockdowns. Whilst this will have affected the human impact on the data collected, the building's heating system remained operational throughout. It is likely that with more continuous occupancy, we would have detected more periods of overheating due to heat from occupants and increased IT and other equipment use.

The quality of the air (particulates, volatile compounds, smells etc.) has not been a focus of this current work; but we acknowledge 'good air' is important to perceived comfort, health and wellbeing, and hope to include this in future work.

IV. ANALYSIS

A. Life in the building

Our data reveals a rich and detailed picture of the thermal conditions in the study building for a full winter and summer season. Generally, we consider the temperatures to be warm, with median temperatures of over 22°C. As Figure 3 illustrates for the heating season, there is a clear difference between North and South facing rooms, with the South facing being noticeably warmer. Floor height was not as big a factor as orientation, although we were slightly surprised to find the middle (not the top) floor was generally the warmest; presumably being sandwiched and thus insulated by the other floors. From the inter-quartile ranges, air temperatures are typically in a range of 21.5–23.5°C and 21–22°C in the winter, but there are periods of overheating. The highest temperature recorded is in summer at 37.5°C on the top floor South facing side in July; although high twenties are regularly observed even on the North side during the winter heating season—mid-30s°C was reached several times during the winter on particularly sunny days. The highest winter temperature we logged was an incredible 35.8°C! This is particularly surprising given the significantly cooler outdoor temperatures and closed-loop control by the building's BMS, and speaks to all the additional sources of heat including of course, the sun.

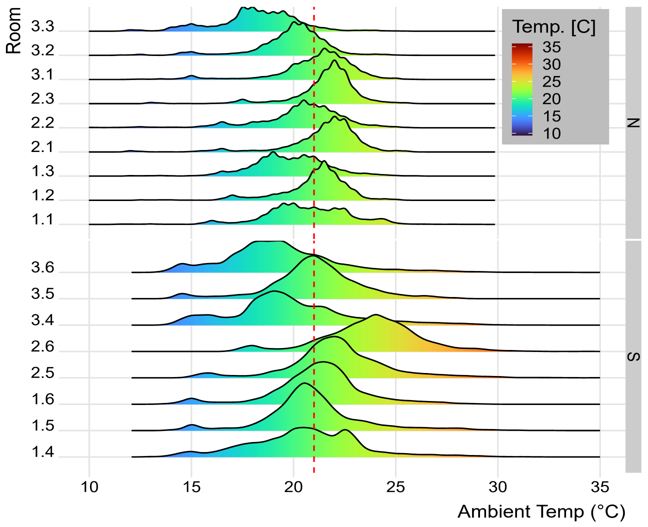

Fig. 3. Comparing ambient air temperature profile across offices during the winter. Extract from ’the heating season’ from 25th–31st May 2021, 1st October–4th December 2021. The room prefix indicates floor from 1–3 from low to high. The red dotted line indicates a setpoint of 21°C.

Focusing in on a winter week in more detail, Figure 4a shows a typical week in January (Saturday to Friday) for room 2.1, a North facing room on the second floor—note that the selected week was not during a period of partial or full COVID-19 lockdown. Despite cool winter temperatures, the room is generally warm, and we can clearly see the role of the heating system. Starting on a weekend when the office is not occupied, the room rapidly heats to around 21°C once the heating comes on at 06:00. During the weekend, the slightly 'sawtoothed' trace indicates the TRV is actuating to maintain the temperature at around 21°C. During the weekdays, the temperature profile of the room changes: the room takes longer to heat up, as there is more thermal mass due to the occupant, their belongings, and additional air exchanges due to the opening of windows and doors typical of room occupation. Small variations of 0.5–1.0°C during the day, particularly on Monday, Tuesday, and Thursday, could suggest additional occupants or equipment use. This additional heat is sufficient to raise the temperature above the TRV set point, so the heating turned off for a short period on Monday and the remainder of Thursday.

The 'high thermal mass design'[4], of the building is important. The building fabric absorbs and re-radiates heat, which plays a significant role in stabilising temperature, and as we will see, how it comes to overheat. This can be seen in Figure 4a, as the room heats up to around 21°C, but from Monday to Thursday, the amount the building can cool overnight reduces due to stored heat in the building fabric. So, despite the outdoor ambient temperature trending slightly downward throughout the week—come the weekend, even with the reduced heat input and lower levels of occupancy implied, some of the excess stored energy is released.

On the South side, the interaction with solar gain (radiant heat) is quite important too. Room 2.6, opposite room 2.1, is shown in Figure 4b for the same period. Room 2.6 is not occupied during the weekend (flat profile), and the daytime temperatures are similar, indicating the TRV's are set to similar values. However, despite being in winter, the additional heat is evident: heat builds throughout the week—ambient temperatures trending upwards, with reduced operation of the space heating and reduced overnight cool-down—the additional heat input, and lack of thermal capacity, means the daytime peak temperatures are significantly higher.

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[4] Lots of material such as concrete in contact with the internal air of the building.

On Tuesday and Wednesday, there are periods when the heating is on, but the room is still cooling down or only maintaining temperature. This likely indicates the occupant had opened the window. Since the TRV is located at the top of the radiator under the window, it may be being artificially cooled and, therefore, still providing heat to the room—highlighting the importance of sensor placement to prevent energy wastage. It should be noted that room 2.6 contains a high-performance GPU workstation for machine learning, which, if operating, would have also contributed a heating effect.

This scenario highlights a real problem endemic of tight and even precision control of space heating and cooling. The high thermal mass of the building and retained heat results in *less capacity* to absorb additional heat from other sources. Over the weekend, we see that continued low level heating (from solar gain and potentially equipment left on), the building is unable to cool. This means that the following week the building starts with even less capacity to absorb heat. The resulting feedback loop ensures the building stabilises at a higher temperature than it is intended to operate at, also above the point the TRVs can regulate and is also likely to be uncomfortable for many occupants.

Occupants' activity and use of controls such as TRVs have an effect on indoor conditions. For example, comparing the two North facing rooms on floor 1—Figures 4c and 4d. Room 1.1 appears occupied or has an intermittent additional heat source from Saturday through Monday afternoon (plus a short period on Tuesday) due to the uneven profile—see Figure 4c. The occupant also appears to be using a source of heat that is not the building's heating system, which is left on 24/7—likely a unsanctioned plug-in electric heater. This maintains the room temperature higher than the TRV threshold, so the building's space heating is not even utilised. Potentially, the heater was turned off, or the window left open overnight on Monday, causing a spike in temperature on Tuesday morning at 09:00 when the occupant returned. For the remainder of the week, the office appeared unoccupied—due to the relatively flat profile—but the alternative heat source remained on.

Room 1.3 appears to be occupied Saturday through to Wednesday early afternoon—heat up curves are not consistent, so occupation or equipment must be in the room—see Figure 4d. Unlike a typical use pattern, this occupant appears to like their TRV fully open. The room is heated all day, including when the ambient temperature reaches 26.5°C. Unconventionally, the occupant appears to turn their TRV off when they are away for an extended period, as there is no space heating provided from approximately 12:00 on Wednesday for the remainder of the week. The relatively smooth cooldown curve shown following the heating being turned off is only interrupted by a small amount of solar gain or gains from neighbouring rooms during the day on Thursday.

The window in Room 2.2 appears to have been left open overnight on the Saturday (space heating on but temperatures going down)—see Figure 4e. The window appears to have been closed at around 11:00 on the Sunday, following which, the room's temperature rises again. Again the window appears to have been opened for twelve hours from 12:00 on Monday. Throughout the remainder of the week, the room temperature continually rises, with no space heating input, so potentially, the occupant prefers the room cooler when they are there. Presumably additional heat sources (such as equipment running) causes it to heat up despite being North facing, see Figure 4e.

B. *What does the BMS know?*

A centralised BMS controls the operation of the heating and ventilation throughout the building from a single indoor ambient temperature sensor, in conjunction with a time control strategy of heating from 06:00 to 18:00, Monday to Sunday—this did not change during our study. When the BMS's indoor ambient temperature sensor registers less than the setpoint 21°C, the boilers are fired (from natural gas), and heat is distributed throughout the building. The ambient temperature sensor is situated physically in the closest occupied space to the BMS controller, to which the sensor is wired back, which is a North-facing, low occupancy room on floor 0. The TRVs in each single-occupant room cannot 'request heat' if the building's heating system is off, but they can restrict heat delivery to a room that is already at its target temperature.

As can be seen from Figures 4f, the temperature that the BMS records is *significantly lower* than that measured in the testbed offices. It is also isolated from the radiant and occupant-related heat sources that we have observed as having an important effect. Comparing room 2.1 (North facing) we find a mean difference of 1.95°C across the study period and 3.92°C for room 2.6 (South facing). The mean recorded BMS indoor ambient temperature was 20.38°C. The BMS temperature was only recorded to be 21°C or higher for 1,452 hours (22% of the study!)

C. *Overheating*

Drawing on the CIBSE TM52 definition of overheating allows us to look at indoor comfort in terms of outdoor conditions.

$$T_{comfort} = 0.33T_{r-mean} + 18.8 \tag{2}$$

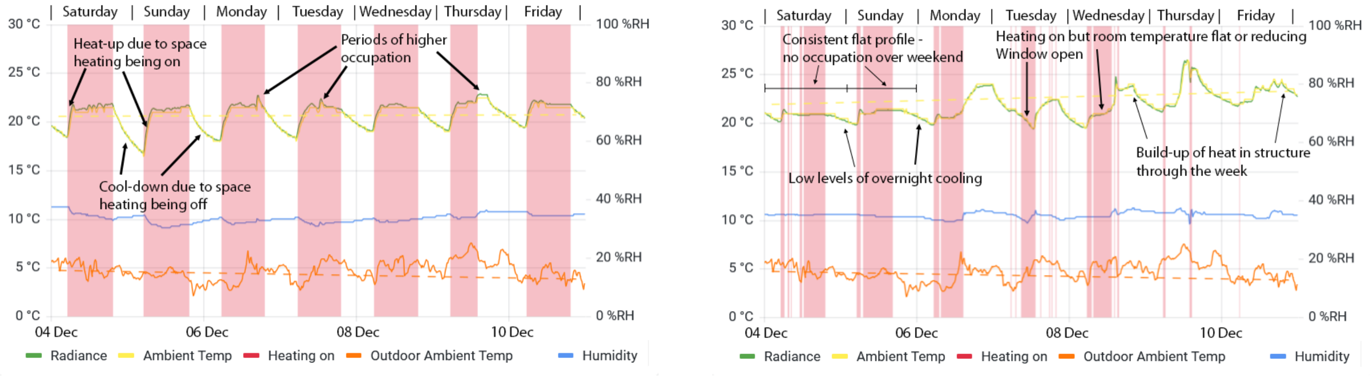
$$T_{r-mean} = 0.2T_{outdoor-1} + 0.8T_{r-mean-1} \tag{3}$$

A 'band of comfort' is defined, the centre point of which, $T_{comfort}$, is calculated using equation 2—where T_{r-mean} is the current day weighted running mean, calculated using equation 3, and the previous day outdoor ambient temperature and weighted running mean [46].

From the centre point, the ±3°C 'band of comfort' is established. To be classed as 'overheated', a space must fail two of three tests T_{1-3} defined around this band:

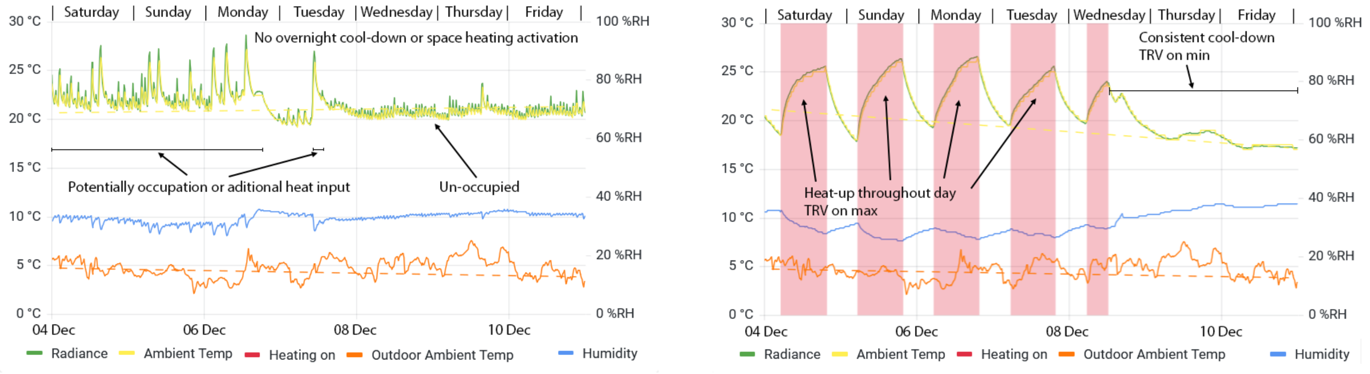
T_1 Considers the period of time that is spent outside the band. If the indoor operative temperature exceeds the upper limit of the band by more than 1°K for more than 3% of the occupied hours in a day, this test fails.

T_2 Considers how severe the spaces' excursion outside the band is. For example, if the indoor operative temperature



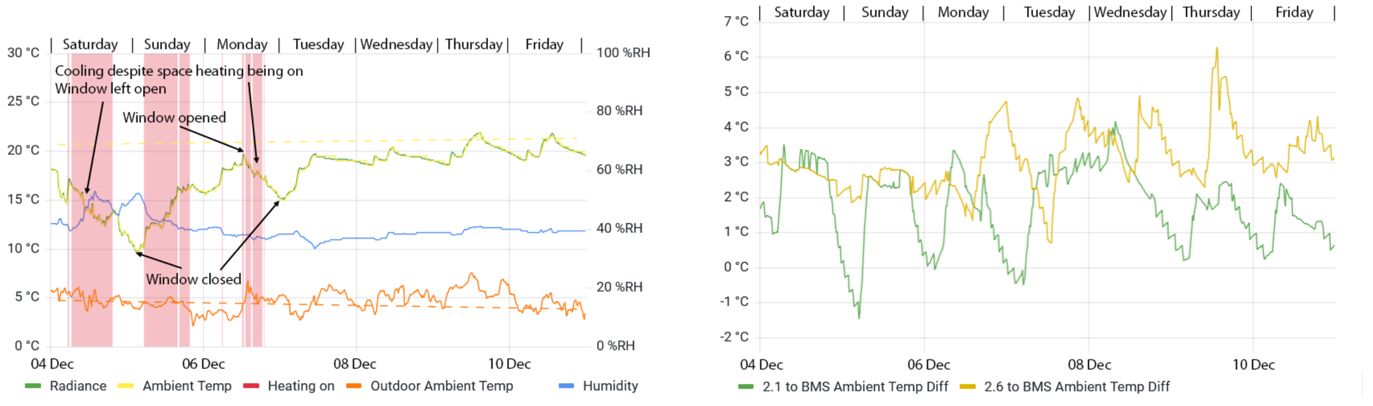
(a) Room 2.1 (North Facing)

(b) Room 2.6 (South Facing)



(c) Room 1.1 (North Facing)

(d) Room 1.3 (North Facing)



(e) Room 2.2 (North Facing)

(f) Difference between recorded ambient temperature in rooms 2.1 and 2.6 and the recorded BMS ambient temperature

Fig. 4. Typical Week: 4th Dec 2021 to 10th Dec 2021

of a room is 1°K greater than the top of the band for an hour in a day, and 2°K greater for two hours, the weighted excursion score is 5 for that day. If a space receives a weighted excursion score of higher than 6 for a day, this test fails.

T$_3$ Puts an upper limit on the indoor operative temperature of a space. If the indoor operative temperature of a space exceeds the upper limit of the band by more than 4°K, this test fails.

In the interest of space, we focus our discussion on a specific pair of rooms that most clearly exemplify our points (see Figure 3, for temperature profiles of all rooms). Figure 5 shows the operative temperature of the room 2.6 on the South-facing middle-floor, and where that lies in the TM52 'band of comfort'. On the 15th of January, the room's operative temperature had a few small excursions outside the band, but these were not sufficient to fail any of he tests. On the 16th, the room's operative temperature was outside the band by more than 1°K for more than 3% of the day—failing T$_1$. On the 17th, in addition to continuing to fail T$_1$, the weighted exceedance was more than 6—therefore, failing T$_2$. Finally, on the 18th, the day continued to fail T$_1$ and T$_2$, but for periods the room's operative temperature exceeded the band by more than 4°K, failing T$_3$ also. For the periods where two or more tests had failed, the room would have been classified as overheating.

Table II shows the summary of the TM52 analysis for the full study period for 2.1 and 2.6 as a pair. Note that the TM52 analysis is reliant on BMS' outdoor ambient temperature for a period before the analysis starts, therefore, the analysis cannot be performed over the full study period—see section III and equation 3. Applying the TM52 analysis, we find that the North-facing room does not fail any tests for the entire 225 days for which sufficient data is available, i.e., the room is *never formally classed as overheating*. On the other hand, room 2.6 failed one test for 24.5 days out of the 225 (10.9%) and two or more for 76.7 days (34.1%), i.e., the room is classed as overheating 34.1% of the time! More troubling still, if the TM52 analysis is applied only when the rooms are being actively heated, the figure is still 25.9%. i.e., for 25.9% of the time that room 2.6 is being actively heated in winter, the energy consumed *is being wasted* as the room is already classified as being overheated.

Making the above assumptions about the flow rate to the radiator and temperature differential (Section III-C) this equates to 121kWh of energy wasted just overheating room 2.6 (South-facing). If these assumptions are applied across all spaces that were monitored as part of the study, it is estimated that 578kWh of energy was wasted in overheating rooms. This is just a subset of the rooms in the building. We could speculate of course that this is unlikely to be the only building on campus being overheated in this way.

For the North-facing rooms in general, the majority (seven out of nine) did not suffer *formally* from overheating whilst being heated, and the two that did for only 1.4% and 5.9% of the time (rooms 1.1 and 1.3). For the South-facing rooms, all rooms experienced overheating whilst being actively heated between 5.8% and 25.9% of the time. Critically, if the TM52 analysis is applied to the data collected from the BMS sensor (the data available to the controller and the facilities team to troubleshoot any complaints), the building *never* experienced overheating!

TABLE II
TM52 ANALYSIS FOR ROOMS 2.1 AND 2.6 FOR THE STUDY PERIOD

	Room 2.1	**Room 2.6**
tests failed < 1	100.0%*	55.1%*
$1 \geq$ tests failed < 2	0.0%*	10.9%*
Tests failed ≥ 2	0.0%*	34.1%*
(whilst heating) tests failed < 1	100.0%*	62.4%*
(whilst heating) $1 \geq$ tests failed < 2)	0.0%*	11.7%*
(whilst heating) tests failed ≥ 2)	0.0%*	25.9%*
energy wasted overheating	0.0 kWh	121.3 kWh

* percentage of time.

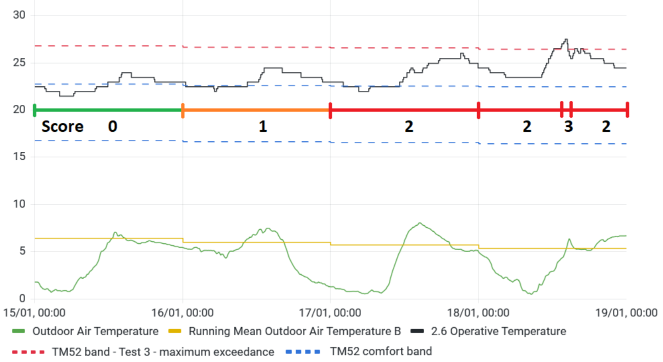


Fig. 5. TM52 analysis for room 2.6 - 15$^{\text{th}}$ Jan 2022 to 19$^{\text{th}}$ Jan 2022

V. DISCUSSION

In this section we discuss three socio-technical gaps between occupant experiences versus limited user controls, the assumed authority of building management systems, and, healthy working and building standards. These gaps make it difficult to find ground truths and make informed decisions, leading to energy waste and limiting adaptivity that could improve comfort for occupants throughout the seasons. In contrast with current commercial best practice, this section explores barriers and opportunities when addressing these gaps that rely not purely on digital technology, but rather a more structural shift in policy and practice surrounding thermal comfort.

A. Gap 1—User Involvement vs. Occupant Experience

There is little question that in our case, more granularity of sensing, coupled with our TM52 analysis has highlighted overheating in several cases (especially in South facing rooms such as 2.6). Whilst the study did not intend to formally collect data on occupants' perception of comfort, numerous people indicated their discomfort informally to us or via departmental communications channels such as email. It is unclear how many formal complaints were made, but we note that similar observations have been reported in other studies [26].

Discomfort and overheating in the workplace may in part be exacerbated by obscure controls. In our building there are few user-facing controls other than thermostats in shared offices, and TRVs on radiators, with windows and doors often used to regulate temperature. The intended and actual effect of these controls and user actions is opaque, which in part explains contrasting patterns we see in the data, like heating systems fighting with open windows.

Some occupants use low-cost off-the-shelf temperature and humidity sensors to gather their own information to work out what is happening. In the past, occupants of shared offices have been actively discouraged from 'meddling' with these thermostats, leading to them often being statically set and leaving no room for occupant control. As perhaps typical of many similar academic environments, occupants may 'vote with their feet' and choose other locations from which to work.

A formal process exists for resolving building-related complaints, but how to do this is not well known. Complaints perhaps feel culturally at odds with the 'provision of the office' as a facility whose environment is intentionally 'taken for granted'. Complaints, once made, are normally, in our experience, swiftly processed but may not lead to perceivable changes 'in situ'. This is hardly surprising when, as our data shows, the BMS is, after all, reporting that the building is operating entirely within normal and acceptable tolerances all of the time.

Here, communication and mutual understanding by both the occupants and with the building is lacking. In one instance recently, complaints about cold were found to originate from one of the hottest and most commonly overheated offices to the South of the building (not part of the study). This suggests not only the high degree of subjectivity of thermal comfort but also, as in this case, the importance of local temperature variation (desks directly below air vents notably 'feel' colder than those elsewhere in larger shared occupancy rooms).

Addressing this calls for better occupant-facing information and methods of engaging occupants actively with their comfort [24]. What if indoor weather and forecast data could be communicated to occupants through an app or digital notice board in the same way that external weather helps us prepare for what to expect outside? What if the thermal landscape was even part of room selection, c.f., Cool Desking [26], so that the use of the building was more closely matched to the current needs of occupants? This might even be part of a more inclusive strategy that is more respecting of cultural backgrounds, personal preferences, and needs [29]. Such strategies will need to be supported by non-technical interventions, such as improved heating policy [48], [24] to make the institution's backing for thermal variation and occupant agency clearer, and establish a new culture of adaptivity. We note here that while there is a recommended minimum of 16°C when working indoors (but no maximum) in the UK Health and Safety at Work Act 1974, there is currently no legally enforceable upper or lower limit to temperature in non-domestic settings.

B. Gap 2—'Ground Truths' of Building Systems vs. Reality

Perhaps surprisingly, as we have seen, the building in our study actually knows relatively little about its own thermal behaviour. We found our BMS linked to a single temperature sensor, acting as the ground truth for all of the spaces studied. From our analysis, it is clear that this single sensor, and therefore the BMS, do not have sufficiently representative data to control the heating of all building spaces effectively. This is generally leading to more heat application than needed and also more natural gas use, in our case.

It is common to install sensors in a convenient location for the installer, such as a corridor, rather than one that makes sense for measuring the occupant's thermal comfort. As shown in Figure 4f, rooms on the South side in our study tended to operate significantly hotter than the BMS appreciates since they receive heat from the heating system plus added heat gains from the sun, equipment, and people. Whilst the rooms on the North side track the BMS measurement more closely, examples can still be found of North facing rooms overheating; see Section IV-C. Due to the presence of TRVs in study rooms, this discrepancy is not believed to be the sole or primary cause of the observed overheating, but having higher levels of heat in the building's heating system will be a contributing factor.

Whilst conceptually adding more sensors to a building may seem intuitive to fix this and provide tighter control, surprisingly, this is *unlikely to improve* the thermal comfort of the occupants. As the 'band of comfort' is tightened, so there is *less potential* to absorb heat from other sources, leading *to more*, not less, overheating. Careful attention is also needed to where these sensors are placed as well as wider changes to control strategy. Additional sensors represent more data and possible system noise for facilities teams to analyse—and, if poorly placed, are not informative. Current control strategies also focus on optimising to *a specific temperature setpoint* which does not allow for the heat gain from other sources or to predict the thermal inertia of buildings as they are currently used. This will be expensive, energy-intensive, and may have health implications for occupants.

This is illustrated to some extent by the manual TRVs in our building, which provide some of this functionality at a lower cost. As we have seen, these valves do automatically shut off heat when a setpoint has been reached, but they cannot *anticipate additional heat gains*, such as from occupants, the sun, or IT equipment.

As shown by [24], once installed, TRVs are rarely adjusted. Perhaps this is unsurprising since many organisations do not provide any training on how building controls are intended to function. Occupants may not, therefore, understand their responsibilities or the conceptual model behind these controls' design, which is frequently misunderstood [49]. Aside from this, thermostats and heating UIs are a known point of controversy in the home and the workplace [24].

Digital and wirelessly controlled radiator valves are increasingly common, especially at home, but they only serve to provide tighter heating control up to a setpoint temperature.

At a commercial scale, most systems of this kind *do not* coordinate back to a central control system. Meaning they can only deliver heat when the central system sends it, rather than prevent heat being sent. Where systems do coordinate, typically, the occupant is required to utilise an app or website, which adds friction to the occupants' use of the system, which in turn may discourage their use [50]. Digital controllers are often powered by batteries, which at an institutional scale results in thousands to tens of thousands of radiator valves requiring battery changes each year—quickly becoming an almost full-time job, never mind the environmental cost of all those batteries!

As we now explore, digital controllers, such as smart TRVs could enable more predictive and adaptive adjustments of the heat input to a space. Attention needs to be paid to where sensors and actuators are placed to reduce noisy data, increase longevity, and reduce the maintenance requirements and environmental impacts of such infrastructures.

C. Gap 3—Building standards vs. Climate change

From our data and experimental deployment, we have already shown that we are able to identify cases that meet the UK standard definition of overheating. We argue this is in part due to naive control strategies. These are insufficient to address the dynamics of the building and its occupants in today's changing workplace and warming climate. Our community could help address this specific challenge of helping users and building stakeholders (including energy managers and facilities staff) in similar buildings to gain better understanding and control strategies for this significant class of building. We would argue that a more adaptive strategy (based around CIBSE TM52) is essential to success in this, as a wider 'band of comfort' can be used to drive less overheated (or overcooled) indoor spaces; and help 'create space' for buildings to use inertia to absorb and radiate heat without additional heating and cooling in a warming and more changeable future climate.

A more adaptive control strategy would be one that builds in this capacity to absorb heat and prevent overheating, rather than allowing it to happen or requiring energy to be expended to prevent it. Looking at the figures in Section IV-A, specifically Figures 4a and 4b, for the first two days, they are unoccupied: spaces are heated up to the target temperature by the radiator, but *no headroom is left* for any uncontrolled heat gains such as solar, occupancy and IT equipment. This is not helped by the building's heating system being controlled from a space that *is not representative* of the typical environment experienced by the building's occupants, nor the rapid heat input potential of the radiator (high flow temperature) and inaccuracies of the TRV control.

As we have argued, tighter control (more sensors and valves) alone would not resolve this. In the above overheating analysis, we used a ±3°C 'band of comfort', as recommended by CIBSE. Note that buildings designed for sensitive or fragile people, such as in hospitals and care homes, may even use an even tighter band, such as ±2°C. This suggests the potential for even higher levels of energy waste.

What if the likelihood of overheating and heat gain could be forecast *ahead of time* through the use fine-grained predictive modelling? Tools could then be developed that turn the radiator off ahead of time to keep the indoor conditions within the 'band of comfort'. This would also take greater advantage of uncontrolled heat gains from building users and external factors—reducing energy consumption for the primary heat generator and the potential of overheating for occupants.

It is important to note that there are a number of non-technological interventions required here, such as augmentations to the building, such as solar shades; new policies on clothing allowable in the workplace; and reimagined approaches and policies for using the building to allow more dynamic use of spaces by occupants. Localised sensing, such as that of our testbed, may be able to help pinpoint where to focus these necessary changes to the building infrastructure.

VI. CONCLUSION

From a year long study of multi-parameter thermal behaviour of an existing shared use building, we contribute an understanding of how the thermal conditions vary and link to overheating. We identify 3 critical gaps in knowledge between the occupants, the building and the building systems which are opportunities for design in ICT4S. We need to rethink our current strategies from implementation to governance to embrace adaptivity to address these gaps and reduce overheating and energy waste. We must: (1) tackle the interface between the building and its occupants to allow them to better adapt; (2) close the gap between what the building systems know and the occupants experience; and (3) anticipate overheating (or overcooling) to reduce energy demand. This sharply contrasts with traditional non-domestic approaches, where more and more energy intensive infrastructures are used to achieve tighter and tighter control.

A final gap exists here, where *serious* uptake of such technologies requires new organisational policy to challenge thermal comfort norms where heating and cooling happens to encourage changes in management and occupant practice (cf. [48]). This requires a systemic mindset shift of architects, building designers, engineers, energy managers, and organisational decision makers to consider adaptation around thermal comfort.

It is worth noting that the kinds of changes we are proposing *are not sufficient* to create the kinds of zero or even *carbon positive* buildings we will need. Technology mediated change, especially retrofit ICT, is only addressing part of the larger systemic challenges of climate change. Nevertheless, we believe ICT4S interventions can have a significant enough role in this case in co-creating more comfortable and sustainable workplaces as we transition the existing built environment.

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