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Indoor environment sensor systems for healthier homes: a feasibility study in social housing

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ABSTRACT

This study examines the feasibility of using an indoor environment sensor system to improve property management and health in social housing. Over a 6-year period, sensors were installed and maintained in 280 homes to monitor temperature, humidity, and air quality, with the sensor data provided to residents and the Housing Association (HA) through co-designed dashboards. Employing a mixed method sequential research design, feasibility was evaluated using the RE-AIM model. From the residents' perspective, monitoring the indoor environment was acceptable, but adoption rates of the dashboard were low and there was minimal evidence of its effectiveness in prompting changes in behavior. From the HA perspective, the system proved effective in identifying high-risk homes, prompting the HA to reach out to vulnerable residents, and provide more timely support and maintenance. The system also facilitated long-term monitoring, planning, and helped the HA achieve its social objectives and legislative responsibilities. Despite initial technical challenges, HA staff expressed a desire to continue using the system, integrate it with existing infrastructure, and expand its deployment to more homes. However, scaling the intervention would require careful planning. In conclusion, sensor systems are a feasible intervention that holds promise in helping to address health risks in underserved communities.

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Indoor environment; health; social housing; sensor technology; feasibility

Introduction

Housing and the quality of the indoor environment is an unequivocal determinant of public health and wellbeing (Gibson et al., 2011; R. A. Sharpe et al., 2018). Indoor

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temperature, air quality, and humidity have a significant impact on respiratory and cardiovascular diseases, allergic diseases, mental health, and other adverse social outcomes (Palimaru et al., 2023; Pevalin et al., 2008; R. Sharpe et al., 2020). Poor housing quality is estimated to cost the British health service £1.4bn per year in treatment bills (Garrett et al., 2021). Although policy and legislation for the design, construction, and maintenance of safe and healthy homes are well established (WHO, 2021) detecting and responding to health risks is a challenge for housing providers, as the causes and health outcomes are dependent on a complex mix of often invisible environmental conditions (e.g., indoor air quality), indoor behaviors, building characteristics, and occupant vulnerability (CMO, 2022; Peek et al., 2023). Furthermore, the impact on health and housing is cumulative, long term, and typically identified retrospectively (CMO, 2022; R. Sharpe et al., 2020).

In the UK, social Housing Associations (HA) are not-for-profit organizations that provide rental properties at around 50–60% of market rates for those whose circumstances may exclude them from the private housing market, as well as affordable rents at 80% of market rates. Currently, there are approximately 3.9 million households in social housing in the UK (MHCLG, 2022). Social housing residents are more likely to live in housing with poor quality indoor environments and are typically more vulnerable to adverse health impacts than other housing populations (Boomsma et al., 2017; Diaz Lozano Patino & Siegel, 2018; Rolfe et al., 2020; R. Sharpe et al., 2020; Wallace et al., 2022). Awareness of risks from the indoor environment has been elevated recently, with the highly publicized tragedy of a child's death being directly attributed to damp and mold because of poor housing management (Brown & Booth, 2022).

Sensor systems for human health in the housing sector

Both housing sector and academic discussions have highlighted the need for smarter interventions and better partnership between organizations for identifying risks and improving the indoor environment (CMO, 2022; HACT, 2021a; Peek et al., 2023; Shafi & Mallinson, 2023). Under the umbrella of the "smart home" (Ding et al., 2011), one potential solution for healthier social housing and increased integration between service providers is indoor environment sensor systems (HACT, 2021a; Shafi & Mallinson, 2023; Walker et al., 2022; Wallace et al., 2022). Sensor systems can collect data on a range of home environmental factors including temperature, humidity, CO2, air quality, and occupants' utilities usage, and can present the information to users via devices such as a dashboard (Ding et al., 2011). The potential value of sensor systems is the real-time capacity to monitor a home environment remotely, identify risks, and inform evidence-based decisions for effective and timely interventions (Ding et al., 2011; Kozubaev et al., 2019; Marikyan et al., 2019Nagapuri et al., 2019; Shafi & Mallinson, 2023). Subsequent interventions to improve health range from behavioral measures such as opening windows to comprehensive interventions in the building structure (Marikyan et al., 2019, Nagapuri et al., 2019).

The use of sensor systems to inform and protect people who work with high-risk pollutants with immediate health consequences, in laboratories or manufacturing for example, is standard practice (CMO, 2022). However, the use of indoor environment sensor systems by the housing sector is in its infancy and its widespread acceptability and feasibility are unknown, despite rapid developments in sensor system functionality, availability, marketing push from developers, and ever reducing costs (Li et al., 2021; Marikyan et al., 2019). Reports from the social housing sector suggest that sensor system adoption rates are low and that "smart social homes remain mainly on the drawing board" (HACT, 2021b, p. 10). One of the barriers to adoption is the lack of real-world feasibility evaluations to enable social housing providers to make an investment decision on system adoption (Ding et al., 2011).

To this end, a small but growing body of evidence is emerging demonstrating the effectiveness of sensor systems to identify risks for residents and to help HAs better maintain buildings (Shahrour et al., 2017; Shukla et al., 2019; Sirombo et al., 2017; Wallace et al., 2022; Wood et al., 2019). The key factors affecting feasibility and system adoption are ease of use and usefulness for operations (Marikyan et al., 2019; Pennings et al., 2010), cost-effectiveness (Li et al., 2021), customer acceptability and ethics of monitoring (Bowes et al., 2012, Nagapuri et al., 2019), and data management and security (Balta-Ozkan et al., 2013; Ding et al., 2011). However, the feasibility of sensor systems remains under-researched in social housing, particularly regarding adoption and implementation. This is important because, as registered charities, social housing associations are a unique type of organization, having both a business mission to build and maintain homes and a social mission to improve the wellbeing of their residents (Blessing, 2012; Chevin, 2014). As such, understanding the feasibility of these systems is important for the sector because of their organizational mission and resident characteristics (Pennings et al., 2010).

Research purpose and theoretical framework

To address this research gap, this study evaluates the feasibility and acceptability of implementing and maintaining a network of homes with indoor environment sensor systems from the perspective of residents and staff of a Housing Association (HA) in the UK. The overall goal is to understand the potential of sensor systems as an intervention to improve homes and health. The design of this study was informed by the RE-AIM model. Drawing from social ecological theory and systems-based perspectives, RE-AIM was developed to improve reporting of health intervention evaluations. RE-AIM is a realist evaluation model suitable for testing an unexamined intervention in a real-life setting where constraints exist over conditions (Glasgow et al., 2019; Holtrop et al., 2021). RE-AIM addresses feasibility across five dimensions which form our research questions:

- **Whom did the system reach?** *Reach* refers to who the intervention was intended to benefit and who actually participated. In this study, the extent to which a sensor system enables a HA to reach vulnerable residents who are living in poor quality indoor environments (CMO, 2022; Peek et al., 2023).
- **Did the system have effect?** *Effectiveness* refers to impact of the intervention on achieving outcomes, including negative or unforeseen outcomes. In this case, the effectiveness of a sensor system to identify risk, enable proactive repairs, and improve outcomes for building quality and resident health (HO, 2023; Shahrour et al., 2017; Shukla et al., 2019).
- **Was the system adopted?** *Adoption* refers to the actual usage, number of staff involved in delivery, and reasons for adoption or non-adoption. This evaluation will

focus on the established factors for smart home adoption, i.e., ease of use and usefulness (Ding et al., 2011; Marikyan et al., 2019; Pennings et al., 2010).

- **How was the system implemented?** *Implementation* refers to staff consistency in delivery, time required, adaptations made, cost of implementation, and how the intervention is received by participants. One major factor affecting the implementation of smart home technology is the acceptability of monitoring for residents, a potential challenge for a sensor system's feasibility which we examine (Balta-Ozkan et al., 2013; Bowes et al., 2012; Pal et al., 2021).
- **Will be the system be maintained?** *Maintenance* refers to the extent to which an intervention is sustained after rollout and the influencing factors for it to become routine in practices and policies. Our evaluation focuses on the technical challenges of maintaining the infrastructure of a sensor system across a large housing stock (Shukla et al., 2019).

Methods

Study location

This study was part of a 6-year (2017 to 2023) research and innovation collaboration with a social Housing Association (HA) in the county of Cornwall, Southwest UK (Menneer et al., 2021, 2022, 2023; Walker et al., 2020; Williams et al., 2021). The University of Exeter with Coastline Housing Association Ltd (hereafter CHA) led the study. CHA is a not-for-profit HA owning and managing ~6000 homes across Cornwall (~12,500 residents). The study was conducted in an area of interlinked conurbations in central Cornwall, namely Camborne, Pool, Illogan, and Redruth (CPIR), where CHA has a high concentration of residents (see Figure 1). The CPIR area includes some of the most deprived neighborhoods in the UK (CC, 2019) and has higher than national average incidences of mold, fuel poverty, and long-term health issues, which combine with a warm and wet maritime climate to increase the risk of people living in poor indoor environments (Johnes et al., 2023; Menneer et al., 2022; Moses et al., 2019; Tu et al., 2022).

Research design

Sensor system research is currently dominated by quantitative-based analyses, with a distinct lack of mixed methods studies, which combine rich qualitative insights with generalizable quantitative data (Creswell & Plano Clark, 2017; Shafi & Mallinson, 2023). Addressing this gap, a mixed method sequential research design was employed to understand the feasibility of using an indoor environment sensor system, and associated summary dashboard, to improve property management and health in social housing. We conducted a large-scale field experiment, recruited residents, and installed and maintained a sensor system in 280 homes. In the first phase, evaluation focused on feasibility from the residents' perspective. Subsequently, based on findings and focus group feedback, we adapted the dashboard, creating Version 2. In the second phase, evaluation focused on feasibility from CHA's perspective. Throughout both phases, quantitative analysis steered the qualitative exploration, providing insights into the trends observed during the field experiments and facilitating the convergence of findings (Johnson &

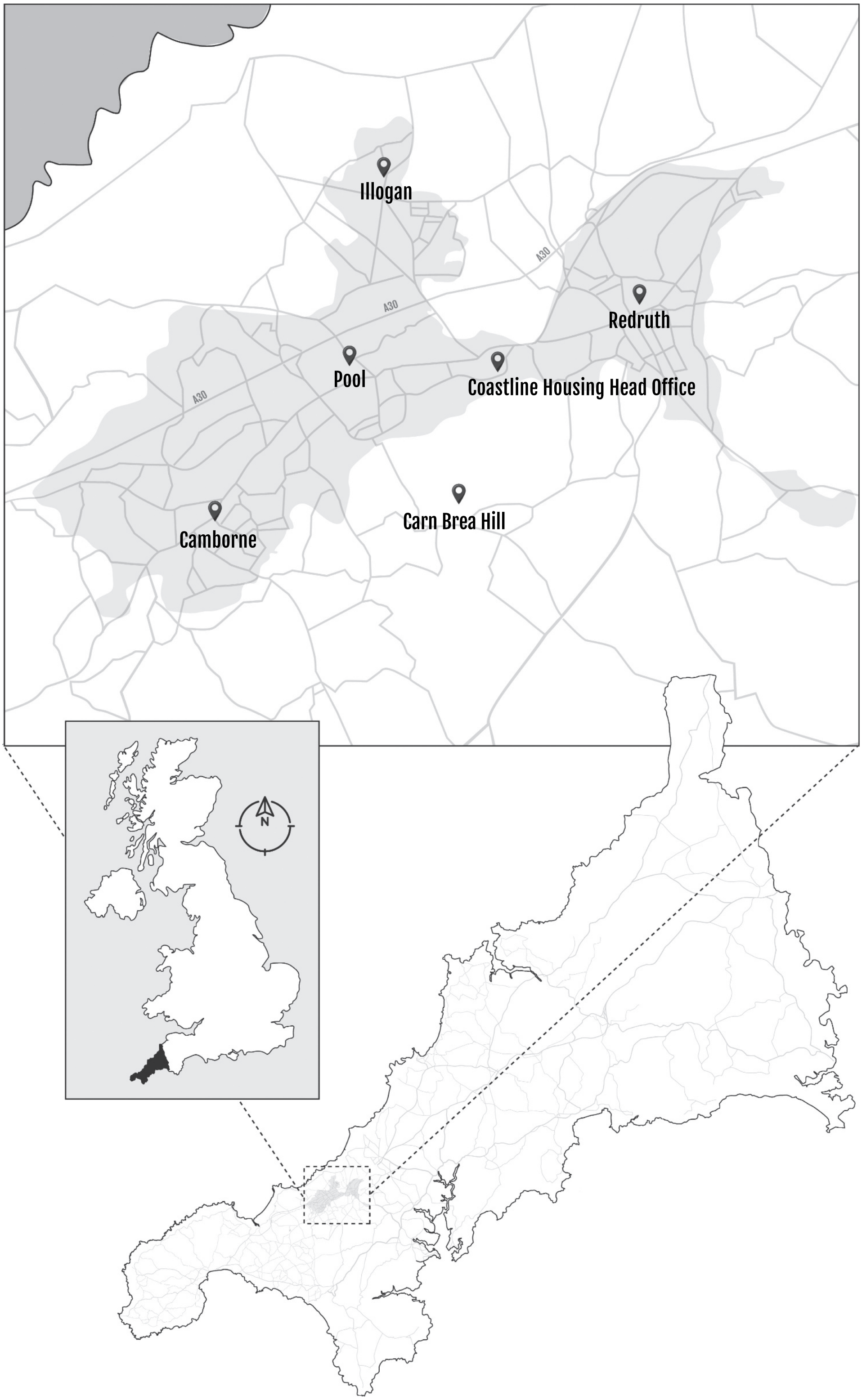

Figure 1. Study location.

Turner, 2003). Figure 2 provides an overview of the study phases, methods, and analysis conducted.

Recruitment and sensor system development

Residents were recruited from the CPIR area using convenience sampling. CHA undertook resident recruitment between September 2017 and November 2018 (Williams et al., 2021). In total, 649 households were approached, via invitation letters and door knocking, and 280 were recruited to the study. At recruitment, residents completed a face-to-face quantitative survey which gathered data on household characteristics: demographics, socio-economics, health, household behaviors, presence of mold, fuel poverty, and technology possession. Sensors were installed in 280 of the resident homes to measure temperature and humidity in the living room and main bedroom, air quality (including volatile organic compounds (VOCs) and particulate matter (PM2.5)) in the living room, and

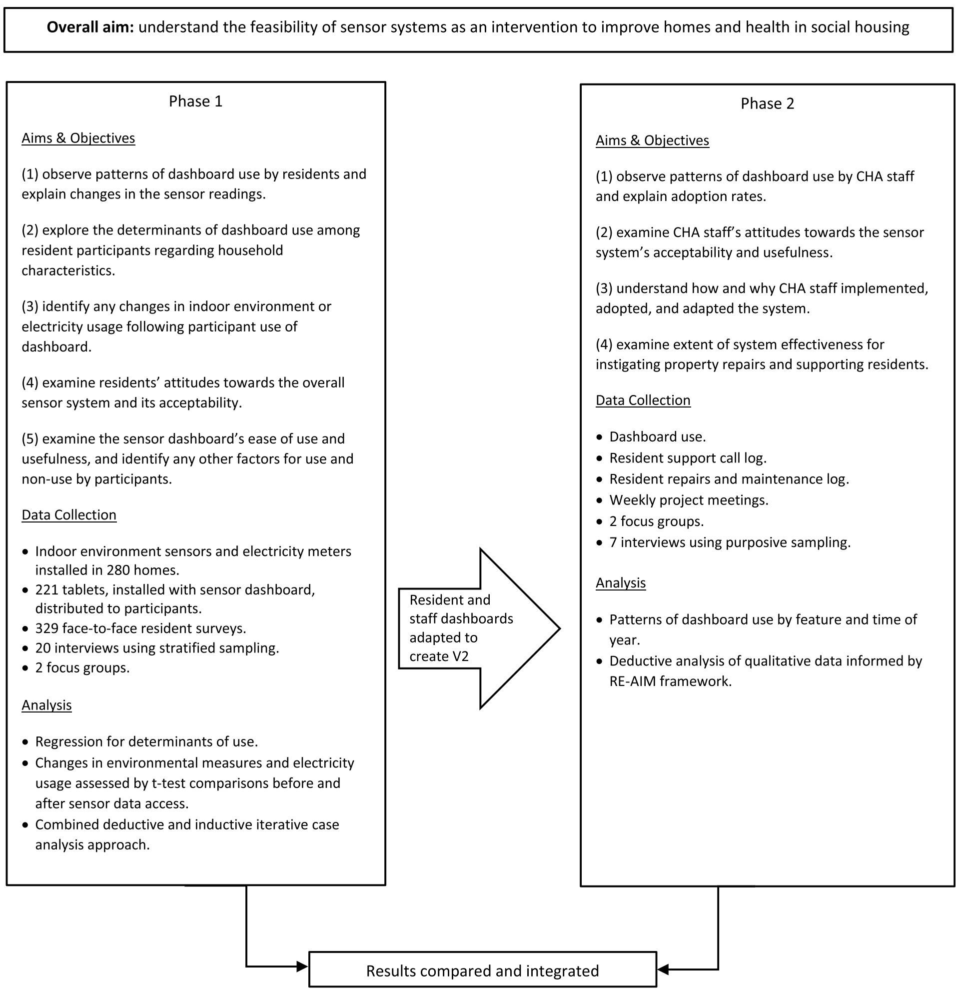

Figure 2. Overview of study phases, methods, and analysis.

electricity usage, with readings recorded every 3–5 minutes. Between 2017 and 2020, residents and CHA utilized an "off-the-shelf" sensor data dashboard (Version 1) provided by the sensor system supplier Invisible Systems. Residents ($n = 221$) received a smart tablet preloaded with the sensor data dashboard (hereafter "dashboard") for real-time monitoring of their home environment. Training sessions for residents on accessing and interpreting the sensor dashboard were conducted in 2018 and 2019.

Resident data and analysis

To quantitatively evaluate feasibility from the residents' perspective we used three data sources: household characteristics survey, sensor data, and dashboard usage data. To assess reach, we used the survey data to report descriptive statistics for the 280 households with sensors (see Tables S1-S6). To assess absolute adoption, we analyzed the number and pattern of resident logins to the sensor dashboard. To understand reasons for adoption, the contribution of household characteristics on the number of dashboard logins was assessed with negative binomial regression analysis (see Table S7 for description of variables used in the regression). To assess effect, we used t-test comparisons on the mean sensor data readings for 14 days before and 14 days after a resident login. The rationale was that changes in the home environment or electricity usage after logging into the dashboard could imply the resident acted in response to viewing their data.

We employed qualitative interviews with a stratified sampled group to assess feasibility, ensuring representation across dashboard engagement levels and persona types (Williams et al., 2021). Descriptive statistics outline participant characteristics (see Table S7). Telephone interviews, conducted by two researchers between March and May 2021, lasted 10–30 minutes, reaching thematic saturation at 20 interviews (Creswell & Plano Clark, 2017). Verbatim transcriptions with pseudonyms were analyzed using NVivo, involving three rounds of coding for reliability (Bazeley, 2009; O'Kane et al., 2021). The lead author initiated coding, and three independent researchers reviewed for analytical process reliability and thematic construct trustworthiness. Member checking through two 2-hour online focus groups in July 2021 with 12 interview participants enhanced credibility (Thomas & Magilvy, 2011).

System adaptation

In 2021, the research team led the development of a user-centered dashboard (Version 2) to improve the dashboard's ease of use, the sense making process of the data, and overall usefulness of the data and dashboard for the residents and CHA (Kim & Li, 2020; Kozubaev et al., 2019; Wood et al., 2019). Employing a user-centered approach, the adaptation process involved four 2-hour co-design workshops with residents, CHA staff, a university IT developer, and researchers. This resulted in the development of a "birds-eye-view" dashboard for CHA. This dashboard allowed CHA to sort and thus identify households according to property risk, such as high humidity, etc. (see Figure 3). Key features of the resident dashboard included an intuitive traffic light system for risk, detailed descriptions, customizable timescales, tips for improving their environment, and links to external resources. The CHA established a Support Team to monitor and intervene based on flagged properties, utilizing the Version 2 system from June 2021 to March 2023. A graphical representation of the whole system was developed by the researchers and CHA (see Figure 4).

Housing association data and analysis

To evaluate feasibility from CHA's perspective, we used three quantitative data sources: dashboard usage data, a resident support call log, and a repairs and maintenance log. To assess adoption and maintenance, metadata on dashboard usage by CHA were extracted from dashboard login records and Google Analytics data. Data examined included login frequency, usage time, and features interacted with. For the qualitative feasibility evaluation, all CHA staff that used the dashboard were interviewed, and other CHA staff were purposively sampled and interviewed according to sensor system user type: operational (Resident Liaison Coordinators, RLC) and strategic (Executive level) (see Table 1). Two RLCs directly used the dashboard, responding to high-risk readings by contacting residents, investigating, and coordinating support and property intervention with other CHA teams. Strategic users contributed to system development and utilized system insights for organizational strategy, despite not directly engaging with the dashboard. Interviews, guided by quantitative analysis and the RE-AIM model, were conducted in June 2022 via video call, with seven participants, achieving thematic saturation within the first five interviews (Creswell & Plano Clark, 2017). Transcriptions were verbatim, and NVivo aided deductive coding under RE-AIM dimensions. The lead author initiated coding, and a second researcher ensured reliability and trustworthiness (Thomas & Magilvy, 2011).

Findings and discussion

System reach

Barriers to reach

Out of 649 households approached, 43.1% (280/649) were recruited for the study. While initial data on barriers to participation were not collected, subsequent research with CHA

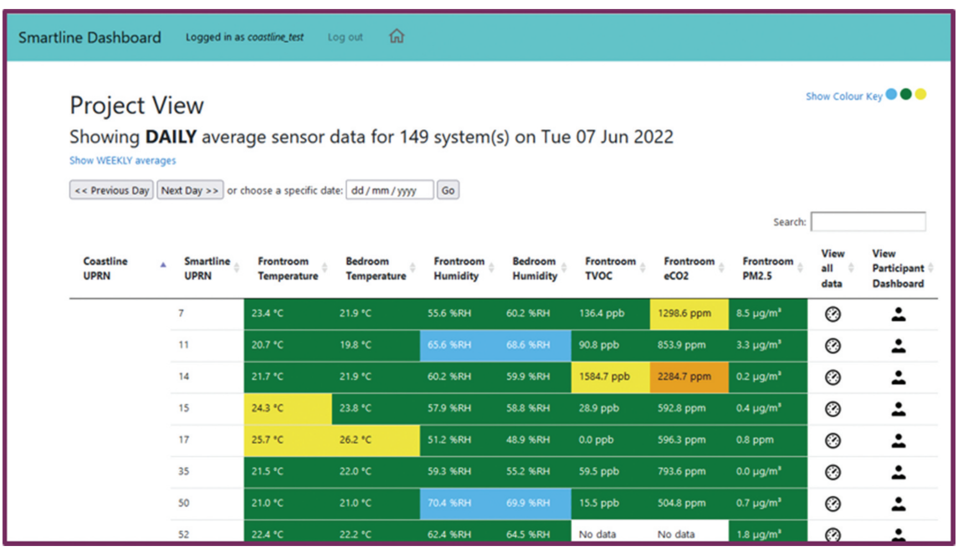

Figure 3. Birds-eye-view example of dashboard Version 2 showing all properties.

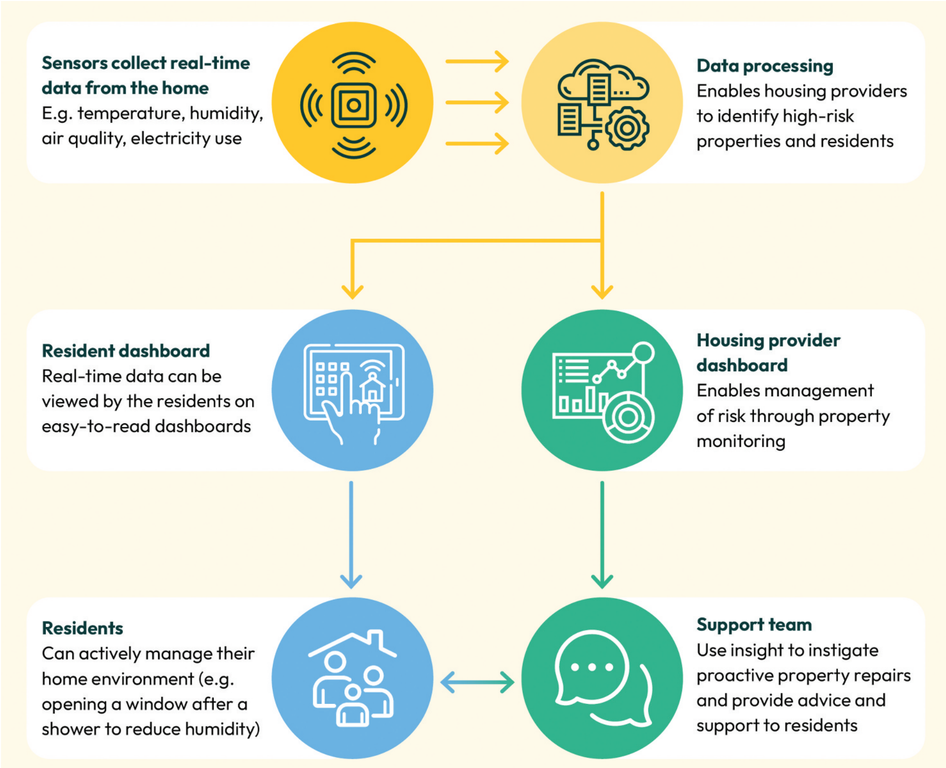

Figure 4. Representation of sensor system components, information flow, and users.

Table 1. List of interviewees and their role in coastline housing association.

Role	Title	Responsibilities
Chief Executive Officer	CEO	Organizational strategy and operational performance
Deputy Chief Executive Officer	DCEO	Organizational strategy, asset performance, and community wellbeing
Director of Finance	DoF	Organizational strategy, finance, and Information and Communications Technology (ICT)
Head of Innovation	HoI	Organizational strategy, innovation projects, procurement, maintenance, and resident service
Resident Access Lead	CAL	Resident database management, contact, and support
Resident Liaison Coordinator 1	RLC1	Sensor dashboard monitoring, resident liaison and support, and intervention coordinator
Resident Liaison Coordinator 2	RLC2	Sensor dashboard monitoring, resident liaison and support, and intervention coordinator
Sensor System Project Manager (University)	SSPM	Sensor system procurement and coordinator of network maintenance

residents identified a range of health (e.g., health conditions and disabilities), social (e.g., caregiving responsibilities), and digital (e.g., competency) barriers to engagement with projects involving technology, reflecting socio-digital inequalities common in this group (Buckingham et al., 2022; Helsper, 2021; Walker et al., 2024). Addressing these barriers is crucial in large-scale sensor system implementations to prevent widening socio-digital gaps and ensure inclusive reach.

Absolute reach

In total, 280 CHA residents had the network of environmental sensors installed in their homes throughout 2017 and 2018. Participants tended to be older adults (average age of 55 years), with more than a third being retired. Recruiting during daytime CHA hours potentially missed working-age residents and resulted in an older cohort. A quarter of participants reported a long-term sickness or disability. Forty-nine percent of the homes were houses or bungalows and half were flats, of varying ages. Smartline participants' health and wellbeing were similar to the national comparators from England and Wales and compared to population estimates for England and for Cornwall participants were older and comprised a higher proportion of females (Williams et al., 2020). On average (mean), there were two residents' and one or two bedrooms per home. Twenty-eight percent of participants reported avoiding heating because of the cost.

Resident drop out

The number reached reduced to 159 by November 2021 and to 144 by the end of the study in March 2023. Similar to previous research (Poortinga et al., 2018), reasons for drop out included "residents moving, passing away, and the lack of resources to move sensors and recruit new homes" (RLC2). Generally, participant characteristics did not vary across the decreasing cohort size throughout the study (see Tables S1-S6 for descriptive statistics of homes and participants with sensors at three timepoints).

Perceived reach by CHA

Detecting and reaching vulnerable residents who are living in poor quality indoor environments is a challenge for HAs (CMO, 2022; Peek et al., 2023). Aligning with age and technology research (Zhang, 2023), staff reported that older and more vulnerable residents were less likely to self-report issues (e.g., leaks, damp & mold, fuel poverty), whereas younger, tech-savvy residents utilized the new CHA's app or social media for reporting (RLC1, CAL). Here, the system was perceived to be a success for expanding CHA's capacity to identify higher-risk environments, residents, and those "living in difficult circumstances" (CEO). Significantly, the system "enabled us to work with vulnerable residents that we otherwise wouldn't have known about, and would have never contacted us" (DoF). However, as the sensor system did not require resident interaction nor digital competence (Boag-Munroe & Evangelou, 2012; Helsper, 2021) CHA staff believed that monitoring the sensors enhanced reach and supported more vulnerable residents effectively.

System effect

Absolute effectiveness for residents

An initial hypothesis was households experiencing high relative humidity (RH), particulate matter (PM2.5) or electricity usage might log in more or might show a larger decrease in these measures than other households, or that households that logged in more might also show a larger decrease. However, there was no evidence for systematic changes in sensor data after participants used Version 1 of the dashboard to view their sensor data nor were the hypothesized changes in RH observed. Of the 20 households interviewed, four demonstrated a decrease in sensor readings (RH or PM2.5) between pre- and post-dashboard login. A further six households reported a change in condition of their indoor environment (see Table S8). One resident changed their behavior after using the dashboard. Others attributed changes to health factors, thermal preferences, and intervention from CHA rather than dashboard use. For example, Mary explained “the temperature was causing me a cough, so I turned it down” and James that he had “been brought some heavy jumpers for Christmas, so turned the living room radiator down.”

Overall, the finding that dashboard use did not result in a behavior change effect, is consistent with studies on smart meter feedback to change energy consumption (Alahmad et al., 2012; Allen et al., 2006; Buchanan et al., 2015). Regarding social housing, external factors and things beyond residents’ control such as fuel poverty and property attributes also influence the home environment and limit residents’ ability to impact it through behavior change alone (Boomsma et al., 2017; Wallace et al., 2022). The complex interplay of various factors affecting the home environment helps to explain the lack of dashboard effect, i.e., the effect of information provision alone. Therefore, to improve the indoor environment it is necessary to take an integrative approach and consider both property and social factors (Peek et al., 2023).

Absolute effectiveness for CHA

The CHA used the dashboard to identify high-risk properties if readings were concerning or irregular. Here, the CHA initiated a process where they would first contact the participant and if appropriate make a home visit to understand the issue in situ and instigate an intervention to address the problem. Four of the changes identified through the interviews were a result of CHA using the dashboard. Out of the 144, 39 homes were identified as high risk and received a contact. Nineteen homes received advice on fuel poverty (low temperature, financial constraints), with 4 having direct supporting interventions, and 23 received advice about high humidity, damp, and mold, with 12 having interventions. In one case, an improvement in health was reported. These results indicate the beneficial effect of the system for CHA in addressing indoor environmental risks which can impact resident health. Crucially, they underscore the system’s effectiveness without need for resident engagement with the dashboard.

Perceived effectiveness for CHA

CHA perceived the sensor system was effective for “protecting our residents and improving their health and wellbeing, but also protecting our housing stock and ourselves as a housing association" (RLC2). The dashboard provided valuable capabilities for CHA:

(1) Identification of high-risk properties, enabling timely investigation and proactive intervention.
(2) Prioritization of risks and efficient management of work.
(3) Access to necessary data for long-term planning.

The system "fundamentally, moves us from being entirely reactive into one that could be more pre-emptive" (DoF). By "intervening early you minimise the problem and stop a whole load of other problems then developing" (RLC2) and this has outcomes for both homes and health. From a homes and asset management perspective, proactive intervention "maximises the life of the building carcass" (HoI), and minimizes "disruption of repairs, and the costs of those repairs" (RLC2). CHA staff explained that proactive contact, "triggered by the data, is an opportunity to speak with the residents" and help the CHA understand and manage the causes of issues such as "income, arrears, heating costs, or repairs" (CAL). Within the context of the 2023 Social Housing Regulation Bill, "Awaab's Law," and recommendations from the Housing Ombudsman, the proactive tackling of issues is a necessity for HAs (HO, 2023).

The CHA reported that the sensors were particularly useful for older or mixed housing stock compared to new build homes, identification of previously unknown building issues (for example, removed loft insulation discovered through low-temperature readings not matching EPC ratings and energy use), or issues that could be rectified at low cost through repairs rather than replacements. Additionally, the system helped CHA staff prioritize risks and streamline their workload, acknowledging that "it is not feasible to focus on every customer at all times" (CAL). The sensor data enabled "rationalising of workload in a smart and manageable way" (CAL)." As previously found (Shukla et al., 2019; Sirombo et al., 2017; Wallace et al., 2022), if interventions were required, staff could review homes before and after interventions (e.g., ventilation system installation) to ensure their effectiveness. It also allowed for comparisons of the success of similar interventions (e.g., insulation upgrades) across different properties. The long-term benefits were perceived to be "better planning and investments for the future" (DCEO), including retrofitting and decarbonization planning.

System limitations

CHA staff identified operational limitations of the sensor system, notably its seasonal accuracy and usefulness. The system was considered more valuable in winter as it helped staff identify issues such as dampness and insufficient heating, and the humidity sensors were less informative in the summer (RLC2). Air quality data were not as useful as temperature and humidity data (HoI) as CHA did not have the resources to filter particles or address resident behaviors that impact air quality. While CHA staff acknowledged that the sensors and interventions would not identify and resolve every issue (RLC1, HoI), they were still considered a "positive step forward" (HoI).

A challenge and limitation for the overall effectiveness of the sensors was that many of the issues identified by the sensors resulted from the complex socio-economic and health-related risks existing in social housing populations and are beyond the scope and typical responsibility of the HAs to address alone (MHCLG, 2022). An example included a case where recent unemployment had led to fuel poverty. This highlights the need for closer partnerships between HAs, the voluntary, community, and social enterprise (VCSE) sector, and the health sector to coordinate action in addressing the social determinants of health inequalities (Chevin, 2014; HACT, 2021b). However, such partnership working necessitates careful consideration of ethical implications, data sharing, governance, and data protection and compliance requirements (DCEO). These issues have been previously identified (Li et al., 2021; Nagapuri et al., 2019; Shafi & Mallinson, 2023) and require significant effort to establish effective partnerships and achieve desired public health outcomes.

System adoption

Absolute adoption by residents

Adoption of Version 1 of the dashboard was very low. Between 2018 and 2020, 124 households, of the 221 with tablets, logged in to the dashboard at least once. Login data and interviewees indicated that participants tended to make several attempts (1–4) to use the dashboard before abandoning, with only 61 participants logging in three or more times and only 11 active users in 2020. The determinants of adoption by residents were investigated. The number of logins and the 12 variables considered to be potential determinants of dashboard use are presented in the Supplementary Materials (Table S7 and S10 for method details). The number of logins significantly increased with participant age and the household technology ownership score (see Table S9). While age is typically negatively correlated with technology use (Zhang, 2023), Attour et al. (2020) found that age was not a significant determinant of frequency of use of an energy monitoring app, only negatively with initial installation (Attour et al., 2020). Other potential determinants, including health measures, were non-significant.

Reasons for low resident adoption

It is established that smart home dashboard adoption is influenced by ease of use and usefulness factors (Marikyan et al., 2019; Pennings et al., 2010) and research into the key design components to make dashboards easy to use and useful is expanding. For example, Kim and Li (2020) identify important features as color coding, normative comparison, historical comparison, plain English descriptions, and advice for action as essential for increasing ease of use. Residents reported that Version 1 of the dashboard was difficult to interpret and “hard to understand” (Martha), due to its “technical language” (James), use of “acronyms like PM2.5,” and “awkward graphs” (David). Gill and Ruth emphasized the lack of explanations about sensor significance. Ruth admitted, “I couldn’t always make sense of what it was telling me” Consequently, residents “struggled to make meaning from the readings” (Michael).

However, despite color coding, normative and historical comparisons and plain English descriptions being incorporated into Version 2 of the sensor, usage remained low among residents. Out of the 144, 28 used the newly updated dashboard, with only 8 homes logging in three or more times. This limited long-term adoption of the sensor dashboard is in line with previous research identifying low long-term usage of other home environment and utilities monitoring technologies, such as smart meters (Hargreaves et al., 2013; Murtagh et al., 2014). Our findings imply that adoption and use of dashboards by residents do not necessarily form an effective component of a sensor system, even if co-designed with intuitive features.

Absolute adoption by CHA

During the study's evaluation period (November 2021 to March 2023), two CHA staff members (RLCs) spent 1 day a week monitoring the dashboard and coordinating interventions. Figure 5 illustrates the number of logins during this time. During this time, CHA accessed the dashboard a total of 277 times. It shows initial high usage of the dashboard when it was initially available, increased usage during the summer of 2022, and peak usage in November and December 2022. These patterns correspond to qualitative reports from CHA, indicating the use of the dashboard to monitor overheating risks during a hot summer spell in 2022 and to address issues related to fuel poverty and cost of living impacts in winter 2022. The time between logins varied significantly, ranging from 6 seconds to 24 days, with an average of 2 days. The median average time between logins was 20 hours, indicating that most logins occurred more frequently than once per day, reflecting staff's active engagement with the system. The main features of the dashboard used by CHA staff were the "bird's-eye view" dashboard (see Figure 6) and the individual

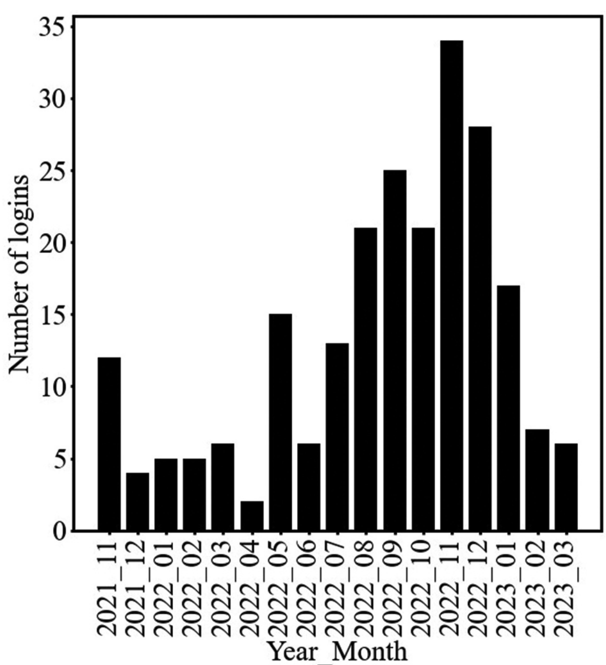

Figure 5. Number of logins by CHA staff for each of the 17 months.

sensor measure graphs for specific homes (see Table 2). Aligning with the findings of the interviews, temperature and relative humidity were the most examined sensor data.

Reasons for CHA adoption

CHA adopted the dashboard for two main reasons. First, CHA staff perceived the sensor system as operationally efficient and informative. Previously, CHA identified risks through occupant reporting, ad-hoc contractor reporting, and stock surveys; however, CHA staff pointed out the disadvantages of these methods in their infrequency and unreliability. For instance, resident reporting was found to be unreliable "due to stigma surrounding damp and mould issues, despite efforts to assure residents that there would be no judgment" (CAL). In contrast, CHA staff believed that the sensor system addressed many of the limitations associated with traditional methods by providing reliable and frequent indications of risk in real-time, thus surpassing the effectiveness of existing systems. This real-time reporting, as noted in previous research (Filippi & Sirombo, 2019; Shukla et al., 2019; Sirombo et al., 2017), was particularly valuable in quickly and clearly identifying potential risks.

The second reason for adoption was the system's alignment with CHA's values, policies, legislative responsibilities, and long-term strategic objectives as a charity.

Figure 6. Photograph of sensors.

Table 2. Description of dashboard use by CHA staff.

		Number of views and percentages by features	Average engagement time and percentages by features
Total	4 November 2021 to 31 March 2023	994	110 minutes
Dashboard functionalities	Dashboard front page showing average readings for all homes and environmental measures, with colour-coding (bird's-eye view')	52.3%	26.1%
	Sensor data graph for a particular home and sensor measure	30.5%	37.2%
	Viewing a specific resident's view of their home's dashboard	7.7%	24.2%
	Resident view of their sensor data	5.9%	6.7%
	All sensor data for a given participant	3.5%	5.8%
Sensor measure graphs	Temperature	63.7%	67.9%
	Relatve humidity	25.4%	17.3%
	Particulate matter ≤2.Sµm	8.6%	12.3%
	CO_2, derived f rom VOCs)	2.0%	1.9%
	Volatile organic compounds (VOCs)	0.3%	0.6%

As a charity, the HA has a social mission beyond providing homes, encompassing support for the communities they serve (Blessing, 2012; Chevin, 2014). The sensor system was seen as fitting well with CHA's organizational ethos, values, culture, and strategic approach. As the CEO noted, "it is inscribed in our DNA, something more than just a roof over someone's head" (CEO). It also aligned with legislation, regulations, and commitments associated with CHA's charitable status. It was also highlighted that proactive sensor work went "beyond what is required from legislation and building safety" (DCEO) and received positive feedback from the Housing Ombudsman. The sensor system was perceived to put CHA "at the vanguard really, of this way of thinking" (CAL) and was considered unique within the social housing sector.

Facilitators to CHA adoption

The incorporation of color-coding and easy to read charts in the CHA "birds eye view" dashboard meant that CHA staff were no longer "trawling through facts and figures, with staff reporting that the simplified traffic light system developed [co-designed as part of study] is useful" (RLC1). At the organizational level, it was noted that adoption of such technology required organizational buy-in and "embedding in the culture" (CAL). Adoption needs to be "led from the top down by the Executive Board, to drive implementation and usage of the data" (CAL). This requires "education [of staff] on what the system can achieve, demonstrating how it will benefit their job role, and some initial training" (CAL).

Risks to adoption for CHA

Addressing adoption concerns, the DCEO emphasized the need for proactive measures in handling data to build trust with residents and avoid disrepair claims. Consensus was that formalizing responsibility for monitoring and responding to data within the CHA and staff job roles is crucial to mitigate the risk of disrepair claims and ensure the protection of resident health and wellbeing.

System implementation

The implementation of the sensor system in practice involved three elements: resident recruitment, the technical implementation of the sensors, and the organizational implementation of using the data. Our findings here contribute to the limited body of research on the processes of implementation to end user adoption (Marikyan et al., 2019; Shafi & Mallinson, 2023).

Resident recruitment

We found recruitment was facilitated by the perceived usefulness of the sensors in daily life and participants' overall attitude to indoor environmental monitoring. Positive attitudes were expressed about the sensor system, with residents describing it as "good idea" (Dennis) and "forward thinking" (Daniel). These attitudes were rooted in perceived usefulness of the system for problem identification and housing management improvement. Mary noted its capacity to "pick up anything that I didn't know about," while David saw its purpose as "to help people, so they [CHA] can know what to do or not to do." There was also anticipation that the system will enhance housing design, as Paul put it, "going forward it is going to help in future housing, isn't it? They're [CHA] going to say, well this needs addressing, perhaps up that insulation, or that needs doing." Our findings suggest that perceived usefulness in sensor systems relates to its capacity to help the CHA tackle property issues beyond resident control.

Indoor environment monitoring data can potentially reveal resident behavior (e.g., bathroom humidity indicating washing routines), movements (e.g., CO2 levels indicating sleep timings), and financial situations (e.g., temperature data indicating fuel poverty). Acceptability was therefore anticipated to be strongly influenced by concerns of privacy intrusion and data security (Balta-Ozkan et al., 2013; Bowes et al., 2012; Ding et al., 2011Nagapuri et al., 2019; Pennings et al., 2010). For example, devices with microphones and cameras, such as smart speakers, have been found to provoke concerns about intrusiveness when used in households (Chalhoub & Kraemer, 2021).

However, we found this was not an issue and did not form a "point of resistance" for implementation (Pal et al., 2021). Although general digital security and data privacy were noted by residents, they had no concerns about how CHA would use the data. As Diana explained, "Well, I do like my privacy, yes … but no, Coastline can [have the data] yes." This lack of concern was driven by a "I've got nothing to hide" (Thomas) mentality and the overall low value associated with such data, relative to other data risks: "as long as somebody is not going into my bank accounts I've not had a problem with the other sort of stuff" (Gill).

Additionally, concerns about privacy and data security in smart home technologies stem from a sense that tech developers own and benefit from the data (Seymour et al., 2024). Trust is established through the previous behaviors of organizations (Pennings et al., 2010), and in this case the HA had developed positive relationships with residents, including credibility of good intentions. Residents did not appear to share these concerns with the knowledge that their data was being accessed by CHA. Participants explained, "You're quite welcome to share my data with Coastline, Coastline's been good to me" (Thomas) and "Coastline, they've been great with us, so no, I didn't have any worries about it" (Mark). This finding highlights the crucial role of community liaison between HA and their residents in adoption of smart technology. For HAs who lack established trust with their residents, this may be a point of resistance to implementation.

Technical implementation

For CHA, sensor installation proved technically manageable, taking approximately 1 hour per home. Retrofitting was found to be more challenging than installing in new builds. Improving internet accessibility for the sensor gateway was identified as necessary. Proposals were made to "standardize sensor fitting and Wi-Fi connections in new builds through tenancy agreements" (HoI). Addressing these technical issues is feasible and would expand the systems reach.

Organizational implementation

Organizational implementation was more complex due to the novelty of the system and required a learning process to effectively utilize the sensor data in day-to-day activities. This involved understanding the resources and skills required by staff to successfully use the system. The CEO acknowledged that "the process taught us a lot and contributed to our confidence in implementing the system." It became clear that implementing a sensor system was not a simple "plug and play" technology. However, the Deputy CEO noted that "We've been able to learn from what works well, what doesn't work well, and adapt." The complexity and demand of implementing such a system has been previously noted (Wallace et al., 2022), although HA staff views have been under-explored.

Perceived cost effectiveness

CHA staff believed that the proactive approach enabled by the sensor system would ultimately lead to cost savings. One key reason was that responding to a crisis was considered more expensive than scheduled work, "even minor issues left unattended could escalate into costly and disruptive repairs over time" (RLC2). However, an analysis of the cost-benefit of sensor system investment was not within the scope of this study and remains poorly understood (Balta-Ozkan et al., 2013; Marikyan et al., 2019; Wallace et al., 2022). With the Housing Ombudsman recommending a shift from reactive to proactive approach to handling problems (HO, 2023), further research is needed to comprehend the cost–benefit case for HAs. Considering the treatment costs to health services arising from poor housing, this analysis should also incorporate the broader social return on investment (Garrett et al., 2021).

System maintenance

Maintaining a sensor system in existing housing stock presents numerous practical challenges (Shukla et al., 2019). It was agreed that the system supplier (Invisible Systems) would monitor disruptions and the support contractor (Blue Flame) would promptly fix issues. In reality, there were challenges with malfunctioning software, depleted batteries during lockdowns, and sensors were sometimes insufficiently fixed on walls. Customer-related problems, including participants unplugging or turning off sensors, removal due to home decoration, and participant relocations, caused significant network disruptions (SSPM). Similar customer-related issues arose in a smaller trial of sensor systems in social housing homes (Shukla et al., 2019).

The result of these practical issues was that, at some point during the second year of the project, 75% of sensors went offline. This posed challenges for repairs and placing a significant burden on CHA and university staff. Moving and reusing sensors also created data ambiguities, and the contractor's records were challenging for machine-reading. Manual checks, time-consuming for both the contractor and research staff, prompted additional hiring for network management. This technical maintenance difficulty led to a CHA decision to procure a future system as a service, outsourcing sensor maintenance (HoI).

Technical adaptations

Several crucial future adaptations were identified to enhance efficiencies and effectiveness of the system, chiefly the integration of data into CHA's existing systems for property and customer management. CHA staff recognize the benefit of data across various teams but emphasize the urgency of making it accessible within their existing IT systems (HoI, CAL). The integration should reach teams such as asset managers, repairs and maintenance, technical services, surveyors, tenancy, and income managers (DCEO, HoI). Consensus among CHA staff favors integrating the data into existing systems rather than introducing new ones, aligning with the strategic goal of limiting the number of systems staff use and presenting information in the right format at the right time (DCEO, DoF, HoI, CAL).

Additionally, future adaptations should include automation and alerts, such as sending texts or flags to the appropriate teams. Currently, Resident Liaison Coordinators manually scan data using traffic-light risk indicators to identify vulnerable residents or properties. Predictive services, including AI, could further enhance this by utilizing environmental indicators to detect unusual activity and prompt HA contact with the resident. CHA's goal is proactive identification of issues, such as predicting heating system failures before they occur, and this requires further development work to determine specific information needs (DCEO, DoF, HoI).

System scale-up

Despite initial challenges, CHA expressed plans to continue using the system beyond the conclusion of the study in April 2023. The CEO emphasized the significance of scaling up the sensor system, envisioning its integration into more households as the next logical step. However, a cautious, incremental strategy, as proposed by Norman and Verganti (2014), was favored, whereby gradual improvements and refinements of existing processes would be integrated with the new sensor capacity and vice versa. At the operational level, incremental scale-up was favored to ensure the process was adequately resourced to "avoid a backload of cases" (RLC2). At the strategic level, incremental scale-up was favored to enable organizational learning, data integration, and staff training. A recommendation for other HAs is that adoption and scale-up should be at a pace which is proportionate to the available resources for managing the process effectively.

Conclusions

Indoor environmental sensors offer an increasingly cheap and effective means to identify the health risks associated with poor indoor environments (Diaz Lozano Patino & Siegel, 2018; Shafi & Mallinson, 2023; Sheppard et al., 2022). However, their systematic uptake remains low across both the private and public housing sector and their use is often limited (HACT, 2021a; Li et al., 2021; Marikyan et al., 2019). To realize these benefits require that residents understand the potential of sensors to facilitate improved indoor environments as a pathway to better health outcomes. Providing housing for up to 16% of the UK population, social housing associations are in a particularly advantageous position to demonstrate the usefulness and effectiveness of sensors by incorporating them within their housing stock as standard. While the complex health needs of their residents mean that such sensors have the potential to have larger than average benefits among a population that spend a higher proportion of their time, due to an older average age, in their homes (Diaz Lozano Patino & Siegel, 2018; Schweizer et al., 2007; R. Sharpe et al., 2020).

In this context, our results have significant implications for housing providers at the operational level. We show that sensor systems are (1) acceptable to social housing residents, despite low engagement with the data themselves, (2) can facilitate and expedite identification of issues by the HA such as fuel poverty or mold, which can substantially impact residents' health but might not be reported, and (3) allow real-time monitoring to inform early interventions thereby mitigating more stressful crisis situations. Positive perception among CHA staff, including the desire for widespread adoption, indicates that sensor systems should become standard installations in CHA homes. The findings also highlight the importance of developing robust implementation strategies during the setup and maintenance phases of sensor systems. These insights could inform procurement decisions, such as opting to outsource system maintenance to specialized contractors and establishing requirements for the sensor provider to ensure data compatibility with existing infrastructure within the organization.

At a strategic level, our study demonstrates that an indoor environment sensor system coupled to targeted interventions can help improve indoor environmental conditions and potentially address health risks in underserved communities. However, facilitating the feasibility and effectiveness of such interventions requires increased investment in stronger partnerships between the housing, health, and voluntary sectors to coordinate action (Chevin, 2014; HACT, 2021b). Alongside university partnerships to robustly evaluate whether these systems have the potential to reduce health inequalities. Finally, this study also highlights the way in which internal environmental data can be used to identify household and individual behavioral patterns, preferences, and occupation levels (Menneer et al., 2021). Given the potential for this data to improve human health and housing stock, this study highlights the need to develop clear ethical and governance protocols when integrating sensor systems into housing practices (Li et al., 2021; Nagapuri et al., 2019; Shafi & Mallinson, 2023).

Study strengths and limitations

Strengths of this study include the relatively large scale of sensors installed in 280 homes, long-term period of observation, the real-world nature of the research in an understudied population, sampling strategies, and the sequential mixed methods assessment, including consideration of long-term adoption and outcomes. Limitations of the research include the lack of a quantitative assessment of cost-effectiveness, social return on investment, and the small number of system users. Quantification of health outcomes is an area for future research. It should also be noted that the findings may not be generalizable to other HAs; this study observed properties in rural locations, in a wet and mild climate, and where the resident participants displayed a high level of trust toward the HA. Future studies should explore the feasibility and acceptability of sensor systems within different housing providers across a range of locations.

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Disclosure statement

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Institutional review board statement

The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the University of Exeter Research Ethics Committee (eUEBS002996 v2.0 on 16 June 2017 and 5 December 2019).

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

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