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HOUSE RETROFITS: IMPACTS OF SUSTAINABILITY MEASURES ON HEALTH

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ABSTRACT

The UK faces an estimated demand for 345,000 new homes annually. Retrofitting the existing housing stock presents significant opportunities to mitigate housing shortages while addressing sustainability challenges. However, current retrofit initiatives have predominantly prioritised energy efficiency while neglecting health implications from retrofits. This paper examines the relationship between sustainable housing retrofits and health outcomes, exploring strategies to address these interrelated challenges. A literature review identifies links between health considerations in retrofits through the application of lean principles, particularly from a user value generation perspective. The paper highlights synergies between health, lifestyle, and technology factors and Lean. The findings indicate the need for robust data on the health impacts of housing retrofits, as well as participatory approaches that enable the prioritisation of needs of occupants. The evidence highlights the need for empirical research to develop solutions that integrate health considerations into retrofit policy and practice, ensuring that retrofits deliver benefits for both occupants' well-being and environmental sustainability.

KEYWORDS

Retrofit, health and well-being, smart home technology, lean

INTRODUCTION

Poor-quality housing has significant adverse effects on physical and mental well-being. Unhealthy housing conditions cost the NHS approximately £2.5 billion annually to treat illnesses associated with cold, damp, and hazardous environments (GOV.UK, 2019). Retrofitting the UK's existing housing stock offers opportunities to alleviate housing shortages and enhance sustainability (Jensen & Maslesa, 2015). Energy retrofits targeting inadequately heated homes can also substantially improve health outcomes (Healy, 2003; Monteiro et al., 2017). However, retrofit initiatives have predominantly focused on technological advancements and energy efficiency, often neglecting user-centred considerations such as health and wellbeing (Jansson-Boyd et al., 2017).

The widespread adoption of energy retrofits, driven by climate goals such as Net Zero 2025, raises critical questions about their health implications (Petrou et al., 2022). Poorly executed retrofits can lead to inadequate ventilation, dampness, and mould, which contribute to respiratory diseases and other health risks. Moreover, health considerations must be embedded into retrofit design frameworks to balance environmental objectives with public health outcomes (Ortiz et al., 2020). For example, there is insufficient data on how low-carbon technologies affect indoor air quality (Department for Business, Energy & Industrial Strategy, 2020). The benefits or potential disbenefits of energy efficiency

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measures in health outcomes remain underexplored, creating a significant research gap (Hoisington et al., 2019). Understanding the motivations, behaviours, and needs of occupants is also essential (Schimpf et al., 2017). Effective retrofit strategies must adopt participatory planning approaches, integrate users' health needs, and mediate among stakeholders (Pemsel & Widén, 2011).

The aim of this paper is to identify research priorities that address the links between housing retrofits and occupant health. This paper examines house retrofitting in the UK and identifies three key challenges linking health and retrofit strategies: (i) poor consideration of health determinants in retrofits, (ii) gaps in housing condition analysis, and (iii) poor consideration of lifestyle factors in retrofits. It proposes a framework that integrates health and lifestyle considerations into retrofit planning, emphasising comprehensive housing condition analysis, user needs identification, and participatory approaches. By aligning retrofit interventions with occupant health, this framework provides a foundation for future empirical research to inform policy development.

Findings are discussed through the lean construction lens, specifically value generation. Lean value generation is a strategic approach that focuses on maximising user value while minimising waste (Koskela, 2002). The approach incorporates user needs in retrofit interventions. Rooted in lean value generation principles, the proposed approach should emphasise continuous improvement, streamlined retrofit processes, and efficient use of technology to deliver occupant satisfaction. Building on these findings, the authors propose an interdisciplinary research initiative to design a comprehensive system for monitoring and improving environmental and health conditions in pre- and post-retrofit homes. However, further empirical data is required to validate and expand upon these findings.

RESEARCH METHOD

There is a growing interest in a better understanding of the link between retrofit and health outcomes. This led to increased funding opportunities for research in this area. Some notable examples are net zero and health research hubs (UKRI-NIHR, 2023); In2air studies (NIHR, 2023); healthy homes research initiative (University of Huddersfield, 2023); transforming housing and homes (University of Bath, 2024), and climate impact and resilience (Wellcome, 2025), among others.

To better understand the research gaps, a rapid review of the literature has been conducted to establish the research link. A review of the literature relevant to housing, retrofit, and health was conducted. Literature reviews allow analysis and evaluation of existing knowledge to identify a specific research gap (Aveyard, 2023). This is foundational to any scientific research by collecting, depicting, interpreting, and combining vast amounts of information and data (Badger et al., 2000). Furthermore, a literature synthesis summarizes and integrates key findings from multiple sources, identifying trends, gaps, and relationships. It provides a cohesive overview, offering insights through analyzing textual, statistical, and graphical materials (Snyder, 2019). Figure 1 presents the methodology adopted in this investigation.

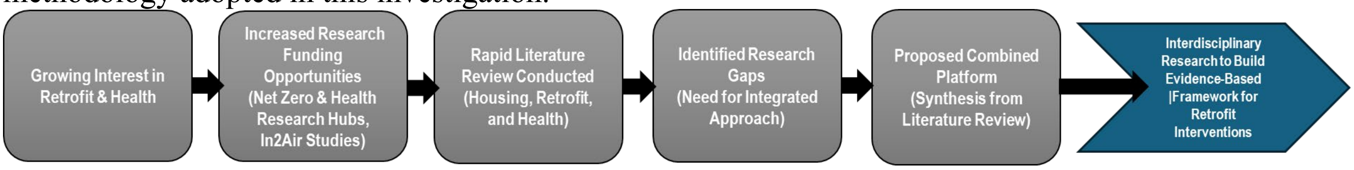

Figure 1 Methodology adopted to develop the paper

The proposed approach, which has been developed from the literature synthesis, formulated a combined platform as shown in Figure 2. There is a need to better understand, implement, and evaluate the approach, suggesting larger interdisciplinary research to establish a robust evidence-based framework in retrofit.

LITERATURE SYNTHESIS

HOUSING RETROFIT BENEFITS

The home environment significantly influences the occupants' physical, physiological, and mental health (Ortiz et al., 2019). Indoor environmental factors, including thermal comfort, air quality, and noise levels, play vital roles in health and well-being (Vu & Harrison, 2019; Horne et al., 2023). Investments in housing retrofits to enhance thermal comfort can yield significant health benefits, particularly for vulnerable populations (Monteiro et al., 2017). For example, improving the building envelope and airtightness has been shown to address discomfort and improve health outcomes in public housing in Lisbon (Monteiro et al., 2017).

Similarly, deep retrofits have demonstrated substantial energy savings, with studies reporting reductions of 47% to 90% in energy use (Less & Walker, 2014; Mohammadpourkarbasi et al., 2023). These measures contribute to reducing carbon emissions and enhancing environmental sustainability (Swan et al., 2017).

Energy parameters for space heating are connected with building design, material specification, structural condition, and building envelope (Elsharkawy, 2015). Less & Walker (2014) showed 47% less energy was consumed in 116 deep retrofitted homes in the United States. Ardente et al. (2011) investigated the energy and environmental benefits in public building retrofit, showing that envelope thermal insulation, e.g., glazed windows and thermal insulating boards, provided substantial energy savings.

Enhanced thermal comfort also provides wider benefits, like fostering social cohesion, increasing productivity, and reducing absenteeism (Elsharkawy, 2015). Sustainable retrofitting delivers dwellings that are environmentally, socially, and economically better than existing housing (Jensen & Maslesa, 2015).

Financial benefits are often a compelling motivation for undertaking housing retrofits. Energy-focused retrofit initiatives not only contribute to environmental sustainability but also act as a strategic measure to protect vulnerable households from financial hardships, such as the recent surge in energy prices (Pillai et al., 2023). By reducing energy consumption, retrofits help alleviate financial pressures, particularly for economically disadvantaged households (Tovar Reaños et al., 2023). Overall, retrofits provide a range of interconnected benefits, including enhanced health outcomes, economic resilience, and environmental sustainability.

HOUSING RETROFIT ISSUES IN THE UK

Top-down approach

Retrofits in the UK, specifically for social housing, face challenges stemming from a 'top-down approach' (Masoud Sajjadian, 2023). For instance, the UK follows PAS 2035, which is a process guiding retrofits (The Retrofit Academy, 2025). This approach suggests limited user engagement, which may lead to disconnection between retrofit strategies and occupant needs (Masoud Sajjadian, 2023). It is observed in the PAS document that due to a lack of detail on 'user engagement advice', the procedure is implemented inconsistently.

Such a "top-down" approach can lead to overlooking human factors (Morgan et al., 2024). Occupants' lack of awareness about retrofit benefits further impedes progress (Jansson-Boyd et al., 2017). Additionally, disruptions during retrofit work, such as noise, dust, and temporary displacement, can generate user dissatisfaction (Tzortzopoulos et al., 2019), which negatively impacts retrofit outcomes (Baldauf et al., 2020). Addressing these challenges requires a participatory, "bottom-up" approach that incorporates user input and minimises disruptions.

This highlights the need for further research to inform UK policymakers toward advancing retrofit legislation. There is a need for better community engagement and communication to improve the benefits delivered through retrofits (Grey et al., 2017).

Potential negative impacts of retrofit in health

The literature provides examples of the potential negative impacts of retrofit, especially on indoor air quality. Retrofits that seal gaps and add insulation help reduce energy loss, but they can also trap indoor pollutants and moisture in the building. Coggins et al (2022) reported that the concentration of indoor air pollutants in 14 deep energy-retrofitted Irish dwellings is higher. Especially high concentration of CO2 (>800 ppm), TVOCs, and formaldehyde was detected more frequently in bedrooms than in living areas.

A study by Pampuri et al (2018) specifically looked at Radon concentrations in buildings before and after the retrofit. Though the study did acknowledge that Radon levels will vary depending on local geological conditions, it was concluded: "When converting existing buildings into energy-efficient buildings, the balance between energy saving and the quality of the indoor environment is a factor that must be taken into account". Kang et al (2023) discussed the need for research to investigate the effects of various home interventions on indoor air quality and health outcomes, as well as the economic costs and benefits of such improvements.

In a retrofit evaluation in Australia, Willand et al (2019) noted a call for an alignment of housing, energy, and health policies and programs to ensure health and equity were maintained.

RETROFIT AND HEALTH

The following section discusses housing retrofit and health outcomes in terms of (i) poor consideration of health determinants in retrofits, (ii) gaps in housing condition analysis, and (iii) poor consideration of lifestyle factors in retrofits.

POOR CONSIDERATION OF HEALTH DETERMINANTS IN RETROFITS

Indoor air quality plays a critical role in human health (Horne et al., 2023; Milner, 2023; Vu & Harrison, 2019). Horne et al. (2023) highlight that building parameters such as ventilation rates, access to natural ventilation, airflow direction and speed, air stability, pollution levels, and the compartmentalisation of indoor spaces are directly associated with morbid diseases. Poor housing conditions, including low indoor temperatures and dampness, are linked to respiratory diseases (e.g., chronic bronchitis and obstructive pulmonary diseases), cardiovascular problems, and mental health issues (Healy, 2003). Additionally, indoor moisture and mould often contribute to infections (Vu & Harrison, 2019).

Epidemiological and toxicological studies further indicate that exposure to ambient air pollution is associated with severe health outcomes, including cardiovascular problems, asthma exacerbation, and increased mortality and morbidity rates (Vu & Harrison, 2019). Bioaerosols—ubiquitous particles of biological origin, such as metabolites, toxins, or fragments—pose significant health risks. Exposure to microbial aerosols, in particular, has been identified as a growing concern due to their adverse health effects (Kim et al., 2018; Lee & Jo, 2006). Household air pollution remains a major contributor to fatal diseases, accounting for 27.9% of chronic obstructive pulmonary disease (COPD) deaths, 16.9% of lower respiratory infection deaths, 12.1% of stroke deaths, 8.8% of ischemic heart disease deaths, and 7.8% of lung cancer deaths, amounting to 2.9 million deaths globally in 2013 (Vu & Harrison, 2019).

Calderón-Larrañaga et al (2017) conducted a cross-sectional study of hospital admission rates for COPD in England and found that there may be an association of COPD admission rates for people with higher levels of deprivation. The indoor contaminant levels and thermal comfort parameters determine the effect of indoor air quality on occupant health (Persily & Emmerich, 2011). Any impact that retrofit technologies have on indoor air quality and warmth has the potential to directly impact respiratory conditions such as COPD and Asthma.

In the context of net-zero goals, energy efficiency measures aim to reduce unintended ventilation as a means of minimising energy consumption (Petrou et al., 2022). However, limited empirical data exist on the health implications of these interventions, and some measures can inadvertently harm human health (Petrou et al., 2022; Milner, 2023). For instance, implementing energy efficiency improvements without proper ventilation can lead to higher exposure to indoor pollutants, negatively impacting health (Milner, 2023).

Achieving a balance between maintaining a healthy indoor environment and reducing the environmental impact of buildings, such as energy consumption and greenhouse gas emissions, is critical (Persily & Emmerich, 2011). Furthermore, retrofit strategies often neglect mental health considerations, such as access to natural light, noise reduction, and safety, which are rarely incorporated through user requirement assessments (Hoisington et al., 2019). Addressing these factors is essential for fostering healthier living environments.

GAPS IN HOUSING CONDITION ANALYSIS

Pre retrofit analysis

Comprehensive housing condition analysis is critical for effective retrofits. However, current practices often neglect pre-retrofit assessments (Higney & Gibb, 2024). For instance, the evaluation of existing temperature and humidity parameters, internal insulation conditions, ventilation systems, and energy efficiency measures are often not considered in assessments (Coggins et al., 2024). Generic assessment methods overlook the individual characteristics of buildings that require tailored interventions. There is limited long-term data on how retrofit measures, such as airtightness improvements, affect issues such as dampness, mould, and overheating.

Maximising health benefits from retrofits is not possible without comprehensive health-related data. Sensing technologies can be used in pre-retrofit assessment to understand the condition of indoor air quality through the measurement of particulate matter, temperature, humidity, and other parameters (Matsui, 2018; Awwal et al., 2024;).

Limited Use of Ventilation systems in UK home retrofits

There are a number of ventilation strategies adopted in European countries, e.g. natural and mechanical ventilation strategies (Van Rooyen & Sharpe, 2024). Ventilation systems such as heat recovery ventilation (HRV) and energy recovery ventilation (ERV) are used in energy efficiency upgrades. These systems can be used in deep retrofits that focus on airtightness and insulation improvements, such as Passivhaus renovations or EnerPHit-certifies projects (Dodoo et al., 2011). There are other alternative approaches such as positive input ventilation (PIV) systems, which can be used in older homes with moisture issues, and mechanical extract ventilation (MEV) (Kang et al., 2022).

The most used ventilation strategy in the UK is intermittent extract ventilation, where water vapour or pollutants are released, especially from bathrooms and kitchens (Van Rooyen & Sharpe, 2024). Many UK homes are poorly insulated, and HRV/ERV systems are less effective unless significant airtightness improvements are made. One of the main reasons is the high cost and complexity of installations, especially in older UK homes that were not designed for ducted ventilation systems. Furthermore, IAQ can also deteriorate owing to improper installations of heat recovery units (Bai et al., 2022). From the Building regulation-Part F document, it is seen that the UK government incentives focus more on insulation and heat pumps but do not strongly enforce the use of heat recovery heat ventilation systems (The Building Regulations, 2021).

UNADDRESSED LIFESTYLE FACTORS

Lifestyle factors entail daily routines, user preferences in comfort level, and household activities. Cultural practices, family dynamics, and adaptability to changing living conditions are also related to lifestyle factors (Pérez-Sánchez et al., 2022). However, retrofit programs frequently fail to account for occupants' lifestyles and preferences, for instance, being unfamiliar with smart devices, causing inconvenience to the users (Urbed, 2016). Retrofit design strategies need to incorporate household needs, e.g., activity patterns to create efficient living spaces and reduce inconvenience for residents that affect user comfort and satisfaction (Awwal, Mishra, et al., 2024)

Additionally, retrofits often overlook the needs of vulnerable groups, such as the elderly or individuals with disabilities, exacerbating inequalities (Abed et al., 2023). A study by Bednar et al (2017) in the USA shows that low-income, racial minority households are less energy efficient and exposed to diseases related to cold homes. Another study by (Abed et al., 2023) demonstrates a stronger effect of air pollution on poor health among ethnic minorities and non-UK-born individuals, identified by location-specific differences. Cultural and social practices differ in indoor-outdoor living patterns, cooking and eating habits, and comfort levels. Addressing these factors through inclusive design strategies is crucial for creating adaptable and user-friendly homes.

Hamilton et al (2015)'s research showed that failing to properly consider ventilation in home energy retrofits can negatively impact occupants' health. Energy retrofits tend to be airtight and suffer from inadequate ventilation and poor environmental quality. Studies have shown that the primary cause of insufficient ventilation in homes is improper usage of ventilation systems. Such as home occupants failing to integrate them into daily routines(Dimitroulopoulou, 2012). Many residents keep their windows closed for extensive periods to conserve energy, unknowingly trapping pollutants and moisture indoors (Holden et al., 2023).Another example is trickle vents, which are quite common in UK homes and are designed to offer continuous background ventilation and need to remain open (The Building Regulations, 2021). But a recent survey of 80 homes in England revealed that only 29% of trickle vents were opened, although 86% of occupants claimed to understand their purpose (Dimitroulopoulou, 2012).

In summary, lifestyle factors, cultural practices, and household characteristics play a crucial role in the success of retrofit intervention programs. The exclusion of these considerations can exacerbate social inequalities, particularly among low-income households, who are more susceptible to poor indoor air quality. Retrofit strategies must integrate inclusive and adaptable design approaches that align with occupants' health and well-being.

PROPOSED APPROACH

We argue for a combined platform integrating health and lifestyle factors with thorough housing condition analysis in retrofit strategies. Real-time energy monitoring and an automated adaptive control system enable occupants to track usage patterns, identify inefficiencies, and implement data-driven approaches to reduce waste (Awwal et al.,2024). Technological interventions positively impact health outcomes (Grey et al., 2017). Lifestyle factors, behavioural patterns, and smart technology can play a crucial role in successful retrofits. The proposed approach supports user-centred sustainable, and health-promoting retrofit solutions, delivering better value generation. Figure 2 presents the key factors proposed in the approach.

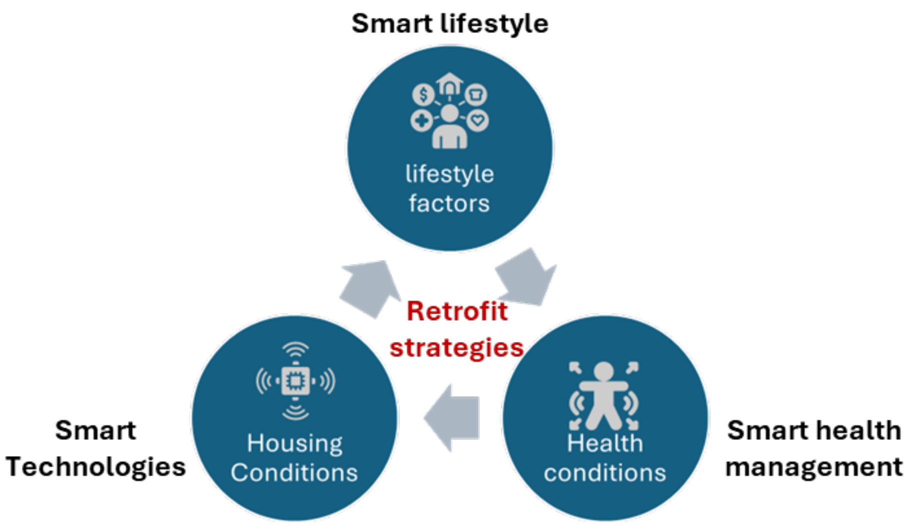

Figure 2 Key factors proposed in combined platform

HOUSING CONDITIONS THROUGH SMART TECHNOLOGY

Smart technologies can play a pivotal role in helping buildings adapt to various requirements, such as occupant needs and external factors like climate conditions and energy grid demands (Al Dakheel et al., 2024). A smart home represents a network of integrated devices and sensors within an intelligent system, enabling control, monitoring, support, and responsive services to meet user needs (Basarir-Ozel et al., 2023). The smart home concept has three major domains: (i) smart building, (ii) smart sensor and systems, and (iii) smart devices (Ghafurian et al., 2023; Javaid et al., 2021; Zhang et al., 2023). The proposed approach focuses on smart sensing technologies, as the smart building would often require structural renovation, which is unachievable due to retrofit policy and budget constraints. Smart sensors can be integrated to collect data on home environment parameters that are less intrusive (Coggins et al., 2024).

Smart sensors can collect real-time data on thermal performance, indoor air quality, and structural integrity (Javaid et al., 2021). For example, environmental sensors can monitor temperature, humidity, and air quality—specifically tracking particulate matter—to identify areas prone to mould growth or poor ventilation (Awwal et al., 2024). Energy-monitoring sensors can identify insulation gaps and areas of heat loss, which are crucial for designing effective, targeted retrofit strategies (Coggins et al., 2024).

IoT-enabled wireless sensors can be deployed in residential spaces to collect data over time. Using regression analysis, patterns and irregularities in the data can be identified, providing actionable insights for retrofit recommendations (Deb et al., 2021). This process can be further enhanced by integrating the collected data with Building Information Modelling (BIM), offering a visual representation of the building's current state (Awwal et al., 2023). Such integration can help maximise energy savings and minimise unforeseen costs during retrofitting.

Moreover, addressing issues like poor insulation and inadequate ventilation through these evaluations not only reduces the building's carbon footprint but also improves indoor comfort and occupant health (Ozarisoy, 2022). Therefore, sensor-based evaluations are essential for retrofit assessments as they streamline workflows and ensure effective outcomes.

Despite several advantages, smart sensing technology in retrofit projects presents several challenges, such as compatibility issues with existing buildings, high installation cost, data security and privacy concerns, and regulatory compliance (Iwuanyanwu et al., 2024). One critical issue is limited user awareness and technical expertise, which leads to resistance or improper use (Awwal et al., 2023). Addressing these challenges will require a well-planned interdisciplinary approach.

OCCUPANT'S HEALTH: SMART HEALTH MANAGEMENT

Assistive and smart home technologies can help mediate the relationship between housing conditions and well-being. For instance, Jimenez (2021) highlighted the association between exposure to outdoor environments and improved mental health outcomes, such as enhanced cognitive functions and overall well-being. The study emphasised the positive impact of exposure to nature on mental health.

Understanding users' health conditions is essential for designing retrofit strategies that improve both physical and mental well-being (Healy, 2003). A variety of approaches can be employed, including a combination of sensor-based monitoring and occupant feedback, as well as tools such as interviews, surveys, and occupancy evaluations, to better understand and address health concerns (Willand et al., 2019). Incorporating health considerations in retrofits is crucial for fostering sustainability while enhancing the health and well-being of occupants (Sovacool et al., 2020).

The key challenge in implementing smart health management is the integration with healthcare service that would require communication between smart devices, caregivers, and medical professionals (Li et al., 2024). Moreover, regulatory and ethical concerns regarding health monitoring and data usage must be addressed to ensure trust and compliance (Chung et al., 2016).

SMART LIFESTYLE

Prior to retrofit, assessing occupants' needs and lifestyle factors ensures targeted retrofit interventions that are aligned with requirements and preferences (Soliman-Junior et al., 2022). It is crucial to understand how occupants utilise the functional space, energy consumption habits, and comfort needs, e.g., regular habits, desired temperature ranges, and peak energy usage period. These insights enable retrofitting requirements to better address individual occupants' demands (Ortiz et al., 2020).

User adoption and adaptability pose challenges for residents who are not tech-savvy or resistant to change in lifestyle (Wang et al., 2023). Cost constraints can further limit access to smart technology, especially for marginalised communities that have limited resources. Furthermore, interoperability issues among systems often lead to inefficiencies, making it difficult to create a cohesive smart home environment (Bednar et al., 2017).

Surveys, interviews, behavioural tracking, and data from smart devices (e.g., sensors, wearables) can be used in retrofit assessment processes. A resident questionnaire can be conducted to understand the comfort levels, preferred energy usage, and inadequate ventilation (Awwal et al., 2023). Smart home devices can provide real-time information on thermal comfort and indoor air quality. By integrating the qualitative and quantitative data, retrofit suppliers can provide tailored solutions to improve the quality of life for occupants.

LIMITATIONS

The proposed approach requires empirical studies for validation. The results presented in the above section are based on the literature review only. Furthermore, the approach needs to be tested to determine the most effective method of delivery, as different homes will present unique challenges. The qualitative aspect assessing the lifestyle and health factors might require a different approach to account for contextual variation. Therefore, interdisciplinary research is needed. The proposed approach considers three key factors related to lifestyle, health, and smart technology. However, other factors, such as cost, regulatory compliance, and ethical challenges, may also need to be considered.

DISCUSSION & CONCLUDING REMARKS

This paper highlights the need for further empirical research. The relationship between housing retrofits and health outcomes presents a critical opportunity to address public health, housing deficits, and sustainability challenges. Retrofitting existing housing offers the potential to significantly reduce carbon emissions, improve energy efficiency, and create healthier living environments.

However, as highlighted, retrofit efforts have often prioritised technological and performance outcomes with sometimes inadequate consideration of health impacts. This highlights the need for a holistic approach to retrofit planning and implementation that considers both environmental issues and health outcomes. Future research could focus on developing and deploying sensing technologies in homes to understand pre- and post-retrofit conditions. It is also proposed that post retrofit evaluations are conducted to understand the immediate and longer-term retrofit benefits, or identify disbenefits, to health

A starting point for the proposed approach can be associated with a user value-driven approach. In the proposed approach, occupants are fundamental actors, and their requirements and health conditions are key factors in retrofit intervention, which includes health determinants as a significant parameter. Participatory approaches are vastly reported in lean research (Koskela, 2002; Soliman-Junior et al., 2021), and a similar principle is applied in the proposed approach, summarised in Table 1. A summary of potential synergies between the proposed approach and lean is generated, highlighting the connection to lean principles.

Table 1: Links between proposed approach and Lean Principles

Need	Proposed Approach	Lean Principles
Focus on occupants' health requirements	Assistive and smart home technologies to support occupants' health, leading to smart home technology adoption in retrofit intervention	User Value
Link internal home environment and health outcomes	Sensor data to link health issues with internal environment in pre-and post-retrofit.	Design process improvement – enabling evidence-based retrofit design
user engagement and collaboration	Occupants’ lifestyle factors are incorporated into retrofit intervention, ensuring residents are included in the process from the beginning.	Increase Value Process transparency
Energy efficiency retrofit, better indoor air quality, better health outcomes	Targeted energy efficiency, along with occupant health in retrofit intervention, reduces energy usage. Improving occupant health reduces pressure on NHS and hospitalisation	Reduce Waste
Replacement of ‘Top-Down’ retrofit approach	Opportunity to support retrofit policy framework with user and stakeholder involvement	Value Generation

Table 1 is limited to conceptual analysis from literature synthesis. This needs to be supported with future empirical studies. Future research should emphasise user value, needs, and requirements to be at the core of retrofits. We suggest involving users actively in the retrofit assessment stage to identify needs and preferences, linking occupant health directly to retrofit intervention strategies.

Figure 1 illustrates the interconnection among three key factors that are closely aligned with lean principles. By integrating continuous feedback from users and data-driven insights from health parameters embedded in the process, retrofit strategy can deliver sustainable, health-promoting, and energy-efficient solutions that connect health and sustainability to provide occupants. Other areas for future research include:

(i) Longitudinal Studies on Health Impacts: Investigating the long-term health effects of retrofits, as the current lack of robust empirical data limits our understanding of how interventions affect physical and mental health over time.

(ii) Indoor Air Quality and Respiratory Health**:** Building on the literature review, further studies should explore how retrofit measures influence indoor air quality, particularly in addressing mould, ventilation, and respiratory health conditions such as asthma.

(iii) Behavioural Factors and Occupant Engagement: Expanding on the participatory strategies, research should assess how occupant behaviour and interaction with retrofitted environments influence health outcomes, emphasising the role of education and engagement.

(iv) Policy Development and Systemic Integration: The absence of integrated health considerations in retrofit policy and practice represents a significant gap. Research should focus on developing frameworks that align health objectives with sustainability goals in retrofit programs.

By addressing these research priorities, housing retrofit programs can evolve to not only meet sustainability and housing targets but also improve occupant health and wellbeing. Integrating health considerations into policy, design, and practice will ensure that retrofits deliver benefits that are equitable, effective, and sustainable. Collaboration across disciplines, including policymakers, researchers, healthcare professionals, and communities, will be essential to achieving these transformative goals.

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