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CONCEPTUALISING A VALUE STREAM MAPPING (VSM) - BASED DECISION - MAKING MODEL FOR LEAN ENERGY RETROFITTING OF HVAC SYSTEMS IN HIGH-RISE BUILDINGS: LITERATURE REVIEW APPROACH

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ABSTRACT

The built environment sector accounts for a considerable global energy consumption, making energy retrofitting a critical strategy for enhancing energy efficiency while reducing operational costs. However, conventional energy retrofitting exhibits several limitations often caused by fragmented interventions and limited long-term impacts. Previous studies across different industries demonstrated that the lean concept is capable of optimising processes while maximising the value. Hence, it is worth to explore on how to integrate lean concepts in energy retrofitting to optimise energy consumption and energy costs. As the initial step, this study aims to investigate the value stream mapping (VSM) as a decision-making approach for lean energy retrofitting through a non-systematic review approach. The collected data were analysed using thematic analysis technique. The findings reveal that the incorporation of the lean concept in energy retrofitting enables various advantages. Further, VSM, one of the key lean tools, can be identified as a promising solution for energy retrofitting that enables facilities managers to visualise energy flows and identify non-value adding items. Secondary data evidence indicates that VSM-guided interventions can yield significant reductions in both energy consumption and project lead times compared to conventional methods. Accordingly, this study proposed a conceptual VSM-based decision-making model for lean energy retrofitting in HVAC systems in high-rise buildings as the key outcome of this research. Overall, the study identified that lean-integrated energy retrofitting facilitates a more adaptive, resource-efficient, and sustainable approach for energy retrofitting than the conventional method.

Keywords: *Energy Retrofitting; High-rise Buildings; HVAC System; Lean Energy Retrofitting; Value Stream Mapping.*

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1. INTRODUCTION

Energy consumption in buildings has been a significant concern since the late 20th century, particularly due to its environmental and economic impacts (Omer, 2008; Shahid et al., 2025). According to Di Foggia (2018), the building sector stands out as one of the largest energy consumers globally, accounting for nearly 50% of total annual energy usage. The global energy demand in buildings has steadily increased due to urbanization and economic growth in many developed countries. The combined energy consumption of residential and commercial buildings now represents between 20% and 40% of total energy use, surpassing sectors like industry and transportation (Pérez-Lombard et al., 2008). Some building systems, such as HVAC systems and lighting systems are especially energy-intensive in buildings, and inefficiencies arising from design flaws, occupant behaviour, and maintenance practices result in significant energy wastage (Pompei et al., 2023). Also in Sri Lanka, as a developing country, the energy demand for buildings is rising rapidly due to strong economic growth and ongoing urban development (Siriwardhana & Namal, 2017). Olatunde et al. (2024) demonstrated that some buildings still use outdated HVAC systems and lack energy-efficient design features, resulting in high electricity consumption and operational costs.

To regulate this excessive energy consumption for HVAC systems in buildings, different approaches, including renewable integration, demand response, passive design, and energy retrofitting, have been adopted. Among these approaches, energy retrofitting is widely recognised as a cost-effective means of reducing consumption and operational costs without constructing new buildings (Ascione et al., 2021). Energy retrofitting means upgrading existing building systems to improve energy efficiency. However, conventional retrofit approaches often focus narrowly on technical upgrades and neglect process inefficiencies and operational waste (Dadzie et al., 2022). In 2003, Womack and Jones (2003) introduced lean principles to overcome these limitations in conventional retrofitting to eliminate waste and to optimize value, which were later applied to the energy management domain (Womack & Jones, 2003). When considering lean integration in energy retrofitting, it aims to systematically remove non-value-adding activities and streamline retrofit processes, thereby improving energy efficiency and reducing costs more effectively (Antony & Laureani, 2002; Ahamad et al., 2022). Among various lean tools, VSM can be identified as one of the most suitable approaches for energy retrofitting, as it facilitates resource optimisation and cost savings. VSM has been shown to effectively visualize energy usage, identify bottlenecks in building operations, and optimize energy consumption (Antony & Laureani, 2012). Several studies have demonstrated the utility of VSM in energy management, particularly in identifying inefficiencies in HVAC systems and implementing strategies to improve energy flow (Stanica et al., 2021). However, despite this significance, limited attention has been paid to the integration of VSM for energy retrofitting, particularly for HVAC systems in buildings.

Hence, this research aims to address this knowledge gap, focusing on developing a VSM-based decision-making model for lean energy retrofitting of HVAC, as it is the highest energy consumption system in high-rise buildings. This paper presents the conceptual model developed for integrating VSM and lean energy retrofitting of HVAC systems in high-rise buildings. To achieve this aim, two (02) research objectives are formulated: (i) To review the applications of VSM-based decision making for lean energy retrofitting of

HVAC systems, and (ii) To develop a conceptual decision-making model integrating VSM for lean energy retrofitting in HVAC systems in high-rise buildings.

2. LITERATURE REVIEW

2.1 ENERGY RETROFITTING OF HVAC IN BUILDINGS

According to Hossain et al. (2023) reveals that HVAC systems typically constitute over 40% of the total energy consumption in commercial office settings, followed by 20-25% of lighting, 15%-20% of plug loads, and 10%-15% of others from the total energy, which are critical areas for potential energy-saving strategies. The efficiency of HVAC equipment plays a crucial role in determining energy consumption (Alves et al., 2016; Olatunde et al., 2024). Recent research highlights that improving HVAC efficiency can reduce energy bills by 20-40%, depending on the building type and climate zone, representing one of the most cost-effective energy-saving strategies in commercial offices (Feng et al., 2024). Accordingly, the optimization of HVAC systems is a critical aspect of improving energy efficiency, reducing operational costs, and enhancing indoor environmental quality in buildings (Loonen, 2018). Various methods and strategies have been developed to address inefficiencies in HVAC operations, ranging from traditional control techniques to advanced intelligent systems (Buffa et al., 2021). Among these strategies, Duran (2018) identified HVAC energy retrofitting enable cost-efficiency approach while enhancing occupant comfort.

According to Ahmed and Asif (2021), energy retrofitting can be defined as "Upgrade a building's components which directly or indirectly impact the energy consumption of the building". Previous studies demonstrated that energy retrofitting has become a pivotal approach for optimizing energy costs in office buildings, due to its economic and environmental benefits (Zuhaib, 2019; Martek et al., 2025). A study conducted by Bleyl et al. (2019) to explore the long-term cost benefits of retrofitting in office buildings found that energy retrofits in commercial office spaces can reduce energy consumption by up to 10%, with further savings achieved through optimized building management systems (BMS) (Data, 2021). By reducing energy costs, retrofitting also enhances building value, supporting both economic and environmental sustainability (Iwuanyanwu et al., 2024). A need to incorporate climate resilience in retrofit planning, as increased temperatures due to climate change exacerbate cooling demands, making energy-efficient retrofitting essential for future cost optimization (Robert & Ballarini, 2023). Furthermore, to improve the energy retrofitting can combine the principles of the lean concept to optimize the energy cost and enhance the building's energy performance.

2.2 TRADITIONAL VS VSM-BASED LEAN ENERGY RETROFITTING DECISIONS

Conventionally, the decision-making process for energy retrofitting follows a linear, phase-based model aimed at achieving energy efficiency improvements within existing buildings (Luther & Rajagopalan, 2014). According to Luther and Rajagopalan (2014), this process can be segmented into five (05) key phases, including (i) Project set up and pre retrofitting survey, (ii) Energy auditing and performance assessment, (iii) Identification of retrofit options, (iv) Site implementation and commissioning, and (v) Validation and verification and presented in Figure 1.

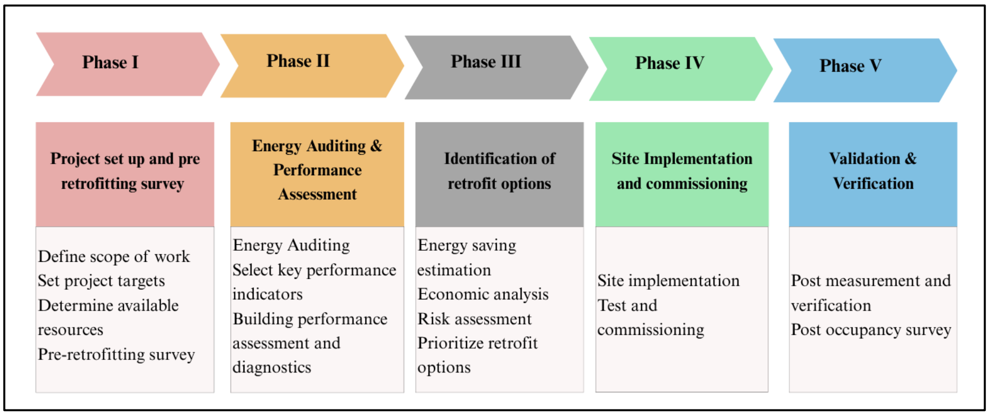

Figure 1: Conventional energy retrofitting process

While this conventional approach has provided structured guidelines for energy retrofitting, it has certain limitations. One of the main drawbacks is the rigidity of the phase-based model, which can lead to delays, increased costs and inefficiencies when unforeseen issues arise during the retrofitting process (Albatici et al., 2016). The linear progression of the model does not always accommodate the dynamic and complex nature of energy retrofitting, which often requires flexible adaptation to emerging challenges.

Hence, the integration of lean concept in energy retrofitting alleviates these limitations while maximizing energy efficiency while minimizing resource consumption, using low-impact, cost-effective measures that optimize existing building systems without the need for extensive modifications. By integrating lean principles, the energy retrofitting process becomes less reliant on heavy investments in new infrastructure, thus ensuring that the long-term benefits of sustainability and cost reduction can be realized in both the short and long term (Naylor et al., 2018; Panakaduwa et al., 2025). Thus, while traditional retrofitting offers substantial energy savings and performance improvements, the lean retrofitting approach presents a more efficient, cost-effective, and environmentally conscious alternative, aligning more closely with modern principles of sustainability and waste reduction (Ramos & Almeida, 2018). Table 1 presents comparison between conventional retrofitting and lean retrofitting.

Table 1: Comparison between conventional retrofitting and lean retrofitting

Conventional Retrofitting	Lean Retrofitting
Achieves substantial energy savings by improving building systems	Focuses on a more efficient approach that optimizes overall processes
Improves building performance through system upgrades	Delivers improvements in a more cost-effective manner by reducing inefficiencies
Often involves high implementation costs due to major upgrades	Reduces costs by minimizing waste generation
Mainly focuses on technical upgrades of building systems	Emphasizes optimized utilization of existing resources
Limited emphasis on waste reduction	Environmentally conscious approach by actively minimizing waste
Primarily energy-performance oriented	Strongly aligns with sustainability principles through continuous improvement and resource efficiency

Lean energy retrofitting for consumption optimisation involves applying lean principles to upgrade building systems, such as HVAC systems, to minimise energy consumption, reduce waste, and lower operational costs (Correia et al., 2022). In terms of the lean integration in energy retrofitting, VSM can be identified as a visual tool used in lean methodologies to analyse and optimise processes by identifying waste, inefficiencies, and areas for improvement (Rother, 1999; Martek et al., 2025). VSM plays a crucial role in streamlining retrofitting workflows, reducing energy losses, and enhancing overall efficiency.

3. RESEARCH METHODOLOGY

This study carried out a non-systematic narrative literature review to achieve the proposed aims and objectives. Ferrari (2015) also emphasised that narrative reviews can be used to synthesise general arguments, critically appraise previous studies, while also providing rationales for future research and speculating on potential new types of interventions. Accordingly, since this is the initial step in integrating the lean concept with energy retrofitting, a narrative review approach was more suitable for identifying the existing body of knowledge, evolving trends, current research frontiers, and gaps for this research domain.

Accordingly, the literature review was carried out in the Scopus database related to the lean concept, value stream mapping, energy retrofitting, HVAC systems, and high-rise buildings. The search was confined to articles based on the article title, abstract, and keywords using the search string: TITLE-ABS-KEY (“lean” OR “lean concept” OR “lean methodology” OR “lean method” OR “value stream mapping) AND TITLE-ABS-KEY (“energy retrofit” OR “energy renovation” OR “energy upgrade” OR “energy improvement” OR “energy efficiency” OR “energy performance” OR “energy optimisation” OR “HVAC retrofit” OR “HVAC upgrade” OR “HVAC renovation”) AND TITLE-ABS-KEY (“high-rise building” OR “tall building” OR “commercial building”). Initially, the database yielded 278 articles, and then several filtration criteria were applied, including Publication year: 2016 – 2026; Language: English; Document type: Article; Source type: Journal, and removing non-relevant subject areas to enhance the credibility of the retrieved literature. Finally, 52 articles were selected and analysed qualitatively using thematic analysis technique to identify applications of VSM for effective decision making in lean energy retrofitting of HVAC systems, providing a foundation for conceptual model development.

4. RESEARCH FINDINGS

4.1 APPLICATIONS OF VSM FOR LEAN ENERGY RETROFITTING DECISIONS OF HVAC

VSM provides a holistic view of the entire retrofitting process, ensuring that improvements are implemented strategically and sustainably (Hashempour et al., 2020). The significance of VSM in energy retrofitting lies in its ability to identify hidden inefficiencies and energy losses that may not be immediately apparent (Taher & Al Bashar, 2024). Many buildings experience unnecessary energy consumption due to poorly optimized HVAC systems, outdated lighting controls, insulation gaps, and inefficient equipment operation (Khafiso et al., 2025). VSM helps facility managers pinpoint these inefficiencies by creating a step-by-step visualization of energy use and identifying non-value-added activities within the retrofitting process (Shou et al., 2017). For example, an energy audit might reveal that a building's air conditioning system operates continuously, even in unoccupied spaces, leading to excessive energy consumption (Dadzie et al., 2022). By using VSM, facility managers can analyse why this inefficiency exists, whether it is due to lack of automation, incorrect thermostat settings, or system malfunctions, and implement targeted solutions such as demand-controlled ventilation or occupancy-based HVAC controls (Pompei et al., 2023). One of the primary benefits of VSM is its ability to streamline retrofitting workflows by eliminating process bottlenecks (Stadtländer, 2009). In traditional retrofitting projects, delays often occur due to inefficient procurement, lengthy approval processes, and poor coordination among stakeholders (Raimi & Newell, 2024). VSM allows facility managers to map out the entire retrofitting process, from initial energy audits to project implementation and monitoring, identifying areas where time and resources are wasted (Seth et al., 2017). By analysing lead times, energy consumption patterns, and process inefficiencies, VSM enables the development of an optimized workflow that reduces downtime, accelerates implementation, and ensures that energy-saving measures are deployed effectively (Madushika et al., 2023).

A key aspect of VSM in energy retrofitting is its ability to provide quantifiable insights that guide decision-making (Fontoura et al., 2023). By measuring energy consumption at different stages of the retrofitting process, VSM helps facility managers identify which interventions will yield the highest Return on Investment (ROI) (Womack & Jone, 2003). For instance, if lighting upgrades provide quick energy savings but HVAC improvements require a longer payback period, VSM helps prioritize the most impactful energy-saving measures first (Rother, 1999). This strategic approach ensures that resources are allocated efficiently, leading to cost-effective retrofitting projects that maximize energy efficiency (Antony & Laureani, 2012). Several case studies demonstrate the effectiveness of VSM in improving energy retrofitting outcomes. For example, a large commercial office building in the United States implemented VSM to analyse HVAC inefficiencies and excessive energy use. The VSM process revealed that air handling units (AHUs) were running at full capacity during off-peak hours, leading to unnecessary energy consumption (Albatici et al., 2016).

By redesigning the HVAC schedule using demand-based controls and occupancy sensors, the facility reduced its energy costs by 20% within one year. Similarly, a manufacturing facility in Germany applied VSM to its lighting retrofit project, identifying delays in material procurement and installation scheduling. By optimizing the procurement process and implementing Just-in-Time (JIT) delivery for LED lighting components, the company reduced project lead time by 30% and achieved a 15% reduction in total energy costs. VSM is a powerful Lean tool that enhances energy retrofitting by identifying inefficiencies, reducing waste, and optimizing workflows (Stanica et al., 2021). By providing a clear visualization of energy consumption patterns and process flows, VSM enables facility managers to implement targeted and strategic interventions that maximize energy savings (Kumanayake et al., 2018). The successful application of VSM in office buildings, manufacturing plants, and university campuses highlights its potential to transform traditional retrofitting approaches into more efficient, cost-effective, and sustainable processes (Stadtlander, 2009). As buildings continue to seek energy efficiency and carbon footprint reduction, the use of VSM in Lean energy retrofitting will play a critical role in achieving long-term sustainability goals.

4.2 THE PROPOSED VSM-BASED DECISION-MAKING MODEL FOR LEAN ENERGY RETROFITTING OF HVAC SYSTEMS IN HIGH-RISE BUILDINGS

The application of Value Stream Mapping (VSM) in the HVAC operation and maintenance phase offers critical insights into system performance, inefficiencies and opportunities for process optimization. In this context, the VSM serves not only as a Lean management tool but also as a performance diagnostic framework that aligns with sustainable building operation goals. Accordingly, a VSM-based decision-making model for lean energy retrofitting of HVAC system in high-rise buildings was conceptualised as shown in Figure 1, which illustrates the Value Stream Mapping (VSM) framework applied to the HVAC operation and maintenance (O&M) process within a Lean Energy Retrofitting context. The diagram is grounded in Lean production theory, where VSM is used as a diagnostic and analytical tool to distinguish between value-adding and non-value-adding activities across a process flow.

In this model, the HVAC system is represented as an integrated energy system, where environmental conditions (hot and cool air) are continuously monitored through a feedback control loop. The system is governed by the Building Management System (BMS), which acts as the central decision-making interface connecting field devices such as thermostats, air handling units (AHUs), chillers, and control room operations.

The developed model focuses on the operational phase of the HVAC lifecycle, where repetitive tasks begins with, temperature sensing, followed by signal processing, chiller activation, water circulation, air distribution, and finally room cooling. Each stage is mapped with associated operational performance indicators including process time, cycle time, waiting time, downtime, and energy consumption. This enables the identification of inefficiencies such as delays in signal transmission, system idling, and energy losses during equipment transitions.

The lower section of the figure distinguishes between non-value-adding time and value-adding process time, reinforcing Lean principles by highlighting where inefficiencies accumulate in the HVAC operational cycle. This supports decision-making for energy retrofitting interventions such as automation upgrades, predictive control systems, and optimization of high-energy components.

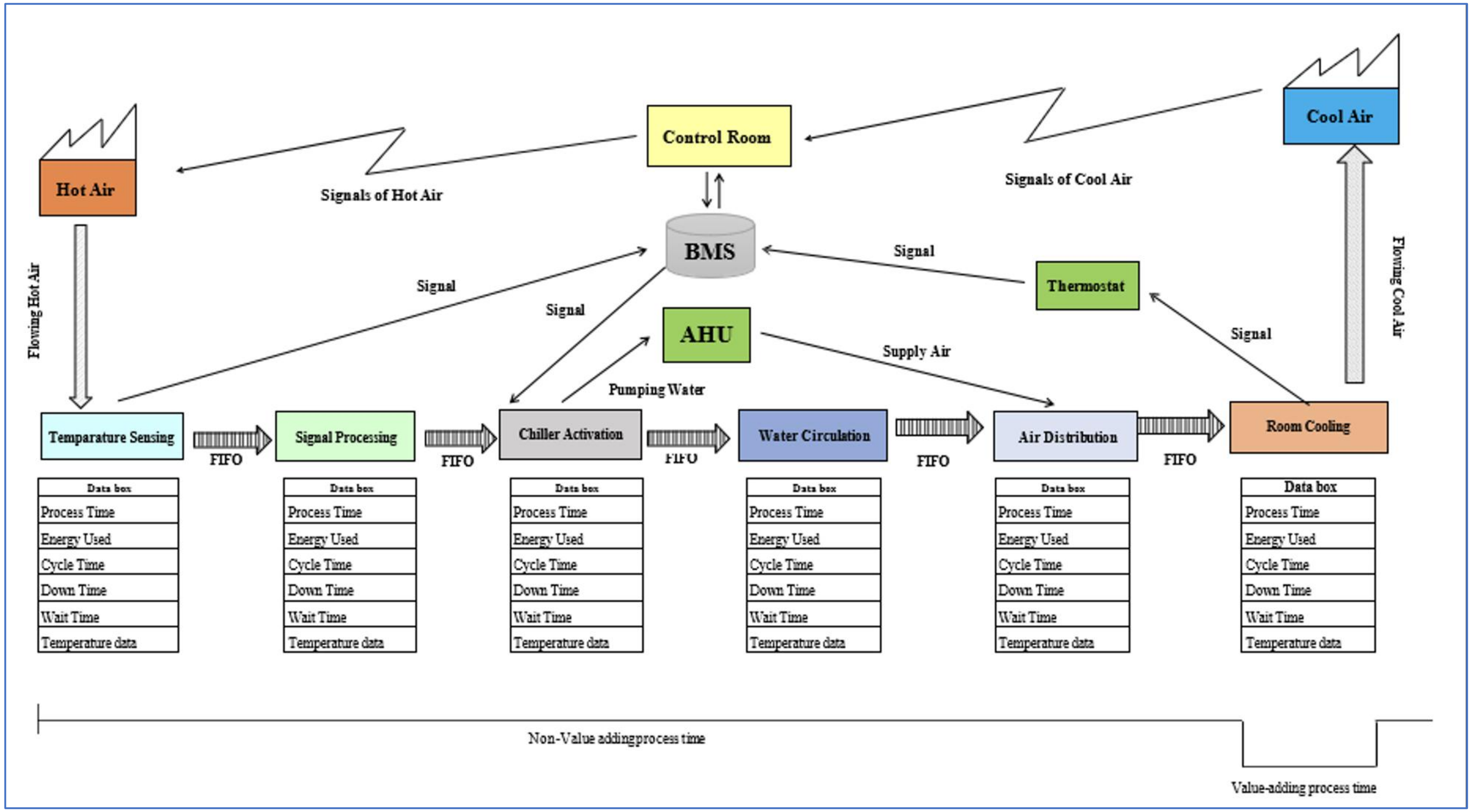

Figure 1: Proposed VSM-based decision-making model for energy retrofitting in HVAC systems in high-rise buildings

5. CONCLUSIONS AND THE WAY FORWARD

Increasing energy demand is one of the critical concerns in the current built environment sector. In this background, energy retrofitting gained considerable attention due to its various advantages in terms of economic and sustainability aspects. However, conventional energy retrofitting practices exhibit several limitations, such as fragmented, technology-focused, lack of process efficiency, and poor integration. Hence, this study aims to integrate VSM with energy retrofitting in HVAC systems for optimizing energy consumption and energy costs in high-rise buildings. As the initial step of this collaboration, this study conducted a non-systematic literature review in this research domain to identify the current research frontiers. Accordingly, several key research findings have been derived, integrating VSM for lean energy retrofitting decisions in buildings.

This study contributes to the body of knowledge by introducing a novel approach to energy retrofitting, emphasizing the importance of considering energy efficiency as a process flow issue rather than a technical challenge. The research demonstrates that lean principles, when integrated with traditional retrofitting practices, can provide a more sustainable and effective solution for optimising energy consumption in office buildings. By using VSM to map energy flows, identify inefficiencies, and prioritize improvements, building managers can achieve significant long-term energy savings while improving operational efficiency. For industry practitioners, the research highlights the importance of adopting a systemic approach to energy retrofitting. It recommends integrating lean principles into energy management strategies, encouraging the use of VSM in decision-making, and fostering professional development to ensure the effective implementation of lean practices. Further, the findings revealed from the study, particularly the conceptual model, support industry practitioners in decision-making in reducing unnecessary operational costs while maintaining proper indoor environmental quality conditions.

Despite the academic and industry contributions, this study also reveals some significant research gaps. Since the model was conceptually designed, further studies can be recommended to focus on the empirical evaluation of this model using a real-world case study. These studies can provide solid evidence regarding the effectiveness of incorporating lean principles in HVAC energy retrofitting. Further, a comparative analysis between conventional and lean-integrated energy retrofitting can be conducted to validate the operational and financial benefits of lean energy retrofitting.

Beyond this, it is recommended to focus on integrating novel technologies with lean energy retrofitting. Here, the incorporation of the Internet of Things (IoT), Building Information Modelling (BIM), Artificial Intelligence (AI), and Building Management Systems (BMS) can be considered. These collaborations can strengthen the informed decision-making on energy retrofitting based on real-time data.

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