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CRITERIA FOR SELECTING RETROFITTING OPTIONS FOR HVAC SYSTEMS IN SRI LANKAN COMMERCIAL BUILDINGS

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ABSTRACT

The heating, ventilation, and air conditioning (HVAC) systems are among the largest consumers of energy within buildings, constituting about 51% of the overall energy consumption. Thus, implementing energy retrofit measures can yield a noteworthy reduction in energy consumption of buildings. However, the process of selecting suitable energy retrofit options is complex and requires consideration of numerous different criteria. This research aims to propose a comprehensive set of evaluation criteria relevant to the selection of HVAC retrofitting options for commercial buildings in Sri Lanka. Through a thorough literature review and expert interviews with respondents selected using purposive sampling in which the collected data were analysed using manual content analysis, 35 sub-criteria that should be considered when selecting HVAC retrofitting options for commercial buildings in Sri Lanka were identified. These were categorised under 07 main criteria as Economic factors, Technical properties, Physical properties, Flexibility, Reliability, Comfortability and Environmental aspects. Thus, the findings mark the first step in developing a structured approach for evaluating and selecting HVAC retrofit options, streamlining decision-making processes, and potentially leading to more efficient and cost-effective building upgrades.

Keywords: *Commercial Buildings; Evaluation Criteria; Heating, Ventilation, and Air Conditioning (HVAC) Systems; Retrofit Options.*

1. INTRODUCTION

The construction industry significantly contributes to global energy consumption (Madushika et al., 2023). Buildings alone account for about 36% of global final energy use and nearly 40% of total direct and indirect CO_2 emissions (Y. Wang et al., 2022). Both residential and commercial buildings demand substantial energy for heating, cooling, lighting, and operating various equipment and systems (Hong et al., 2015). Therefore, building energy efficiency retrofits are considered essential for achieving energy reduction and sustainable development goals (X. Liang et al., 2015).

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The heating, ventilation, and air conditioning (HVAC) systems are among the largest consumers of energy within buildings, constituting about 47% of the overall energy consumption (Hong et al., 2015). In parallel, lighting accounts for approximately 25% of total energy usage (Dolšak, 2023). Specific components like vertical transportation, pumps, and related equipment collectively represent around 5-10% each. The cumulative effect of HVAC and lighting system energy usage typically constitutes around three-quarters of the aggregate energy demand for buildings (Y. Wang et al., 2022).

Retrofitting refers to the process of adding new technology or features to existing systems that were not present during their initial construction phase (J. Liang et al., 2018). This is particularly relevant in the context of HVAC systems in commercial buildings, where the goal is to enhance energy efficiency, reduce operational costs, and minimize maintenance expenses. This process aims to curb energy consumption and advance energy efficiency enhancements (Fasna & Gunatilake, 2019). Retrofitting projects for existing HVAC systems aim to address inefficiencies and integrate advanced technologies to enhance performance (Ligade & Razban, 2019). Common retrofit measures include upgrading to energy-efficient components, implementing advanced control strategies, and optimizing system operation through continuous monitoring and diagnostics (C. Liu et al., 2023).

The process of selecting suitable energy retrofit options is complex and requires a well-organised, step-by-step approach (Ma et al., 2012). For instance, Krajčík et al. (2023) has highlighted the need for a comprehensive retrofit evaluation encompassing economic, risk, social, environmental, and health impact assessments. However, despite the benefits of HVAC retrofitting, there is a lack of comprehensive guidelines and frameworks for implementing these projects effectively (Amanda & Sanjei, 2019). This is particularly pertinent in the context of Sri Lanka, where the commercial building sector faces unique challenges in implementing retrofit projects. Local climatic conditions, building designs, and occupancy patterns must be carefully considered to ensure the success of retrofit initiatives (De Silva & Sandanayake, 2012). Additionally, local environmental regulations and energy policies play a crucial role in shaping retrofit strategies.

Despite the recognised benefits, the process of selecting appropriate retrofit options is complex and often lacks a standardised framework, particularly in developing countries such as Sri Lanka. Hence, this research aims to propose a comprehensive set of evaluation criteria relevant to the selection of HVAC retrofitting options for commercial buildings in Sri Lanka. The findings of this study provide the basis for developing a structured decision-making framework for selecting HVAC retrofitting options for Sri Lankan commercial buildings using multi-criteria decision making.

2. LITERATURE REVIEW

2.1 ENERGY CONSUMPTION IN BUILDINGS

Heating, Ventilation, and Air Conditioning (HVAC) systems are critical components in buildings, significantly impacting their overall energy consumption (Hong et al., 2015). HVAC systems are responsible for approximately 39% of the total energy consumption in commercial buildings (Nalley & LaRose, 2022). This substantial proportion underscores the importance of HVAC systems in the broader context of building energy management. The efficiency of HVAC systems is vital not only for reducing energy consumption but also for maintaining indoor air quality and thermal comfort, which are essential for occupant health and productivity (Ma et al., 2012). Despite their importance, many existing HVAC systems are outdated and operate inefficiently, leading to high energy usage and increased operational costs (Ligade & Razban, 2019). Additionally, maintenance costs for HVAC systems can be substantial, further adding to the operational expenses of commercial buildings (Y. Wang et al., 2022). Consequently, improving HVAC system efficiency is a critical focus area for reducing building energy consumption and associated costs.

In the Sri Lankan context as well, the energy consumption in commercial buildings is notably high, primarily due to the extensive use of HVAC systems, which can represent up to 60% of a building's total energy consumption (Kumar & Raposa, 2020). This high percentage underscores the critical need for energy-efficient retrofitting solutions to reduce energy consumption and operational costs. Urban commercial buildings in Sri Lanka rely heavily on HVAC systems for cooling and ventilation, resulting in substantial energy demands (Kumar & Raposa, 2020). By implementing energy-efficient HVAC retrofits, these buildings can achieve significant energy savings, contributing to the country's overall energy efficiency goals.

2.2 HVAC SYSTEMS IN SRI LANKAN COMMERCIAL BUILDINGS

Commercial buildings are structures primarily used for business activities, including offices, retail spaces, hotels, and educational institutions (Hong et al., 2015). These buildings significantly contribute to energy consumption due to their extensive use of lighting, heating, ventilation, and air conditioning (HVAC) systems. In the Sri Lankan context, commercial buildings are typically concentrated in urban areas such as Colombo, Kandy, and Galle, where the demand for energy is high to maintain comfortable indoor environments (Sustainable Energy Authority of Sri Lanka, 2020).

Given Sri Lanka's tropical climate, air cooling systems are essential, whereas heating systems are seldom used. The country experiences high temperatures and humidity levels throughout the year, making cooling systems critical for occupant comfort. Districts such as Colombo and Gampaha, which are highly urbanized and densely populated, rely heavily on air conditioning systems to provide a comfortable indoor climate (Sustainable Energy Authority of Sri Lanka, 2020). This necessity underscores the importance of efficient HVAC systems in these regions. Retrofitting such systems can involve upgrading components to more energy-efficient models, integrating advanced control systems, and optimizing the overall system performance to reduce energy consumption (Madushika et al., 2023). This process not only enhances the efficiency but also extends the lifespan of the HVAC systems.

2.3 RETROFITTING HVAC SYSTEMS

Existing HVAC systems, particularly package units, often face numerous issues as they age. Common defects include reduced efficiency, frequent breakdowns, and increased operational costs due to wear and tear (Karunaratne & De Silva, 2019). After five years, systems typically begin to show signs of inefficiency, and by ten to fifteen years, the frequency of repairs and maintenance increases significantly, often leading to higher energy consumption and operational disruptions. Retrofitting offers a viable solution to these identified defects (Ligade & Razban, 2019).

Retrofitting involves the process of adding new technology or features to existing buildings to improve their functionality, efficiency, and sustainability (Ebrahimi et al., 2023). Building retrofits can encompass various aspects, including structural, energy, and aesthetic improvements. Energy retrofits, a subset of retrofitting, specifically focus on enhancing the energy performance of buildings to reduce energy consumption and operational costs (Y. Liu et al., 2023).

Building retrofits are particularly important in commercial buildings, where energy consumption is significantly high due to extensive use of HVAC systems, lighting, and other equipment (Mohamed & Wang, 2020). The major advantages of retrofitting over other methods, such as complete system replacement, include cost-effectiveness and minimized disruption to building operations. Retrofitting allows for incremental improvements without the need for extensive downtime, making it a practical option for commercial buildings that cannot afford long periods of inactivity (Karunaratne & De Silva, 2019). Moreover, retrofitting enhances the sustainability of buildings by reducing energy consumption and greenhouse gas emissions, contributing to broader environmental goals.

Retrofitting in commercial buildings can lead to substantial energy savings by implementing advanced technologies and optimizing energy management systems (Hong et al., 2015). For instance, upgrading to high-efficiency HVAC systems can drastically reduce energy usage, while smart building technologies can further enhance energy efficiency by optimizing the operation of various systems within the building (C. Liu et al., 2023).

HVAC retrofitting typically encompasses several measures, including upgrading HVAC equipment, improving insulation and sealing, and implementing advanced control systems (Bird et al., 2022). Notably, these measures aim to enhance the energy performance of the building while ensuring occupant comfort. This often yields long-term benefits by reducing energy costs and carbon footprints (Ma et al., 2012). By upgrading components such as compressors, fans, and control systems, the efficiency of aging HVAC systems can be significantly improved. Additionally, retrofitting can involve implementing advanced monitoring and control systems that optimize the operation of HVAC units, thereby reducing energy consumption and enhancing performance (Madushika et al., 2023). For instance, replacing old, inefficient chillers with high-efficiency models can result in substantial energy savings and improved reliability. The process of selecting suitable energy retrofit options is complex and requires consideration of numerous criteria that may change depending on the context. Hence, there is a need to clearly identify a set of evaluation criteria relevant to the selection of HVAC retrofitting options for commercial buildings in Sri Lanka.

3. RESEARCH METHODOLOGY

A comprehensive literature review was conducted to identify the evaluation criteria for HVAC retrofit options. The search was carried out in databases such as Science Direct, Web of Science, and Scopus, and included keywords such as “retrofit”, “energy efficiency”, “criteria”, and “evaluation”. The search was limited to the papers published in the 20 year period between 2005 and 2024. Altogether, 56 journal papers were selected for the identification of criteria through the above systematic selection process. Then, interviews with three industry experts were conducted to refine and confirm the relevance and importance of each identified criterion, ensuring that they would be grounded in practical and expert knowledge. The small sample helped to facilitate researchers’ close association with the respondents and allowed fine-grained, in-depth interviews (each interview lasted for over 60 minutes) to be carried out on the selection criteria. Further, the selected respondents could be considered as experts in the research area possessing over 15 years of first-hand experience in HVAC retrofitting. Table 1 presents profile of the three experts interviewed.

The expert interviews were conducted as semi-structured interviews with an iterative and interactive process. The interviews were carried out in an iterative process with each expert's views been considered by the others. The first expert's decision was communicated to the second expert, facilitating a more comprehensive discussion and a refined consensus. Subsequently, during the interview with the third expert, the previous experts' opinions were presented to provide context and foster a deeper dialogue. The final decision was reached through a rigorous analysis of all three expert perspectives, coupled with a synthesis of existing knowledge from the literature. This allowed for a detailed review of the criteria and their application to the local context. Manual content analysis was used to analyse both the literature review and interview data to identify the evaluation criteria. The findings presented in this paper mark the first step in a broader research study aimed at developing a structured decision-making framework for selecting HVAC retrofitting options for Sri Lankan commercial buildings using multi-criteria decision making.

Table 1: Profile of interview respondents

Respondent	Designation	Current Sector	Experience (Years)	Qualifications		Awareness	
				Educational	Professional	HVAC	Retrofit
R1	Director (Facility Manager)	Consultant	30	M.FM, BSc. Eng	Chartered FM	Well	Well
R2	Manager (Facility Manager)	Contractor	15	BSc FM, Dip in Arb.	Chartered FM	Well	Well
R3	Manager (Engineer)	Contractor, Lecturer	33	PhD, M.Eng, BSc Eng	Chartered Engineer	Well	Aware

4. FINDINGS AND DISCUSSION

4.1 OVERVIEW OF RETROFITTING HVAC SYSTEMS IN SRI LANKAN COMMERCIAL BUILDINGS: FINDINGS FROM EXPERT INTERVIEWS

Retrofitting commercial buildings involves enhancing energy efficiency and operational performance through various methods. Experts generally agree on the significance of this practice, albeit with nuanced perspectives. For instance, R1 described retrofitting as upgrading existing systems to modern standards, focusing on energy efficiency. Similarly, R3 emphasised the addition of new components to boost energy performance, while R2 pointed out the replacement of outdated systems. Collectively, these views underline retrofitting as a comprehensive approach aimed at modernisation and energy optimisation.

Regarding HVAC systems in Sri Lankan commercial buildings, a clear preference for package systems in light commercial buildings is evident. R1 and R2 mention the use of water-cooled package systems due to their balance of cost and efficiency.

4.2 CRITERIA FOR SELECTING HVAC OPTIONS

Table 2 summarises key criteria identified from literature that should be considered when selecting HVAC retrofitting options. These criteria highlight the essential factors that can influence the success and effectiveness of such projects.

Table 2: Criteria for selecting HVAC options: Findings from literature review

Criteria/Sub-criteria	Sources	Description
Economic Factors		
Capital Cost	[5] [6] [15] [16]	Initial expenditure required to implement a retrofit project
Maintenance Cost	[5] [6] [15] [16] [17]	Ongoing expenses for the upkeep of the retrofitted system
Operational cost	[5] [6] [12] [19] [21]	Day-to-day expenses involved in running the retrofitted systems
Payback Period	[5] [6] [12] [14] [18]	The time it takes for the investment in retrofitting to be recovered through cost savings
Life-Cycle Cost (LCC)	[5] [6] [15] [16] [18]	Total cost of owning, operating, and maintaining a building system over its entire life span
Insurance cost	[9]	Expenses related to insuring the retrofitted systems
Technical Properties		
Water Consumption	[18] [19]	The amount of water used by the HVAC system
Energy Consumption	[5] [6] [12]	The total energy used by the HVAC system
CO2 emission	[5] [12] [15] [20]	The amount of CO2 produced by the HVAC system
Refrigeration coefficient	[18] [19]	Efficiency measure of the refrigeration cycle in HVAC systems
COP (Coefficient of Performance)	[21] [22] [23]	A ratio that measures the efficiency of HVAC systems
Humidity control	[5] [6] [7] [8]	The system's ability to regulate indoor humidity levels
Physical Properties		
Area requirement	[5] [6] [12]	Space needed to install and operate HVAC systems
Indoor Appearance	[25] [26]	The aesthetic impact of HVAC systems within the building interior
Outdoor Appearance	[25] [26] [27] [28] [29]	The visual impact of HVAC systems on the building's exterior

Criteria/Sub-criteria	Sources	Description
Loss of usable floor space	[5] [6] [12]	Space that becomes unusable due to the installation of HVAC systems
Noise level	[5] [6] [12]	The amount of noise generated by the HVAC systems
Flexibility		
Installation flexibility	[5] [6] [30] [31] [32] [33]	Ease of installing retrofit systems in existing buildings
Integration flexibility	[5] [6] [30] [31] [32] [33] [34] [35]	Ability of new systems to integrate with existing infrastructure
Ease of maintenance	[35] [40] [41] [42] [43]	Simplicity and convenience of maintaining the retrofitted systems
Future flexibility	[36] [37] [38] [39]	Capacity for future expansions or modifications
Reliability		
Lifetime	[5] [6] [12] [41] [44] [45] [46]	Expected operational life span of the retrofitted system
Lead time	[5] [6] [12] [47] [48]	Time required to implement the retrofit
Repair time	[5] [6] [47] [48] [49]	Time required to fix issues in the retrofitted systems
Vendor availability	[15] [50]	Accessibility of suppliers and maintenance services for the retrofitted systems
Comfortability		
Degree of compatibility	[1] [2] [3] [4] [5]	How well the retrofitted system integrates with the existing building infrastructure
Occupants' health and safety	[5] [6] [9] [10]	Impact of HVAC systems on the well-being and safety of building occupants
Thermal comfort	[13] [14]	The ability of HVAC systems to maintain comfortable temperature and humidity levels
Cleanliness	[13] [14]	The system's ability to maintain a clean indoor environment

[1] (Fisk, 2017) [2] (Batterman et al., 2017 [3] (Mendell et al., 2013) [4] (Wargocki & Wyon, 2013) [5] (Shahrestani et al., 2018) [6] (J. Wang et al., 2009) [7] (Soyguder et al., 2009) [8] (Altun & Yalcinoz, 2008) [9] (Kim et al., 2016) [10] (Yang et al., 2014) [11] (Korkas et al., 2015) [12] (Arroyo et al., 2016) [13] (Heinzerling et al., 2013) [14] (W. Wang et al., 2018) [15] (Stadler et al., 2009) [16] (Chinese et al., 2011) [17] (Au-Yong et al., 2014) [18] (Alipour et al., 2015) [19] (Chakrabarti & Das, 2015) [20] (Alanne et al., 2007) [21] (Yu & Chan, 2005) [22] (Koury et al., 2001) [23] (Mirinejad et al., 2008) [24] (Afram & Janabi-Sharifi, 2014) [25] (Peng et al., 2019) [26] (H. Wang et al., 2023) [27] (Helmis et al., 2007) [28] (Yi et al., 2005) [29] (Tan & Glicksman, 2005) [30] (Wane & Nagdeve, 2012) [31] (Lalji, 2011) [32] (He et al., 2009) [33] (Sudhan, 2011) [34] (Mohebbi et al., 2020) [35] (Zavala, 2013) [36] (Hovgaard et al., 2012) [37] (Sossan et al., 2016) [38] (Kremers et al., 2013) [39] (Niro et al., 2013) [40] (Kusiak et al., 2010) [41] (Tu et al., 2016) [42] (Lu et al., 2005) [43] (Zaheer-uddin & Zheng, 2000) [44] (Ataş et al., 2017) [45] (Lin & Yeh, 2007) [46] (Aynur, 2010) [47] (Stephens et al., 2010) [48] (Siegel, 2016) [49] (Cetin et al., 2014) [50] (Lund et al., 2015)

The literature review identified altogether 31 sub-criteria that should be considered in selecting HVAC options. These 31 sub-criteria were categorized under 06 main criteria as given in Table 2. These criteria and sub-criteria were then refined and checked for relevance and importance to the study context through the expert interviews.

In instances where all three experts reached a consensus on accepting or rejecting a given criterion, the final decision was made accordingly. However, in cases where there was a single dissenting opinion, careful consideration was given to the differing perspectives, alongside a thorough examination of relevant literature, before a final determination was made. If only one expert rejected a criterion, it was kept, as the other two experts provided good reasons for its inclusion. These decisions were also supported by information found in existing research. The goal was to create a clear and comprehensive set of criteria for evaluating HVAC systems relevant to the local context that everyone could understand.

Table 3 provides the findings of the expert interviews in relation to the above.

Table 3: Criteria for selecting HVAC options: Findings from expert interviews

Criteria/Sub-criteria	**Interviewee**			**Decision**
	R1	**R2**	**R3**	
Economic Factors				
Capital cost	Accepted: Critical for initial capital budget assessment	Accepted: Fundamental for financial feasibility studies	Accepted: Essential for upfront cost evaluation	✓
Maintenance cost	Accepted: Influences lifecycle operating expenses	Accepted: Integral to total cost of ownership	Accepted: Affects long-term sustainability	✓
Operational cost	Accepted: Impacts ongoing operational efficiency	Accepted: Vital for energy expense management	Rejected: Variability challenges in cost prediction	✓
Payback period	Accepted: Key for evaluating return on investment	Rejected: Difficulties in accurate financial forecasting	Accepted: Important for financial justification	✓
Life-Cycle Cost (LCC)	Accepted: Crucial for overall cost-benefit analysis	Accepted: Core to comprehensive cost management	Accepted: Essential for total cost considerations over time	✓
Insurance cost	Accepted: Not pivotal for technical retrofit decision-making	Accepted: Minimally impacts project viability	Accepted: Irrelevant to core retrofitting parameters	✓
Technical Properties				
Water consumption	Moved: Peripheral to core HVAC functions	Moved: Insignificant impact on system performance	Moved: Relevant in specific environmental compliance cases	

Criteria/Sub -criteria	Interviewee			Decision
	R1	R2	R3	
Energy consumption	Accepted: Directly correlates with system efficiency	Accepted: Critical for reducing energy costs	Accepted: Fundamental to operational performance	✓
CO_2 emission	Rejected: Lesser immediate retrofit impact	Accepted: Important for environmental sustainability	Accepted: Crucial for regulatory compliance	✓
Refrigeration coefficient	Accepted: Relevant for cooling systems' efficiency	Rejected: Limited applicability outside specific contexts	Rejected: Not widely applicable across HVAC systems	×
COP (Coefficient of Performance)	Accepted: Indicates system performance efficiency	Accepted: Benchmark for energy performance	Accepted: Standard measure of system efficiency	✓
Humidity control	Accepted: Critical for indoor air quality and comfort	Rejected: Region-specific importance	Accepted: Essential for maintaining occupant comfort	✓
Degree of compatibility		Moved: new upgrades should match the existing system	Moved: Include compatibility as a key criterion in your evaluation framework for retrofitting options	+
Physical Properties				
Area requirement	Accepted: Essential for system integration within space	Accepted: Important for retrofit space planning	Rejected: Retrofit should adapt to existing spatial constraints	✓
Indoor appearance	Accepted: Influences occupant perception and satisfaction	Accepted: Affects aesthetics and user experience	Accepted: Enhances interior environmental quality	✓
Outdoor appearance	Accepted: Impacts external aesthetics and compliance	Accepted: Important for building facade integration	Accepted: Vital for architectural harmony	✓
Loss of usable floor space	Rejected: Already consider that as "Area Requirement"	Rejected: Overlap with “Area Requirement"	Rejected: Better consider Area requirement	×
Noise level	Accepted: Crucial for ensuring acoustic comfort	Accepted: Integral to environmental comfort standards	Accepted: Reduces noise pollution and enhances usability	✓
Flexibility				
Installation flexibility	Accepted: Facilitates integration into existing structures	Accepted: Reduces installation complexities	Accepted: Enhances adaptability to building layouts	✓

Criteria/Sub-criteria	**Interviewee**			**Decision**
	R1	**R2**	**R3**	
Integration flexibility	Accepted: Ensures seamless system integration	Accepted: Promotes compatibility with existing infrastructure	Accepted: Critical for comprehensive retrofit solutions	✓
Ease of maintenance	Accepted: Simplifies maintenance, reducing lifecycle costs	Accepted: Decreases operational disruptions	Accepted: Essential for ongoing system reliability	✓
Future flexibility	Accepted: Allows for future technological upgrades	Accepted: Essential for scalable retrofit solutions	Accepted: Facilitates future system enhancements	✓
Energy source flexibility	Accepted: Adapts to diverse energy inputs	Accepted: Supports sustainable energy transitions	Accepted: Enables flexibility in energy sourcing	✓
Reliability				
Lifetime	Accepted: Indicates durability and long-term serviceability	Accepted: Reduces frequency of replacements	Accepted: Ensures long-term operational stability	✓
Lead time	Accepted: Affects project timeline and resource allocation	Accepted: Important for scheduling and logistics	Accepted: Critical for timely project execution	✓
Repair time	Accepted: Minimizes downtime, enhancing operational continuity	Accepted: Reduces maintenance impact on operations	Accepted: Vital for quick recovery and serviceability	✓
Vendor availability	Accepted: Ensures access to essential parts and services	Accepted: Facilitates reliable maintenance and upgrades	Accepted: Critical for continuous system support	✓
Comfortability				
Occupants' health and safety	Accepted: Directly impacts well-being and regulatory standards	Accepted: Fundamental to occupant safety	Accepted: Ensures compliance with health codes	✓
Thermal comfort	Accepted: Affects energy efficiency and occupant comfort	Accepted: Integral to environmental control	Accepted: Essential for maintaining optimal indoor climates	✓
Cleanliness	Accepted: Impacts air quality and cleanliness	Accepted: Integral to maintaining hygienic conditions	Accepted: Essential for occupant health and satisfaction	✓
Environmental Aspects				
Carbon emissions	Moved: Aligns with global sustainability goals	Moved: Essential for environmental stewardship	Moved: Critical for meeting modern environmental standards	+

Criteria/Sub-criteria	Interviewee			Decision
	R1	R2	R3	
Water consumption		Moved: Important for water conservation	Moved: Aligns with eco-friendly practices	+
Type of refrigerant	Added: Affects global warming potential and ozone depletion		Added: Critical for environmental compliance	+
Renewable energy sources		Added: Facilitates transition to greener energy sources	Added: Essential for sustainable energy integration	+
Waste management	Added: Enhances sustainability and reduces retrofit impact	Added: Vital for minimizing environmental footprint	Added: Integral to eco-friendly retrofit practices	+

The experts agreed to move "Water Consumption," "CO_2 Emission," and "Refrigeration Coefficient" from the "Technical Properties" category to the "Environmental Aspects" category. This change better reflected the environmental impact of these factors. "CO_2 Emission" was renamed "Carbon Emission" for clarity. Expert R2 suggested adding a new criterion, "Degree of Compatibility," under "Technical Properties," which expert R3 also agreed with. If two out of the three experts rejected a criterion, it was removed. For example, "Loss of Usable Floor Space" was removed because it was considered similar to "Area Requirement," which was already included. Similarly, "Refrigeration Coefficient" was also removed as this was not widely applicable across HVAC systems. Figure 1 provides the finalised evaluation criteria for selecting HVAC options.

Economic Factors (E) **E1** Capital Cost **E2** Maintenance Cost **E3** Operational cost **E4** Payback Period **E5** Life-Cycle Cost (LCC) **E6** Insurance cost	**Technical Properties (T)** **T1** Water Consumption **T2** Energy Consumption **T3** CO_2 Emission **T4** Refrigeration coefficient **T5** COP (Coefficient of Performance) **T6** Humidity control **T7** Degree of compatibility
Physical Properties (P) **P1** Area requirement **P2** Indoor Appearance **P3** Outdoor Appearance **P4** Loss of usable floor space **P5** Noise level	**Flexibility (F)** **F1** Installation Flexibility **F2** Integration Flexibility **F3** Ease of Maintenance **F4** Future flexibility **F5** Energy Source Flexibility
Reliability (R) **R1** Lifetime **R2** Lead Time **R3** Repair Time **R4** Vendor Availability **Comfortability (C)** **C1** Occupants' health and safety **C2** Thermal comfort **C3** Cleanliness	**Environmental Aspects (En)** **En1** Carbon Emissions **En2** Water Consumption **En3** Type of Refrigerant **En4** Renewable Energy Sources **En5** Waste Management

Figure 1: Finalised evaluation criteria for selecting HVAC options

Experts highlighted that the key stakeholders' preferences in the retrofit process reflect a focus on cost-effectiveness, energy savings, and feasibility. R1 and R2 emphasized the importance of financial feasibility and quick returns on investment (ROI), with R3 highlighting the role of cost savings and brand value in driving decisions. Experts also noted that high energy costs often prompt retrofit initiatives. Further, the importance of regulatory compliance and environmental impact was also highlighted. These perspectives reveal that stakeholders prioritise solutions offering economic and environmental benefits, aiming for operational efficiency and sustainability in retrofit projects. Economic incentives, such as reduced operational costs and increased property values, play a crucial role in driving retrofit decisions. Environmental motivators are also significant, with a strong focus on reducing energy consumption and carbon emissions, aligning with global sustainability targets. Additionally, technical improvements through retrofitting can increase the functional performance and safety of buildings, addressing the growing concern over natural disasters in the region (Ranawaka & Mallawaarachchi, 2018). These key motivators collectively support a comprehensive approach to building retrofitting in Sri Lanka, emphasizing the importance of integrated strategies that cater to economic efficiency and environmental responsibility.

Thus, expert opinions converge on the critical role of retrofitting in enhancing the energy efficiency and operational performance of Sri Lanka's commercial buildings. The preference for package systems in light commercial buildings is driven by their cost-effectiveness and efficiency. Stakeholders' decisions are guided by a balance of financial feasibility, energy savings, and regulatory compliance, ensuring that retrofitting efforts yield both economic and environmental advantages. The comprehensive insights from these experts provide a robust understanding of the strategies and preferences that shape retrofitting initiatives in the region.

5. CONCLUSIONS

This paper identified a set of evaluation criteria relevant to the selection of HVAC retrofitting options for commercial buildings in Sri Lanka. Altogether, 35 sub-criteria were identified. These were categorised under 07 main criteria as Economic factors, Technical properties, Physical properties, Flexibility, Reliability, Comfortability and Environmental aspects. Findings highlighted that the stakeholders' decisions are often guided by a balance of financial feasibility, energy savings, and regulatory compliance, ensuring that retrofitting efforts yield both economic and environmental advantages. Further, research is required to assign weightages to the identified criteria so that a comprehensive decision support criterion could be developed for evaluating and selecting retrofit options. This will in turn streamline the decision-making processes, potentially leading to more efficient and cost-effective building upgrades.

6. REFERENCES

Afram, A., & Janabi-Sharifi, F. (2014). Theory and applications of HVAC control systems: A review of model predictive control (MPC). *Building and Environment*, *72*, 343–355. https://doi.org/10.1016/j.buildenv.2013.11.016

Alanne, K., Salo, A., Saari, A., & Gustafsson, S. I. (2007). Multi-criteria evaluation of residential energy supply systems. *Energy and Buildings*, *39*(12), 1218–1226. https://doi.org/10.1016/j.enbuild.2007.01.009

Alipour, V., Mahvi, A. H., & Rezaei, L. (2015). Quantitative and qualitative characteristics of condensate water of home air-conditioning system in Iran. *Desalination and Water Treatment*, *53*(7), 1834–1839. https://doi.org/10.1080/19443994.2013.870724

Altun, H., & Yalcinoz, T. (2008). Implementing soft computing techniques to solve economic dispatch problem in power systems. *Expert Systems with Applications*, *35*(4), 1668–1678. https://doi.org/10.1016/j.eswa.2007.08.066

Amanda, H. A. H., & Sanjei, C. (2019). Energy performance and energy efficiency retrofitting in existing hotel buildings: A review. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, *52*(4), 51-61. https://doi.org/10.4038/engineer.v52i4.7393

Arroyo, P., Tommelein, I. D., Ballard, G., & Rumsey, P. (2016). Choosing by advantages: A case study for selecting an HVAC system for a net zero energy museum. *Energy and Buildings*, *111*, 26–36. https://doi.org/10.1016/j.enbuild.2015.10.023

Ataş, Ş., Aktaş, M., Ceylan, İ., & Doğan, H. (2017). Development and analysis of a multi-evaporator cooling system with electronic expansion valves. *Arabian Journal for Science and Engineering*, *42*(11), 4513–4521. https://doi.org/10.1007/s13369-017-2523-1

Au-Yong, C. P., Ali, A. S., & Ahmad, F. (2014). Preventive maintenance characteristics towards optimal maintenance performance: A case study of office buildings. *World Journal of Engineering and Technology*, *2*(3), 1–6. https://doi.org/10.4236/wjet.2014.23B001

Aynur, T. N. (2010). Variable refrigerant flow systems: A review. *Energy and Buildings*, *42*(7), 1106–1112. https://doi.org/10.1016/j.enbuild.2010.01.024

Batterman, S., Su, F. C., Wald, A., Watkins, F., Godwin, C., & Thun, G. (2017). Ventilation rates in recently constructed U.S. school classrooms. *Indoor Air*, *27*(5), 880–890. https://doi.org/10.1111/ina.12384

Bird, M., Daveau, C., O'Dwyer, E., Acha, S., & Shah, N. (2022). Real-world implementation and cost of a cloud-based MPC retrofit for HVAC control systems in commercial buildings. *Energy and Buildings*, *270*, 112269. https://doi.org/10.1016/j.enbuild.2022.112269

Cetin, K. S., Tabares-Velasco, P. C., & Novoselac, A. (2014). Appliance daily energy use in new residential buildings: Use profiles and variation in time-of-use. *Energy and Buildings*, *84*, 716–726. https://doi.org/10.1016/j.enbuild.2014.07.045

Chakrabarti, S. S., & Das, P. K. (2015). Performance investigation of air washer for different psychometric conditions. *Computational Thermal Sciences: An International Journal*, *7*(3), 217–230. https://doi.org/10.1615/ComputThermalScien.2015012415

Chinese, D., Nardin, G., & Saro, O. (2011). Multi-criteria analysis for the selection of space heating systems in an industrial building. *Energy*, *36*(1), 556–565. https://doi.org/10.1016/j.energy.2010.10.005

De Silva, M. N. & Sandanayake, Y. G. (2012). Building energy consumption factors: A literature review and future research agenda. In S. Senaratne & Y. G. Sandanayake (Eds.), *World construction conference 2012: Global challenges in construction industry* (pp 90-99). Ceylon Institute of Builders. https://www.irbnet.de/daten/iconda/CIB_DC25108.pdf

Dolšak, J. (2023). Determinants of energy efficient retrofits in residential sector: A comprehensive analysis. *Energy and Buildings*, *282*. 112801. https://doi.org/10.1016/j.enbuild.2023.112801

Ebrahimi, P., Ridwana, I., & Nassif, N. (2023). Solutions to achieve high-efficient and clean building HVAC systems. *Buildings*, *13*(5). 1211. https://doi.org/10.3390/buildings13051211

Fasna, M. F. F., & Gunatilake, S. (2019). Energy retrofits to enhance energy performance of existing buildings: A review. In Y. G. Sandanayake, S. Gunatilake, & K. G. A. S. Waidyasekara (Eds.), *Proceedings of the 8th world construction symposium* (pp. 308-319). Ceylon Institute of Builders. https://ciobwcs.com/downloads/WCS2019-Proceedings.pdf

Fisk, W. J. (2017). The ventilation problem in schools: Literature review. *Indoor Air*, *27*(6), 1039–1051. https://doi.org/10.1111/ina.12403

He, Y., Men, Y., Zhao, Y., Lu, H., & Ding, Y. (2009). Numerical investigation into the convective heat transfer of TiO2 nanofluids flowing through a straight tube under the laminar flow conditions. *Applied Thermal Engineering*, *29*(10), 1965–1972. https://doi.org/10.1016/j.applthermaleng.2008.09.020

Heinzerling, D., Schiavon, S., Webster, T., & Arens, E. (2013). Indoor environmental quality assessment models: A literature review and a proposed weighting and classification scheme. *Building and Environment*, *70*, 210–222. https://doi.org/10.1016/j.buildenv.2013.08.027

Helmis, C. G., Tzoutzas, J., Flocas, H. A., Halios, C. H., Stathopoulou, O. I., Assimakopoulos, V. D., Panis, V., Apostolatou, M., Sgouros, G., & Adam, E. (2007). Indoor air quality in a dentistry clinic. *Science of The Total Environment*, *377*(2–3), 349–365. https://doi.org/10.1016/j.scitotenv.2007.01.100

Hovgaard, T. G., Larsen, L. F. S., Edlund, K., & Jørgensen, J. B. (2012). Model predictive control technologies for efficient and flexible power consumption in refrigeration systems. *Energy*, *44*(1), 105–116. https://doi.org/10.1016/j.energy.2011.12.007

Hong, T., Piette, M. N., Chen, Y., Lee, S. H., Taylor-Lange, S. C., Zhang, R., Sun, K., & Price, P. (2015). Commercial building energy saver: An energy retrofit analysis toolkit. *Applied Energy, 159*, 298-309. https://doi.org/10.1016/j.apenergy.2015.09.002

Karunaratne, T. L. W., & De Silva, N. (2019). Demand-side energy retrofit potential in existing office buildings. *Built Environment Project and Asset Management, 9*(3), 426-439. https://doi.org/10.1108/BEPAM-10-2017-0103

Kim, W., Jeon, Y., & Kim, Y. (2016). Simulation-based optimization of an integrated daylighting and HVAC system using the design of experiments method. *Applied Energy*, *162*, 666–674. https://doi.org/10.1016/j.apenergy.2015.10.153

Krajčík, M., Arıcı, M., & Ma, Z. (2023). Trends in research of heating, ventilation and air conditioning and hot water systems in building retrofits: Integration of review studies. *Journal of Building Engineering*, *76*, 107426. https://doi.org/10.1016/j.jobe.2023.107426

Korkas, C. D., Baldi, S., Michailidis, I., & Kosmatopoulos, E. B. (2015). Intelligent energy and thermal comfort management in grid-connected microgrids with heterogeneous occupancy schedule. *Applied Energy*, *149*, 194–203. https://doi.org/10.1016/j.apenergy.2015.01.145

Koury, R. N. N., Machado, L., & Ismail, K. A. R. (2001). Numerical simulation of a variable speed refrigeration system. *International Journal of Refrigeration*, *24*(2), 192–200. https://doi.org/10.1016/S0140-7007(00)00014-1

Kremers, E., González de Durana, J. M., & Barambones, O. (2013). Emergent synchronisation properties of a refrigerator demand side management system. *Applied Energy*, *101*, 709–717. https://doi.org/10.1016/j.apenergy.2012.07.021

Kumar, M., & Raposa, S. (2020). *The World Bank group greenhouse gas emissions inventory management plan for internal business operations 2019.* The World Bank. https://documents1.worldbank.org/curated/en/151321613709801444/pdf/The-World-Bank-Group-Greenhouse-Gas-Emissions-Inventory-Management-Plan-for-Internal-Business-Operations-2019.pdf

Kusiak, A., Li, M., & Tang, F. (2010). Modeling and optimization of HVAC energy consumption. *Applied Energy*, *87*(10), 3092–3102. https://doi.org/10.1016/j.apenergy.2010.04.008

Lalji, M. K. (2011). Heat transfer enhancement in packed bed solar air heater. *Indian Journal of Science and Technology*, *4*(7), 747–749. https://doi.org/10.17485/ijst/2011/v4i7.16

Liang, J., Qiu, Y., James, T., Ruddell, B. L., Dalrymple, M., Earl, S., & Castelazo, A. (2018). Do energy retrofits work? Evidence from commercial and residential buildings in Phoenix. *Journal of Environmental Economics and Management*, *92*, 726–743. https://doi.org/10.1016/j.jeem.2017.09.001

Liang, X., Shen, G., & Guo, L. (2015). Improving management of green retrofits from a stakeholder perspective: A case study in China. *International Journal of Environmental Research and Public Health*, *12*(11), 13823–13842. https://doi.org/10.3390/ijerph121113823

Ligade, J., & Razban, A. (2019). Investigation of energy efficient retrofit HVAC systems for a university: Case study. *Sustainability, 11*(20), 5593. https://doi.org/10.3390/su11205593

Lin, J.L., & Yeh, T.J. (2007). Identification and control of multi-evaporator air-conditioning systems. *International Journal of Refrigeration*, *30*(8), 1374–1385. https://doi.org/10.1016/j.ijrefrig.2007.04.003

Liu, C., Sharples, S., & Mohammadpourkarbasi, H. (2023). A review of building energy retrofit measures, passive design strategies and building regulation for the low carbon development of existing dwellings in the hot summer–cold winter region of China. *Energies*, *16*(10), 4115. https://doi.org/10.3390/en16104115

Liu, Y., Xue, S., Guo, X., Zhang, B., Sun, X., Zhang, Q., Wang, Y., & Dong, Y. (2023). Towards the goal of zero-carbon building retrofitting with variant application degrees of low-carbon technologies:

Mitigation potential and cost-benefit analysis for a kindergarten in Beijing. *Journal of Cleaner Production*, *393*. 136316. https://doi.org/10.1016/j.jclepro.2023.136316

Lu, L., Cai, W., Chai, Y. S., & Xie, L. (2005). Global optimization for overall HVAC systems—Part I problem formulation and analysis. *Energy Conversion and Management*, *46*(7–8), 999–1014. https://doi.org/10.1016/j.enconman.2004.06.012

Lund, P. D., Lindgren, J., Mikkola, J., & Salpakari, J. (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews*, *45*, 785–807. https://doi.org/10.1016/j.rser.2015.01.057

Ma, Z., Cooper, P., Daly, D., & Ledo, L. (2012). Existing building retrofits: Methodology and state-of-the-art. *Energy and Buildings*, *55*, 889–902. https://doi.org/10.1016/j.enbuild.2012.08.018

Madushika, U. G. D., Ramachandra, T., Karunasena, G., & Udakara, P. A. D. S. (2023). Energy retrofitting technologies of buildings: A review-based assessment. *Energies, 16*(13), 4924. https://doi.org/10.3390/en16134924

Mendell, M. J., Eliseeva, E. A., Davies, M. M., Spears, M., Lobscheid, A., Fisk, W. J., & Apte, M. G. (2013). Association of classroom ventilation with reduced illness absence: A prospective study in California elementary schools. *Indoor Air*, *23*(6), 515–528. https://doi.org/10.1111/ina.12042

Mirinejad, H., Sadati, S. H., Ghasemian, M., & Torab, H. (2008). Control techniques in heating, ventilating and air conditioning (HVAC) systems. *Journal of Computer Science*, *4*(9), 777–783. https://doi.org/10.3844/jcssp.2008.777.783

Mohamed, R., & Wang, E. (2020). Optimizing building retrofitting schemes through BIM-based value engineering analysis for sustainability. In H. Keathley, J. Enos, M. Parrish (Eds.), *41st International annual conference of the American society for engineering management (ASEM 2020): Leading organizations through uncertain times* (pp. 505-511). American Society for Engineering Management. https://www.proquest.com/openview/1c76bd77c52484903887e3bef7dcf5eb/1?pq-origsite=gscholar&cbl=2037614

Mohebbi, A., Achiche, S., & Baron, L. (2020). A fuzzy-based framework to support multicriteria design of mechatronic systems. *Journal of Computational Design and Engineering*, *7*(6), 816–829. https://doi.org/10.1093/jcde/qwaa059

Nalley, S., & LaRose, A. (2022, March 03). *Annual energy outlook 2022 (AEO2022).* U.S. Energy Information Administration. https://www.eia.gov/outlooks/AEO/pdf/AEO2022_ReleasePresentation.pdf

Niro, G., Salles, D., Alcântara, M. V. P., & da Silva, L. C. P. (2013). Large-scale control of domestic refrigerators for demand peak reduction in distribution systems. *Electric Power Systems Research*, *100*, 34–42. https://doi.org/10.1016/j.epsr.2013.03.002

Peng, S., Yu, J., Gang, W., Tian, L., Yang, Q., & Tao, J. (2019). Study on load characteristics of different air conditioning systems in large space railway station. *IOP Conference Series: Earth and Environmental Science*, *238*, 012038. https://doi.org/10.1088/1755-1315/238/1/012038

Ranawaka, I., & Mallawaarachchi, H. (2018). A risk-responsive framework for green retrofit projects in Sri Lanka. *Built Environment Project and Asset Management, 8*(5), 477-490. https://doi.org/10.1108/BEPAM-10-2017-0088

Siegel, J. A. (2016). Primary and secondary consequences of indoor air cleaners. *Indoor Air*, *26*(1), 88–96. https://doi.org/10.1111/ina.12194

Soyguder, S., Karakose, M., & Alli, H. (2009). Design and simulation of self-tuning PID-type fuzzy adaptive control for an expert HVAC system. *Expert Systems with Applications*, *36*(3), 4566–4573. https://doi.org/10.1016/j.eswa.2008.05.031

Shahrestani, M., Yao, R., Cook, G. K., & Clements-Croome, D. (2018). Decision-making on HVAC&R systems selection: A critical review. *Intelligent Buildings International*, *10*(3), 133–153. https://doi.org/10.1080/17508975.2017.1333948

Sossan, F., Lakshmanan, V., Costanzo, G. T., Marinelli, M., Douglass, P. J., & Bindner, H. (2016). Grey-box modelling of a household refrigeration unit using time series data in application to demand side management. *Sustainable Energy, Grids and Networks*, *5*, 1–12. https://doi.org/10.1016/j.segan.2015.10.003

Stadler, M., Krause, W., Sonnenschein, M., & Vogel, U. (2009). Modelling and evaluation of control schemes for enhancing load shift of electricity demand for cooling devices. *Environmental Modelling & Software*, *24*(2), 285–295. https://doi.org/10.1016/j.envsoft.2008.07.003

Stephens, B., Novoselac, A., & Siegel, J. A. (2010). The effects of filtration on pressure drop and energy consumption in residential HVAC systems (RP-1299). *HVAC&R Research*, *16*(3), 273–294. https://doi.org/10.1080/10789669.2010.10390905

Sudhan, E. P. J. (2011). Synthesis of silver nanofluid by a novel one pot method for heat transfer applications. *Indian Journal of Science and Technology*, *4*(4), 417–421. https://doi.org/10.17485/ijst/2011/v4i4.8

Sustainable Energy Authority of Sri Lanka. (2020). *Sri Lanka energy balance 2020*. https://www.energy.gov.lk/images/energy-balance/energy-balance-2020.pdf

Tan, G., & Glicksman, L. R. (2005). Application of integrating multi-zone model with CFD simulation to natural ventilation prediction. *Energy and Buildings*, *37*(10), 1049–1057. https://doi.org/10.1016/j.enbuild.2004.12.009

Tu, Q., Zou, D., Deng, C., Zhang, J., Hou, L., Yang, M., Nong, G., & Feng, Y. (2016). Investigation on output capacity control strategy of variable refrigerant flow air conditioning system with multi-compressor. *Applied Thermal Engineering*, *99*, 280–290. https://doi.org/10.1016/j.applthermaleng.2015.12.102

Wane, S. S., & Nagdeve, M. B. (2012). Design of air cooling system for college auditorium. *Journal of Environmental Research and Development,* *6*(3). 562-568. https://www.academia.edu/40257593/design_of_air_cooling_system_for_college_auditorium

Wang, H., Zhu, J., Dai, Y., & Hu, H. (2023). A simplified cooling load calculation method based on equivalent heat transfer coefficient for large space buildings with a stratified air-conditioning system. *Energy and Buildings*, *296*, 113370. https://doi.org/10.1016/j.enbuild.2023.113370

Wang, J., Jing, Y., & Zhang, C. (2009). Fuzzy multi-criteria evaluation model of HVAC schemes in optimal combination weighting method. *Building Services Engineering Research and Technology*, *30*(4), 287–304. https://doi.org/10.1177/0143624409338502

Wang, W., Wang, J., Chen, J., Huang, G., & Guo, X. (2018). Multi-zone outdoor air coordination through Wi-Fi probe-based occupancy sensing. *Energy and Buildings*, *159*, 495–507. https://doi.org/10.1016/j.enbuild.2017.11.041

Wang, Y., Dong, L., & Li, H. (2022). Economic evaluation of energy-saving retrofit of existing hotels. *Energies*, *15*(3), 757. https://doi.org/10.3390/en15030757

Wargocki, P., & Wyon, D. P. (2013). Providing better thermal and air quality conditions in school classrooms would be cost-effective. *Building and Environment*, *59*, 581–589. https://doi.org/10.1016/j.buildenv.2012.10.007

Yang, L., Yan, H., & Lam, J. C. (2014). Thermal comfort and building energy consumption implications: A review. *Applied Energy*, *115*, 164–173. https://doi.org/10.1016/j.apenergy.2013.10.062

Yi, L., Chow, W. K., Li, Y. Z., & Huo, R. (2005). A simple two-layer zone model on mechanical exhaust in an atrium. *Building and Environment*, *40*(7), 869–880. https://doi.org/10.1016/j.buildenv.2004.08.018

Yu, F. W., & Chan, K. T. (2005). Experimental determination of the energy efficiency of an air-cooled chiller under part load conditions. *Energy*, *30*(10), 1747–1758. https://doi.org/10.1016/j.energy.2004.11.007

Zaheer-uddin, M., & Zheng, G. R. (2000). Optimal control of time-scheduled heating, ventilating and air conditioning processes in buildings. *Energy Conversion and Management*, *41*(1), 49–60. https://doi.org/10.1016/S0196-8904(99)00094-1

Zavala, V. M. (2013). Real-time optimization strategies for building systems. *Industrial & Engineering Chemistry Research*, *52*(9), 3137–3150. https://doi.org/10.1021/ie3008727