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A COMPARATIVE ANALYSIS OF OPERATIONAL ENERGY BY SIMULATION STUDY BETWEEN MODERN BUILDINGS AND ADAPTIVE REUSE OF HISTORIC BUILDINGS IN SRI LANKA

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ABSTRACT

The adaptive reuse of buildings is emerging as a sustainable solution within the built environment, addressing global challenges like climate change and greenhouse gas emissions faced by the world's population. Opting to repurpose energy-efficient historic buildings during the operational phase instead of demolishing and constructing new structures is recognized as a protective mechanism for urban cultural heritage. The escalating operational energy consumption in the building sector poses direct and indirect environmental, economic, and social concerns for occupants. This study aimed to compare the operational energy efficiency of adaptive reuse historic buildings and modern structures, seeking to identify the most energy-efficient building type. Energy consumption patterns, especially for air conditioning and lighting in residential houses, were gathered and simulated using DesignBuilder software, considering building materials as variables in both the old and new phases of the buildings. Ten Dutch-era residential dwellings were selected, and a specific schedule was analysed for energy simulations. The average Energy Use Intensity (EUI) value for old buildings in the scheduled case was lower than the newly modelled buildings. The research concludes that old historic buildings are comparatively more energy-efficient and environmentally friendly than new buildings for operational use based on the building envelope in the selected study area.

Keywords: *Adaptive Reuse; Design Builder; Energy Use Intensity; Operational Energy; Residential Buildings.*

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1. INTRODUCTION

The construction industry is essential for all nations as it is one of the condemnatory constituents of sustainable economic, social, and national development. From the total world's energy, buildings solely account for 40% of the energy consumption (Romani et al., 2015). Nearly 35% of all building energy is utilised for the building's operations, such as heating, ventilation, air conditioning, and equipment (Yang et al., 2016). The operational energy consumption patterns of buildings are different from each building by the functions they perform and the type of building they belongs to. Those factors are climate or temperature, the kind of building envelope, and the effectiveness of the electrical systems in operation. The implementable strategy that can be followed to attain a high comfort level while using less energy in buildings is to enhance the thermal performance of the building envelope and significantly the walling material and insulations (Meng et al., 2018). The composition of the construction materials and their properties influence the operational energy utilisations in the building. Incorporating eco-friendly materials and older construction materials in building envelopes can help to lower the demand for both energy and cost.

The cost for the operation and maintenance of buildings seems to be increasing day by day. Adaptive reuse can be considered a resourceful, innovative approach that can be applied to achieve the goal of an ecologically sustainable built environment while preserving valuable heritage ethics by focusing on existing different structures (Abdulameer & Abbas, 2020). Computer simulations are helpful for deriving conclusions based on vast projects of various building systems. They provide accurate and predictable simulation results for circumstances that have not yet been tested in reality. They help forecast how these changes will influence energy balance and comfort levels inside the buildings. DesignBuilder software is one of the Building Energy Simulation (BES) tools that includes a variety of uploaded data templates for a range of building simulation inputs, such envelope construction components, lighting systems, and occupancy schedules (Wasilowski & Reinhart, 2009).

The research gap identified is the limited extent of studies focusing on operational energy consumption within Sri Lankan residential buildings. This gap suggests a lack of comprehensive understanding regarding the energy usage patterns, efficiency levels, and potential areas for improvement within the residential sector of Sri Lanka. This emphasises an important concern that global attention has been put in minimising the energy consumption of residential buildings by improving the building architectural and structural designs. In this study, the operational energy (OE) consumption patterns among dwellings belonging to historic buildings and modern buildings in Sri Lanka were compared and analysed using DesignBuilder software. The objective of this study is to compare the operational energy of adaptive reuse historic buildings (ARHB) with that of modern buildings to find the most energy-efficient building type. Ten residential dwellings were selected in the old town of Galle Fort area for research purposes. All ten buildings were modelled using the DesignBuilder software (DBS) using the original construction materials as old buildings and new construction materials as modern buildings with a specific schedule of 6 hours of Air conditioning and 7 hours of lighting for the simulation. Then, the OE need for those two building categories were compared to analyse whether the old historic buildings can be used for adaptive reuse in the modern operational phase. The simulated results showed that there is a significant difference between these two types of buildings. Adaptive reuse is one of the most popular methods for achieving sustainability in the construction industry. Adaptive Reuse of Historic Buildings (ARHB) is a relatively new idea introduced by the educationalist as a sustainable approach. The scope of this study is to ensure the sustainability of utilising historical buildings over constructing new ones, particularly in terms of operational phase energy consumption. By conducting simulation studies that account for building materials, researchers can evaluate the efficiency and viability of repurposing old-era structures, thereby contributing to informed decision-making and sustainable urban development.

2. LITERATURE REVIEW

2.1 OPERATIONAL ENERGY CONSUMPTION IN BUILDINGS

A typical building's life cycle energy is comprised of a trio of components: the energy the building itself comprises (Embodied energy), the energy it uses to operate throughout its lifetime (Operational energy), and the energy required to demolish the building and dispose of its waste. The typology "operational energy" means the magnitude of energy utilized during an object's functional use (Li et al., 2020). It specifically refers to the energy needed for the functioning of lighting systems, cooling and heating systems like HVAC, and other electrical appliances like refrigerators, dishwashing machines, and washing machines in a building. The four most common end uses can be stated as lighting, space heating, cooling, and water heaters, which account for approximately 70% of the energy used on the building property (Cao et al., 2016). According to Koezjakov et al. (2018), buildings' operational energy usage, or the energy needed to heat and cool them, accounts for around 33% of the total final energy demand of the globe and 30% of the carbon dioxide emissions related to energy use. The analysis of operational energy, particularly for residential situations, is a challenging task since it involves the intrinsic personal traits of each user, making the actual consumption profile of each residence unique. The operating phase's activity-wise energy split demonstrates that area lighting accounts for 29% of operating energy, with space cooling accounting for 45% (Ramesh et al., 2014).

Many factors can influence the operational energy of buildings. The design of building envelope, types of HVAC system, the performance of the electrical systems in use, pattern or behaviour of occupancy, energy management mechanisms and climate factors. Operational energy intensity relies on tenant behaviour in addition to location (climate zones) (Koezjakov et al., 2018). The authors found that, the Dutch building typology' operational energy consumption ranges from 124 to 682 MJ/(m^2.yr). The design of the building and envelope's material composition directly affect the operational energy performance of a building (Umbark et al., 2020). An air-tight construction and proper insulation can reduce the heat transfers within the building (Zilberberg et al., 2021). During the summer season, it neglects heat gains from outside and during the winter season, it reduces the heat loss from the building. Other factors, such as the orientation of the building and the effective design of the fenestration, can also affect the energy use of the buildings (Haase &Amato, 2009).

2.2 ADAPTIVE REUSE OF HERITAGE BUILDINGS (ARHB)

Adaptive reuse, also known as AR, encompasses the procedural endeavour of reconfiguring architectural structures to serve alternative functionalities (Rodrigues &

Freire, 2017). It involves aspects such as reusing components and materials, considering the life cycle of the building, evaluating aspects and making decisions based on multiple criteria as well as adhering to regulatory guidelines and analysing stakeholder's perspectives. Owojori et al., (2021) highlight that AR offers an improved alternative to construction and demolition, addressing challenges faced by the built environment.

Historic buildings can make a significant contribution to the history and culture of a country (Ayçam et al., 2020). AR of urban cultural heritage buildings gives new life to old buildings and has the potential to help future generations understand their genealogies, including a greater understanding of historical change (Bullen & Love, 2011). When thinking about renovating or retrofitting priceless heritage building structures, it is essential to recognize their substantial historical and architectural added value (Owojori et al., 2021). A vital part of regenerating the built environment to meet the demand for new structures is adaptive reuse of buildings (ARB), which preserves the latent prestige of old buildings. The good capacity of the building is not the sole factor for the successful adaptability of the buildings; the other factors like owner's or user's capacity to adapt and any other numerous variable which supports the dynamic interplay among building and context (Cellucci, 2021).

2.3 SIMULATION STUDY

A building is a complicated thermodynamic object that handles dynamic energy shifts between the various temperature zones inside and outside of the structure. According to (Reinhart & Christoph, 2009), the building energy simulation model control is made up of two primary parts. They are the building fabric contents and plant components. Since simulation tools may be applied at any stage of the life cycle and employ more general notions, computer simulations can assess the effects of many Energy Conservation Measures (ECMs) and their complex interactions more effectively, thoroughly, and correctly than any other method because of the complex nature a building model is (Coakley et al., 2014).

The simulation program has to execute the simulation utilizing hourly values of climate data, such as temperature, humidity, solar radiation, and wind speed and direction from representative climate data, for the location where the proposed design would be deployed (Jentsch et al., 2013). When compared to the standalone EnergyPlus engine, "DesignBuilder" has quality control mechanisms in place to ensure the findings are accurate. EnergyPlus is a ready-to-use program for a dynamic building energy simulation engine for modelling building’s heating, cooling, lighting, ventilation, and other energy flows (Crawley et al., 2001).

Numerous parameters affect and impact the building's energy systems. These parameters can be broadly categorized as enclosure factors, which refer to the thermal characteristics of the construction materials, climatic variables, and occupancy factors (Yu et al., 2015). According to Al-ajmi and Hanby (2008), the following elements could influence a building's energy needs in a simulation study: Location of the building (height, latitude, longitude, and direction) and weather in an area. Albatayneh (2021) ran a sensitivity analysis on 12 design variables in DesignBuilder to determine how they affect the heating and cooling loads to reduce the energy consumed for heating and cooling loads in household buildings in 'Ma'an City. The variables he used are the building envelope's window-to-wall percentage, local shading type, infiltration rate (ac/h), glazing type, flat roof construction, natural airflow rate, window blind type, window shading control schedule, partition construction, site orientation, external wall construction. Motuziene and Vilutiene (2013) demonstrated the simulation findings of the impact of domestic occupancy profiles on the energy efficiency of a Lithuanian home. To demonstrate his findings, he mentioned that the parameters must take into account the age, behaviour, and number of residents.

The DesignBuilder software is a sophisticated and advanced graphical user interface. It was created specifically to run EnergyPlus simulations and can assess how well a structure performs in terms of energy, carbon dioxide emissions, lighting and comfort (Reinhart & Christoph, 2009). According to Harish and Kumar (2016) the applications of DesignBuilder are Building energy simulation, visualisation, CO_2 emissions, solar shading, natural ventilation, daylighting, comfort studies, Computational Fluid Dynamics (CFD), HVAC simulation, pre-design, early-stage design, checking for compliance with building energy codes, OpenGL EnergyPlus interface, building stock modelling, hourly weather data, and sizing of heating and cooling equipment are all topics covered by this (An-Naggar et al., 2017). Wasilowski and Reinhart (2009) utilized the DesignBuilder interface for the energy plus simulation engine by constructing and assessing a model of Gund Hall. It was a complex building and he simulated the energy consumption pattern in it using customized internal loads and weather data. Ismail et al. (2015), calibrated the DesignBuilder and found that the acceptable error rate was 3.17% when calibrating with that software.

3. METHODOLOGY

3.1 DESCRIPTION OF STUDY AREA AND SAMPLE SELECTION

The old town of Galle and its fortifications are listed in UNESCO World Heritage Sites (Jinadasa, 2020). Dwellings belonging to the Dutch period were selected for the study as the adaptive phase of the buildings. The selection criteria were grounded in identifying buildings intended primarily for residential habitation. Employing a purposive sampling methodology, Dutch-era dwellings located in Galle were specifically chosen. So, in selecting the samples, they were chosen with care, considering their period and the current state of the building use. For the study 10 buildings were selected from the study area. Figure 1 shows the location of selected dwellings.

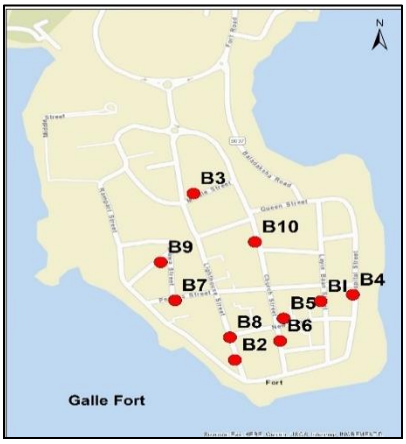

Figure 1: Location of selected ten buildings in Galle fort area

The selected buildings were visited, and the construction materials, the thickness of the walls, and their specifications were clarified during the site visit. Further information regarding the buildings, including floor plans, measurements, architectural specifications and history, were obtained from the Galle Heritage Information Centre**.** Table 1 shows the summary of construction materials used in the modelling.

Table 1: Details of building construction material

	Building Construction Materials	
Components	**Old Dutch Era Building**	**Modern Buildings**
External walls	Clay, Limestone, Granite mix (470 mm)	Brick wall (225 mm) + Plasters
Internal walls	Clay, Limestone, Granite mix (470 mm)	Brick wall (115 mm) + Plasters
Floor	Granite	Tile, Plaster, RC slab
Wall plaster	Clay, sand, Lime (15 mm +15 mm)	Cement/Sand plaster (15 mm +15 mm)
Columns	Clay, Limestone, Granite mix	Concrete
Doors	Timber	Timber
Staircases	Timber	Concrete + Tile
Windows	Timber + Glass	Aluminum + Glass
Roofs	Sinhala clay tiles +Timber	Clay tiles +Timber
Foundation	Concrete	Random rubble

3.2 THE SURVEY

An online questionnaire survey was prepared and circulated throughout different parts of the country, mainly focusing on the urban residential houses in all twenty-five districts of Sri Lanka. After filtering, 400 responses from the participants were included in the analysis of the survey. The main aim of the conducted survey was to find out the prevailing energy usage patterns in the household in Sri Lankan houses to find out the operational energy usage patterns for air conditioning and lighting. Those two are the main energy consumers in a household of tropical countries. Typical building' energy consumption for air conditioning and lighting is 56% and 16%, respectively, in tropical countries (Katili et al., 2015). There are evidences with booming economic report showing that, countries including Sri Lanka has high growth of sales of room air conditioners. This shows the increased usage of air conditioning in households (Mahlia & Saidur, 2010). Figure 2 shows the summary of the questionnaire survey.

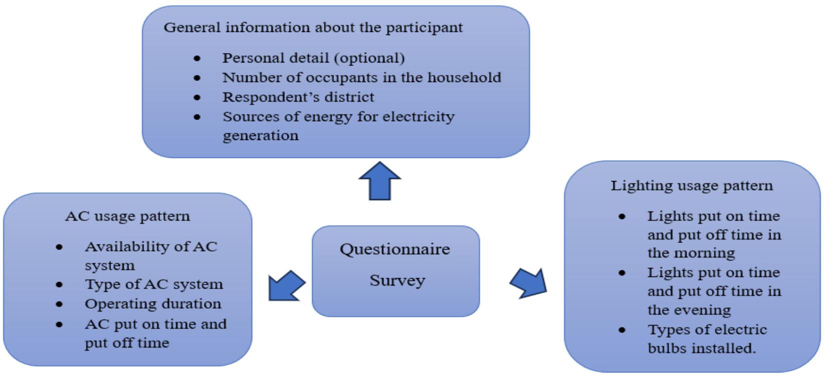

Figure 2: Summary of questionnaire survey

3.3 SIMULATION OF BUILDINGS

For simulating the operational energy consumption of the chosen ten buildings, the DBS (version 6.1.0.006) software was employed. Known for its user-friendly interface and flexibility, DBS adheres to ASHRAE 90.1 guidelines and utilizes EnergyPlus for accurate energy simulations. Input data utilised in the DesignBuilder software are outlined in Table 2.

Table 2: Input data into the DBS

Function Of Building	Residential
Working Profile	07 days per week
Clothing Value	0.665
Metabolic Factor	0.925
Occupancy	4 people per dwelling
HVAC	Split Air conditioning system.
Lux Level	150 lux
Cooling setback Temperature	26 degree C
Lighting Power Density	8 W / m^2

The DesignBuilder's "LKA _ COLOMBO _ KATUNAYAKE _ SWERA" was set as the simulation weather data file as it is similar to the Galle fort climatic conditions. The building's construction material was considered the primary input variable factor for the energy simulation for the selected buildings in the DBS. The Dutch-era buildings with their original construction materials as it is, being considered old buildings and the same buildings with similar dimensions, orientations, purposes and other functional factors, except building construction materials are considered as modern buildings. The selected ten buildings were developed in the DBS according to the actual dimensions of the building materials, heights and thickness, which were gathered during the site visit. A specific schedule, which was analysed from the survey data, was used for the simulation. The bedrooms in each dwelling were simulated with 6 hours of AC, and the whole building was simulated with 7 hours of lighting.

4. RESULTS AND DISCUSSION

The functional purpose of the selected ten buildings was to serve as residential buildings. The energy consumption and the adaptability of using the old historic buildings with the present operational energy consumption with the modern buildings were modelled using the DesignBuilder simulation under the specific schedule individually. The average simulated EUI values for the overall old buildings and new buildings are 50.37 kWh/m^2/yr and 56.42 kWh/m^2/yr respectively. The following Figure 3 shows the DBS simulated total EUI values for the selected buildings.

Here, new buildings show a relatively higher EUI value than older buildings, which indicates lower OE efficiency. Shabunko et al. (2018) did a research study regarding EUI per year in Brunei for residential buildings using EnergyPlus models and obtained the values ranging from 47.8 kWh/m^2 to 64.2 kWh/m^2. A door-to-door survey was conducted among 400 residential buildings to gather details on energy consumption.

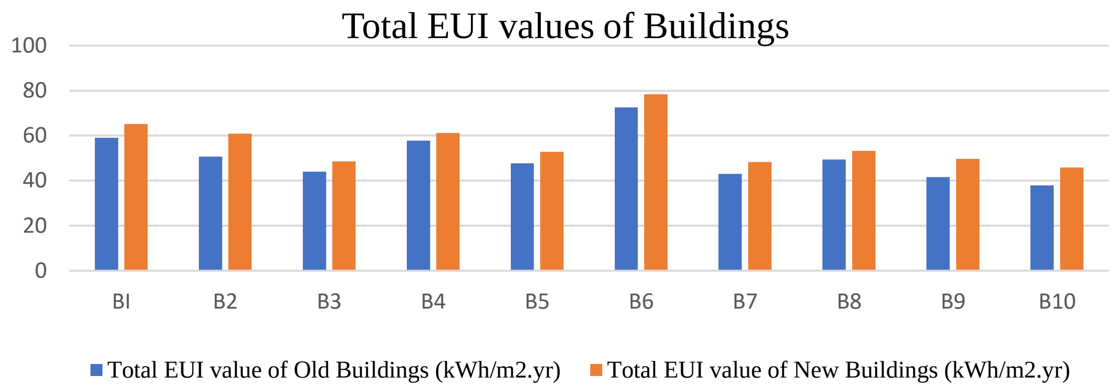

Figure 3: DBS simulated Total EUI values for buildings

These findings can be correlated with the results obtained from simulations conducted using our DBS, as Brunei is located in a tropical equatorial climate, and over 60% of electric load is contributed to HVAC operations. According to Boehme et al. (2015), the EUI values for residential landed housing range between 52.15 kWh/m^2/year to 65.19 kWh/m^2/yr. The findings of EUI were gained from the calculation results by considering building database and electricity consumption statistics, and it can be relatable to our findings as this study was also done in a tropical city – Singapore.

Figures 4 and 5 show the operational EUI values. The average EUI for the cooling in the old and new buildings are 21.41 kWh/m^2/yr and 31.10 kWh/m^2/yr, respectively. The average EUI need for the lighting in the old and new buildings are 28.96 kWh/m^2/yr and 25.33 kWh/m^2/yr, respectively.

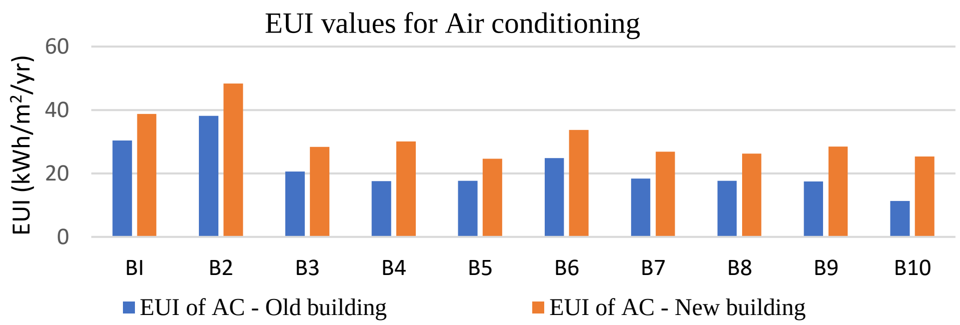

Figure 4: EUI values for AC

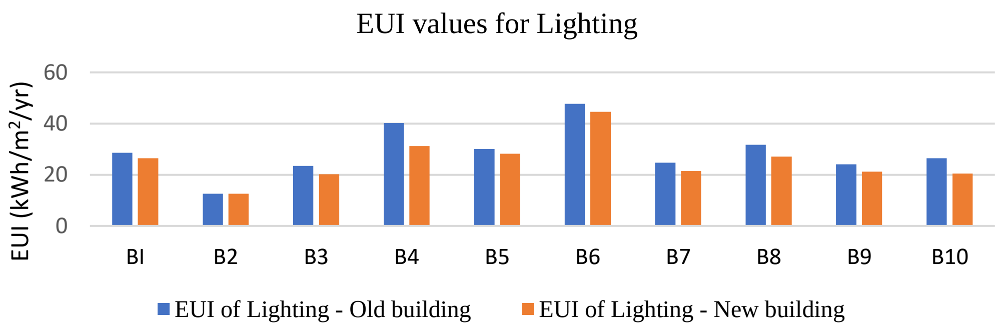

Figure 5: EUI values for Lighting

The specific reason for the simulated result is that cooling energy can be used with the construction materials and the thickness of the walling materials because all the other factors were kept constant during the simulations for the modern buildings. The thermal mass and the insulation properties of older buildings are often high (Reilly & Kinnane, 2017). Because they have thicker wall, and the walling materials are denser. The walls of the Dutch houses are around 0.35 m -1 m, and materials such as limestone, clay and granite have higher thermal mass properties (Waltham, 2002). This property reduces the temperature fluctuations by absorbing and releasing the heat inside the building slowly and contributing to stabilize the indoor temperature (Al-Homoud, 2005). By these features, a favourable comfortable internal environment was created, and it has the potential to reduce the need for frequent cooling.

The DBS simulated result shows that Dutch-era buildings require more energy for lighting compared to their modern counterparts. The reasons behind this can be validated with building design and material properties of the construction: Dutch-era buildings may have darker interior finishes, that comprises of wood panelling which can absorb higher percentage of light (Pajchrowski et al., 2014). Modern buildings with sophisticated designs often incorporate lighter colours and reflective surfaces to enhance and improve the reflection and distribution of light (Santamouris et al., 2011). Modern design principles emphasize open and flexible spaces that allow for better light distribution.

All the simulated results of the study were done in a Tropical climate – Sri Lanka. There are some limitations to the study that was conducted due to the availability of literature sources in the Sri Lankan context (Ariyarathna et al., 2023). The available literatures are regarding the different climatic zones, and this can impact the simulation in a big manner. This study is a significant approach to analyse the operational energy comparison for the adaptive reuse of historic buildings and modern buildings in Sri Lanka.

5. CONCLUSIONS

This research examined the simulated operational energy consumption of Dutch era historic buildings in Galle, which rely on construction materials for the old phase and new phase of the building with present energy usage, to find out the most energy efficient building type for the adaptive reuse of building purposes.

The simulated results validate that the modelled historic buildings are more energy efficient than the modelled new buildings, as the EUI values of new buildings are higher than the EUI values of the old buildings. In the specified schedule the total EUI of new buildings were higher than the total EUI of old buildings. The average EUI values for old buildings and new buildings were 50.37 kWh/m^2/yr and 56.42 kWh/m^2/yr respectively. The results of statistical analysis show an overall significant difference among the EUI values of two building types. That is, the old Dutch-era buildings are more energy efficient than the modern buildings in the selected buildings and locations. So, the objective of the study is to compare the operational energy of adaptive reuse historic buildings and modern buildings to find out the most energy-efficient building type was achieved. The other important feature observed was a better thermal performance in historical buildings resulted in a lower energy load for cooling than modern buildings in the simulated case for selected buildings based on the paired t-test analysis. The visual efficiency of historical buildings was seemed lower than that of modern buildings, resulting in a higher energy usage for lighting in old historic buildings.

Several methods can improve energy efficiency in residential dwellings, mainly targeting air conditioning (AC) and lighting systems for adopting those buildings. These methods encompass utilizing programmable thermostats and adhering to regular maintenance schedules to optimize Air conditioning usage and diminish energy wastage. Strategic deployment of shading devices and implementation of insulation techniques aid in mitigating heat transfer, thus alleviating the burden on air conditioning systems. Furthermore, the adoption of energy-efficient LED lighting fixtures alongside the integration of occupancy sensors serves to reduce unnecessary lighting consumption. Lastly, educating residents about energy-saving practices and fostering behavioural changes are pivotal for making substantial contributions to overall energy conservation within residential contexts. Difficulties arose during the research process, particularly in the validation of results. Acquiring pertinent operational energy data solely for air conditioning (AC) and lighting proved challenging due to the predominant focus in literature on combined usage, encompassing household appliances and domestic hot water systems alongside air conditioning and lighting. The accuracy of the simulation outcomes was guaranteed through validation against empirical data corresponding to studies of comparable scope and comprehensive input parameters. Moreover, the simulation methodology-maintained rigor by confining its assumptions to operational energy considerations primarily attributed to air conditioning and lighting within the designated residential units.

To enhance the comprehensiveness of this study, additional examination of other OE consumption mechanisms is warranted to corroborate the overall efficiency of adopting ARHB for contemporary purposes. Even though the results show a green flag to the adaptive reuse of historic buildings during the operational phase, the final decisions are relying on the building owners and their preferences in adapting them for operational use.

Future researchers can employ this methodology as a foundation for their investigations into the myriad factors influencing the operational energy of adaptive reuse buildings, with a specific emphasis on enhancing energy efficiency. Additionally, they can extend this conceptual framework across different stages of the building lifecycle to assess efficiency and sustainability comprehensively.

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