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ENHANCING THERMAL AND DAYLIGHT PERFORMANCE OF HISTORIC BUILDINGS WITH PASSIVE MODIFICATIONS; A TROPICAL CASE STUDY

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ABSTRACT

Historical buildings worldwide hold immense potential for adaptive reuse within the framework of the circular economy, a concept gaining traction in the building construction industry for its role in reducing carbon emissions. Many of these structures boast passive building design strategies, which inherently lower energy demands. Among these, thermal mass and daylight harvesting emerge as pivotal strategies for achieving indoor thermal and visual comfort, respectively. However, with the advent of significant climate change and evolving built environments, the efficacy of these historical passive strategies is subject to debate. This study focuses on a residential building constructed in the 17th century by Dutch settlers in Galle, Sri Lanka, serving as a case study. The research targets improvements in both thermal and visual comfort. Thermal performance analysis was conducted through air temperature measurements, revealing a notable 3-hour time lag and a 2.5°C reduction in peak air temperature during the day. Conversely, nighttime measurements indicated a rise in indoor temperature compared to ambient conditions. Using Design Builder software, the building was modelled to assess its daylighting conditions. Drawing upon thermodynamic principles and daylight harvesting techniques, the study proposes building envelope interventions and ventilation strategies to address nighttime overheating and enhance daylight utilization. The results demonstrate that these modifications can potentially reduce nighttime heat by 2-3°C, while also decreasing the energy requirement for lighting comfort from 51.10 kWh/m² per annum to 44.84 kWh/m² per annum. This research showcases the effectiveness of judiciously implemented interventions in historical buildings, illustrating tangible improvements in both thermal/visual performance and energy efficiency. Leveraging inherent qualities of historical structures and integrating modern design strategies to these buildings can play a vital role in sustainable urban development and energy conservation efforts.

KEYWORDS— Thermal Comfort, Passive Design Strategies, Historic Buildings, Building Preservation

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1. INTRODUCTION

Buildings are responsible for more than 30% of the global final energy use (Berardi, 2017). When it comes to the operational building phase, a significant amount of energy is used to gain thermal and visual comfort (Pathirana et al., 2019). To achieve Paris Agreement targets, the building sector must be fully decarbonized by 2050. Carbon emissions from buildings can be reduced through triple strategies: reducing energy demand, decarbonizing the power supply, and addressing embodied carbon (United Nations Environment Programme, 2021).

According to the previous research, the thermal comfort of the residential buildings of Sri Lanka should be improved (Karunathilake et al., 2018). When it comes to visual comfort, very little research in this regard has been done in the Sri Lankan context. Thermal comfort, visual comfort and energy efficiency in buildings can be improved by using passive building design strategies (Ahsan, 2009). Higher thermal mass and natural ventilation have been identified as long-used passive strategies to achieve thermal comfort (Rajapaksha and Halwatura, 2020), while full use of natural lighting has been identified as a passive strategy to achieve better visual comfort (Zhen et al., 2019).

The vernacular architecture is transferred from generation to generation, and it is an art developed through trial and error. This vernacular architecture is positively responding to the regional climate (Albatici, 2009). Energy experts believe that old architecture's passive building design strategies can reduce energy usage and reduce emissions (Wang et al., 2021). On the other hand, some researchers argue that the passive building design strategies used in old buildings are no longer valid. Those strategies were developed to fit the climatic and other built environmental conditions of those early years (Shen et al., 2020).

This research intends to evaluate the thermal and lighting conditions of the identified colonial building in Sri Lanka, which can be reused for many years by saving its embodied carbon and energy, and then to fix the uncomfortable period by introducing potential passive design strategies to enhance thermal and visual comfort without compromising the historical value of the buildings.

The Galle Fort is recognized as the largest Dutch colonial city that survives outside Europe. It has a blend of European and South Asian Architecture. UNESCO declared the Galle Fort as a world heritage under criteria (iv) in 1988 (UNESCO World Heritage Center, 2022). The statistics show a dramatic functional change in the Galle Fort area due to the booming tourism industry (Jinadasa, 2020). Both internal and external spaces have been changed due to the changing lifestyles, ethnicities, and needs of the residents (Rajapakse and Silva, 2020). The Galle Dutch Fort area was selected for this research on that base.

2. METHODOLOGY

2.1 Pilot Survey to Select a Suitable Residential Building

Thirty residences that belong to the Dutch-era were selected for the pilot study. The original Building plan and sections of those houses were obtained from the Galle Heritage Foundation (GHF) and evaluated to identify the similarities. Current arrangements of the selected houses were studied through field visits and interviews.

Out of the building plans referred to, No. 28, Middle Street house showed a comparatively excessive wall thickness of 3 feet in its outer envelope, which was impressive in terms of indoor thermal behaviour. Mainly based on the available literature on impressive thermal performances among the selected residences in Galle Fort (Rajapaksha et al., 2013) and further based on the practical scenarios such as the owner's willingness to help with the research, No. 28, Middle Street house was selected for this study

A. Front view of the case study residence from the road

B. Main door area and the living room

C. View of the front verandah

D. View of the courtyard

Fig. 1. Photographs of No 28, Midde Street, Galle Fort

Fig. 2. Location of the No 28, Middle Street,Galle Fort

(Jinadasa, 2020; Rajapakse, 2011). Fig. 1 shows some of the photographs of the building and Fig. 2 shows the location of the selected building. No. 28 Middle Street building was built around 1680s as a residential building and still it is used as a residential building. The floor area of the building is 181 m^2.

In the selected residence, the construction materials used were evaluated through GHF databases and were confirmed by site visits. Those data were verified through expert interviews and literature as well.

2.2 Methodology

Indoor and outdoor air temperature was measured in the selected house on March 06th, 07th, 08th of 2022, considering the average high temperature. Three-hour averaged ambient temperature. data for the same dates were taken from M.E.T Department in Sri Lanka. The air temperature measurements were Recorded in the verandah, living room, dining room and courtyard at the upper level (Fig. 3) in the selected building with Hobo loggers, to identify the thermal behaviour in each space separately.

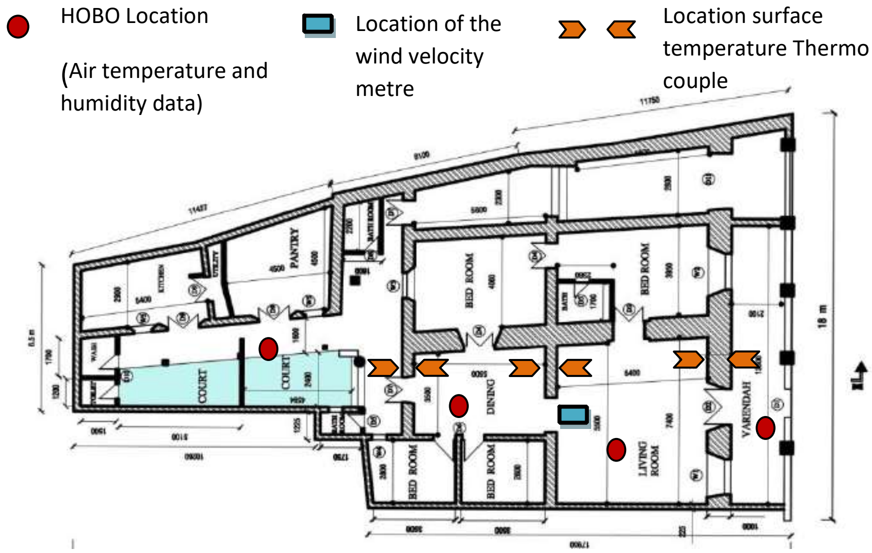

Fig. 3. Locations of the equipment for data collection

Table : 1: Changes introduced and purposes of the changes

Changes Introduced to the Model	Purpose of the Change
Create an upper opening near the ridge level of the roof (facing wind shadow direction)	To remove the indoor heated air out, by stack effect
Low-level openings introduced from front and courtyard side facades	To pull cool air from outside to fill the vacuum created by the stack effect (with top opening) at night and promote wind circulation.
Make a schedule for openings - Lower and upper openings are fully opened during evening and night - About 95% of the external envelop is closed during daytime - Introduced upper openings are operatable and made with 90% transparent material	To promote cross and stack ventilation at night To avoid entering wind inside which carries heated Air outside at daytime For daylight harvesting and improving lighting condition

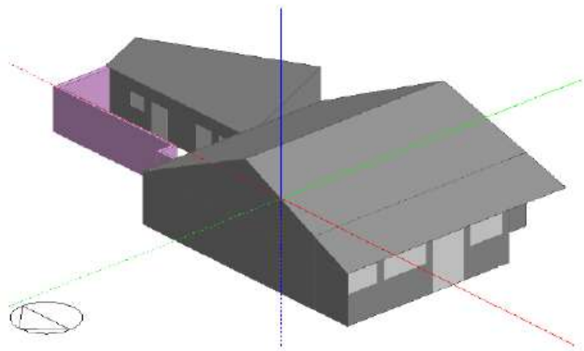

Fig 4: Design Builder model for the selected case study house

Using Design Builder (DB) version 6, the case study house was modelled and validated to make similar conditions and further thermal and lighting performance evaluations of the building were conducted (Fig. 4).

Potential building modifications were analyzed by applying known principles of building physics such as thermodynamics and air-fluid dynamics (Table 01).

The optimum potential modifications to the building envelope were introduced to enhance the thermal and lighting performance of the building. The validated Design Builder model for the actual building was modified according to the newly suggested features.

Then the model was analyzed for indoor air temperature, fluid dynamics, daylighting, and energy consumption.

3. RESULTS AND ANALYSIS

3.1 Thermal Performance

The air temperatures of the selected case study building are shown in Fig 5. According to the temperature graphs, the ambient air temperature reaches its peak at 11.30 a.m., and the indoor air temperature reaches peaks after some hours from the ambient peak time, at 2.30 p.m. In other words, the indoor air temperature reaches its maximum 3 hours after the ambient reaches its maximum; this delay is called 'time lag'. Further, it shows an apparent reduction of 2.5 ^{0}C from the outside temperature. 'X' in the graph shows the temperature difference between nighttime ambient temperature and indoor temperature.

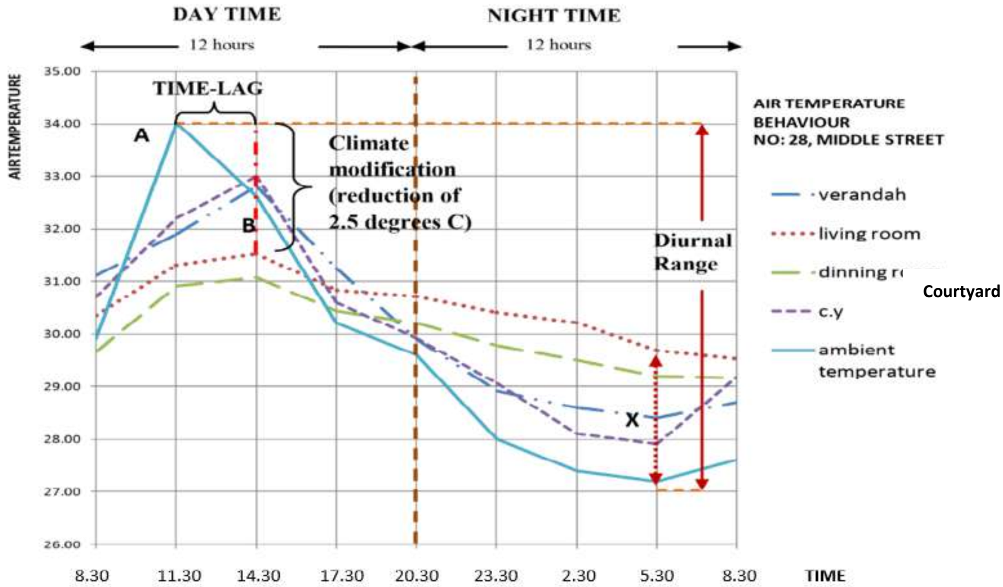

Fig. 5. Air temperature comparison of the building

When it comes to nighttime, the indoor temperature is higher than the ambient temperature. This phenomenon is because the walls are very thick, and they absorb much heat making the indoors cool in the daytime and release much heat at night. The advantage of cool night ventilation is not integrated to reduce indoor air temperature during the night. This is mainly because buildings are not designed for nocturnal ventilation, and thus internal thermal mass does not get sufficiently cooled.

In addition, there are no openings in the building section to remove hot air at night. Due to this stagnation, the indoor temperature at night is higher than the outdoor ambient temperature.

Further, the courtyard temperature is 1.6 ^{0}C higher than the living room temperature in the daytime. The courtyard has become another overheated element, and there is a potential for heat gain indoors from the courtyard. Although the courtyard becomes cool at nighttime, there is no opportunity provided by the building design to take that cool air inside, as all the openings are closed at night. Regarding the above scenario, attention was paid to introducing night ventilation to remove this stagnated heat within the house (Givoni, 2011).

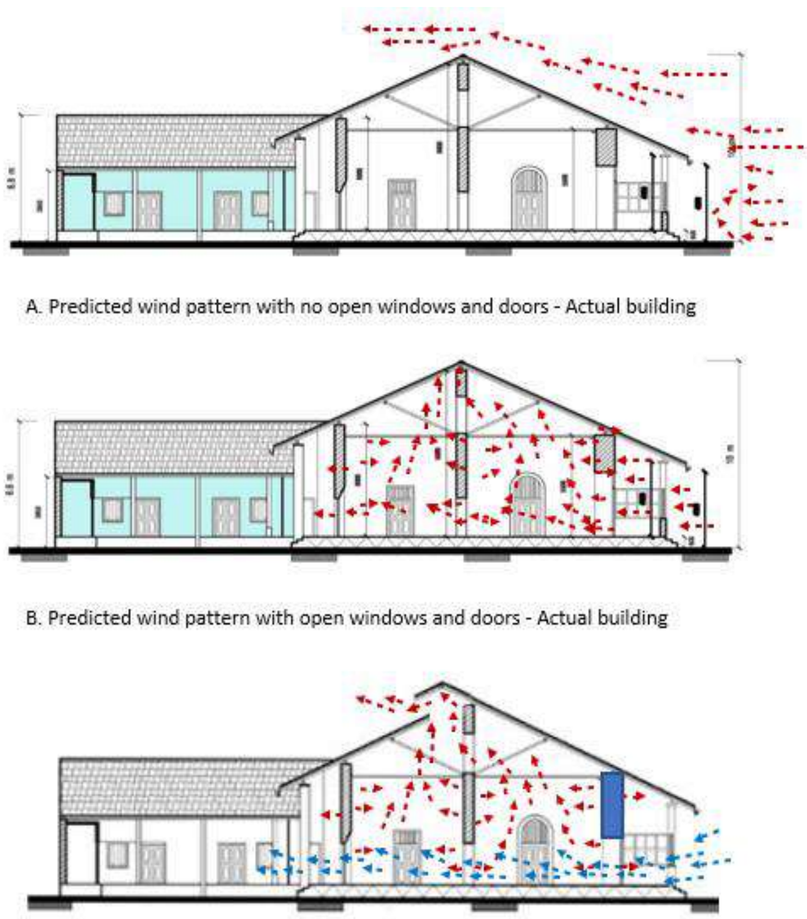

Fig. 6. Predicted wind patterns according to the air-fluid dynamic principles (stack effect and stack-induced ventilation)

The living room and the dining room have low-temperature values compared to the other two locations in the daytime. In the nighttime, these two locations show higher temperature values. This is because living and dining rooms are directly connected to the thicker walls and when it comes to the volume air, living and dining rooms have a higher volume than the verandah area.

For this, priority was given to passive strategies, and it was decided to promote ventilation within the building at night by considering established theories on airflow dynamics and thermodynamics (Fig.6). Scheduled openings were introduced at the bottom of the building to facilitate cool air inflow. Scheduled openings were introduced at the top of the building to facilitate hot air outflow (Toe and Kubota, 2015).

The calibrated Design Builder model was modified with an opening at the top and bottom levels (Fig 7). Further, Table 1 shows the changes introduced to the model and the purpose of the introduced changes. As shown in Fig 8, after promoting night ventilation, the simulation result shows a significant reduction in indoor air temperature from the air temperature in the actual situation during the night and even daytime.

A fluid dynamic analysis was done to identify the airflow pattern of the building, and it was similar to the prediction done at the beginning (Fig 9 and Fig 10). Then the original building was simulated with an HVAC system to get the same thermal comfort, and it gives 36.72 kWh/m^2 per annuum as required cooling energy.

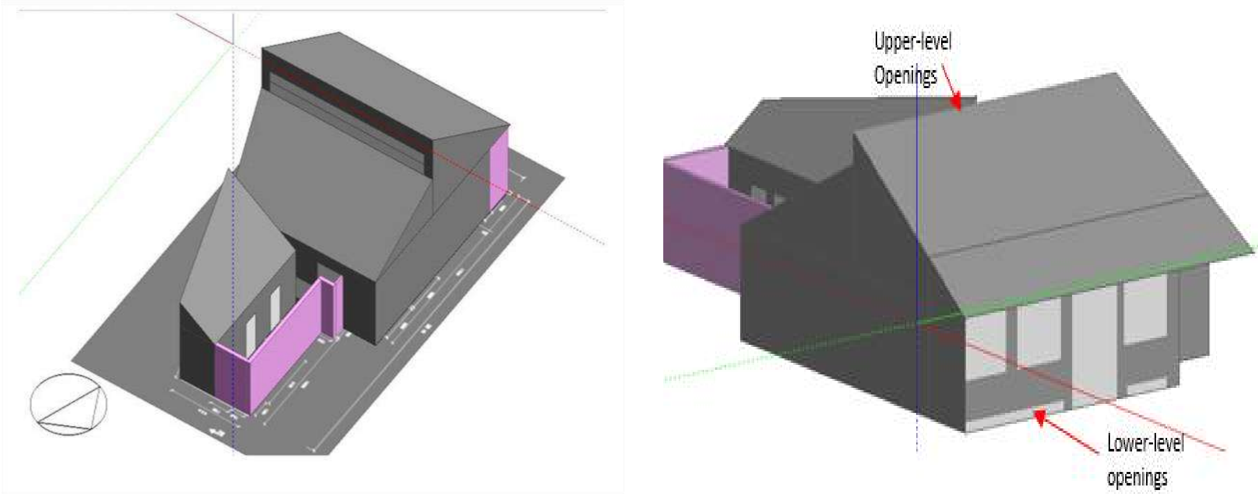

Fig. 7. DesignBuilder model of the modified building

3.2 Lighting Condition

Design Builder software model was analyzed for the daylighting condition of the actual building model (Fig 11 A). According to the model results from the illuminance level of the building, some parts of the building do not get lighting at all. It was very similar to the actual situation in the house.

Then the modified building was simulated for daylighting (Fig 11 B). According to the illuminance level, the lighting condition was improved; still, it needs further modifications. Hence it is planned to study further the modifications that can be adopted to enhance the lighting condition of the building. When it comes to energy consumption, the actual building needs 51.10 kWh/m^2 per annum, while the modified

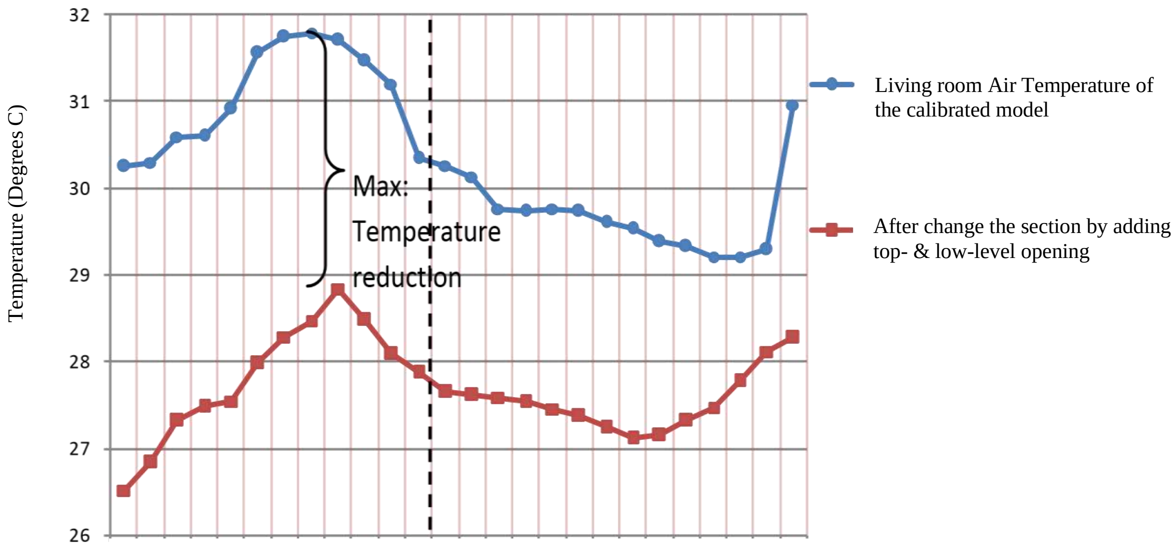

Fig. 8. Air temperature comparison of the actual building and the modified building

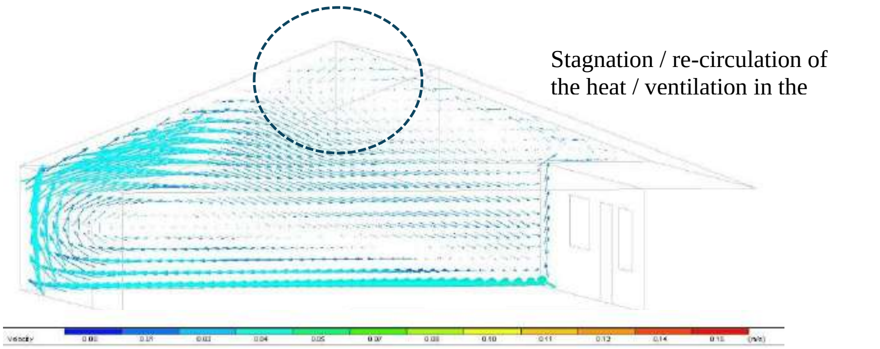

Fig. 9. Air flow pattern of the existing

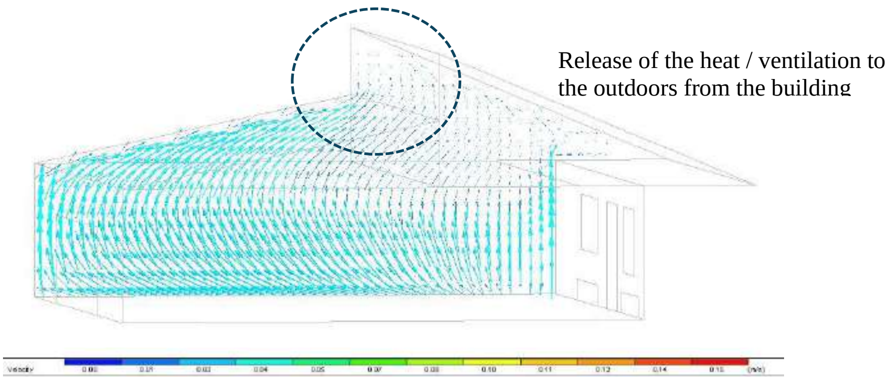

Fig. 10. Air flow pattern after modifying the building with upper and

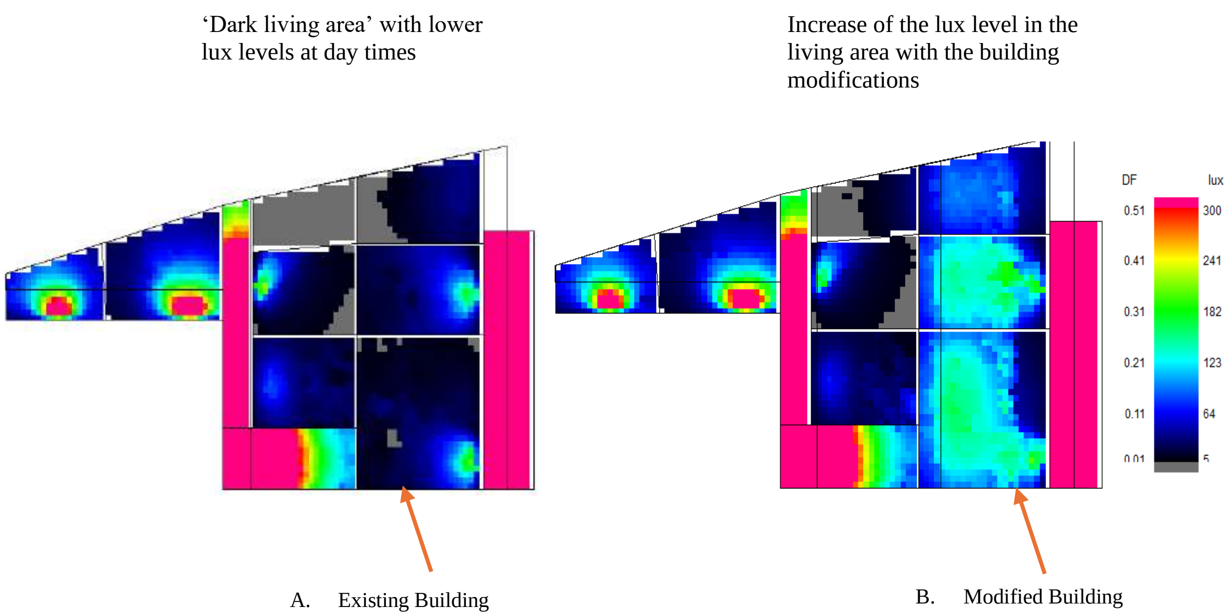

Fig 11. Daylight Conditions

building needs 44.84 kWh/m^2 per annum. In a previous study done by Rabani et al. 2021, the minimum energy requirement for achieving visual comfort was found as 55 kWh/m^2 per annum.

4. DISCUSSION

Vernacular Architecture is renowned for its passive design principles, yet the applicability of these concepts in modern contexts is a subject of debate. The changing climate, evolving built environments, and shifting building standards raise questions about the effectiveness of traditional passive design in present-day scenarios. This study aims to evaluate the thermal and visual comfort of old buildings, proposing design modifications for the building envelope while preserving their historical significance.

The architecture of the Galle Fort Dutch-era buildings blend elements of Sri Lankan vernacular architecture with authentic Dutch design (Rajapakse, 2011). This unique combination results in structures that incorporate features from both hot arid and warm, humid climate architectures. Notably, these buildings exhibit characteristics such as high thermal mass and narrow high courtyards typical of hot arid climates, alongside large openings and open courtyards aligned with the main wind axis for ventilation, common in warm, humid climates.

In the case study, the original building exhibited a 3-hour time lag and a 2.5°C reduction in indoor temperature compared to ambient conditions during the daytime. However, nighttime temperatures were higher indoors due to the building's thick walls and lack of proper night ventilation. To address these issues, scheduled openings were introduced at the base of the building to facilitate the entry of cool air along the wind flow direction. Additionally, upper-level openings were implemented to allow for the escape of hot air, aiding in passive ventilation.

Previous research has highlighted the benefits of using high thermal mass and natural ventilation (Pathirana et al., 2017; Rajapaksha, 2016). Thick earth walls, in particular, have been identified as effective thermal mass materials (Tharanga et al., 2011). Natural ventilation not only enhances indoor air quality but also contributes to passive cooling strategies (Pathirana et al., 2017).

To mitigate the stack effect, which leads to heated air rising and accumulating, openings were strategically positioned at upper levels to facilitate the removal of hot air. Lower-level openings were designed to introduce cool ventilation, creating a circulation pattern within the building. These strategies align with previous research on incorporating secondary wall systems with low-energy mechanical ventilation to further enhance passive cooling (Rajapaksha, 2016; Rajapaksha et al., 2022).

In the current scenario, building occupants resort to artificial lighting during the daytime for visual comfort, highlighting the need to explore the impact of proposed modifications on both thermal and visual comfort. Balancing these two factors can be challenging, as they often conflict (Rabani et al., 2021). However, the introduced interventions aimed to enhance visual comfort while reducing energy consumption for lighting has resulted in a decrease from 51.10 kWh/m^2 per annum to 44.84 kWh/m^2 per annum.

5. CONCLUSION AND RECOMMENDATIONS

In conclusion, the effective utilization of high thermal mass for passive climate modification in warm, humid climates necessitates a careful balance of ventilation strategies. While avoiding daytime ventilation, except through shaded and cooled areas, is advised to prevent the intrusion of polluted urban air and to ensure privacy, promoting night ventilation is crucial for leveraging the stack effect and maximizing the benefits of thermal mass. Independent use of thermal mass without adequate ventilation does not yield the desired results in these climates.

Moreover, the presence of courtyards in these buildings, often intended to enhance ventilation through an air funnel effect, has inadvertently led to inefficient heat transfer and diminished the efficacy of thermal mass. Therefore, a reevaluation of the courtyard design is recommended to prevent the air funnel effect and to optimize thermal comfort indoors.

Additionally, to reduce daytime energy usage for lighting and to enhance overall energy efficiency, the implementation of daylight harvesting systems is strongly encouraged in these buildings. Conducting thorough assessments of actual lighting conditions in vernacular architectural buildings is essential to identify existing issues and opportunities for improvement.

Looking forward, further research should focus on identifying and developing passive strategies that not only promote thermal comfort but also optimize daylight utilization. This includes investigating innovative building technologies and design approaches tailored to warm, humid climates. By implementing these recommendations and advancing research in passive design strategies, architects and engineers can contribute significantly to sustainable building practices that prioritize energy efficiency, thermal comfort, and indoor environmental quality in these challenging climates.

6. ACKNOWLEDGEMENT

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