A framework for AI-based building controls to adapt passive measures for optimum thermal comfort and energy efficiency in tropical climates

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Abstract. The potential for the contribution of the built environment towards sustainable development is recognized around the world. The need to achieve thermal comfort has proven to be the prime source of energy consumption in buildings, with mechanical ventilation and air-conditioning known to represent more than half of the energy bill. The effect of climate change has exacerbated the problem, leading to a vicious cycle of emitting more greenhouse gases in bringing comfortable indoor environments, while contributing further to climate change with warmer summers and colder winters. A very effective way to decouple economic growth and urbanization with increasing carbon footprint of our building stock is through the integration of passive measures, which hold huge potential for climate zones characterized as hot and warm. Moreover, the variability of climate means that permanent passive measures do not represent the optimum configuration for harnessing the natural resources in the form of daylight, natural ventilation and solar radiation, calling for building controls to regulate these passive elements. Furthermore, the need to set suitable control strategies for modulating these passive measures require a knowledge base to understand their influence on the indoor environment with respect to the external climatic conditions. The complexity of the interaction between the external and internal environments through the building envelope has led to renewed interest in adopting an AI approach to the problem. This paper presents a methodology developed to assess and quantify the efficacy of passive measures with associated controls for regulating specific parameters pertaining to the indoor environment, and presents simulation results for the automation of window shading with respect to indoor temperature and illumination level as an example of the proposed framework.

Keywords: Building Passive Design, Thermal comfort, Energy Efficiency, Built Environment, AI and Machine Learning

1 Introduction

1.1 Thermal comfort and energy efficiency in buildings in tropical climates

Green building rating systems like LEED [1] and BREEAM [2] lend high weightage to the energy and atmosphere category, such is the importance to curtail greenhouse gas emissions and mitigate the severe impacts of climate change. Poorly designed buildings, with little or no consideration of the operational conditions that will result when the building interact with the prevailing climatic conditions and its immediate environment have caused unnecessarily high energy performance and a large percentage of the building occupants being not satisfied with the indoor environmental quality, with cascading effects on worker productivity, absenteeism and worker dissatisfaction. Therefore there is every good reason to embark on a holistic thinking at the building concept stage, in what is typically referred to an integrated design approach, where issues can be identified early and possibilities for synergies between designs can be exploited.

In this exercise, passive solar design remains a vital technique to understand the influence of building layout on the subsequent indoor conditions, and in cases where the layout cannot be completely optimized, passive building elements can be considered to regulate the flow of heat and air to the interiors. Indeed, looking for opportunities to use the natural resources available at a project site, be it ground coolth, rainwater, solar radiation, daylight and wind regimes has been reported to yield as much as 80% reduction in energy usage and an important towards designing zero carbon buildings cost effectively.

1.2 Passive and hybrid measures

Passive measures relate to the integration of design elements in the building architecture to regulate heat gains. The heat regulation can be in terms of limiting heat gains for regions and/or periods of the year where there is a need for cooling as well as situations where heat gains are beneficial. Solely relying on building passive measures is not always possible throughout a whole year, needing active building systems. It then becomes important to modulate the operation of these building systems to keep the energy performance as low as possible while maintaining acceptable indoor conditions.

A lack of consideration for passive measures leads to over-reliance on active systems to the detriment of energy performance, and causing high electricity bills, evidenced by an increase in peak electrical demand over the peak summer months, which occurs in December, January and February in Mauritius. This places increased load on the grid, with a concomitant increased frequency in power cuts during the summer periods. Therefore there is a great need to first properly integrate passive design measures in buildings. Tinker and Ghisi (2004) [3] performed a study in Malaysia on a modern low-income house and a traditional Malay house by recording the thermal conditions, and found that the traditional Malay house has a better design and achieved better thermal comfort. Similarly traditional houses in Mauritius were known to be well-shaded, producing comfortable indoor conditions without active cooling systems.

The complexity in the building physics involved has led to the emergence of building simulation packages for predicting the expected performance of design concepts. Taleb (2014) [4] used the software package Designbuilder to perform an annual performance analysis of a villa in the United Arab Emirates, which has a hot and arid climate. The study consisted of assessing various passive design methods such as louver shading devices, double glazing, natural ventilation, green roofing, insulation and evaporative cooling. Lee and Won (2017) [5] modelled two existing buildings and performed numerical analysis to investigate the effect of using window panes of different optical and thermal properties using the eQuest software. Results showed that high visible light transmittance and low solar heat gain coefficient are desirable to minimize energy use in buildings.

The trade-off between daylight penetration and heat gains remains a challenging design task, which is controlled using the Window-to-Wall Ratio (WWR) ratio Alwetaishi (2019) [6] assessed thermal comfort by conducting experiments in schools in three cities of Saudi Arabia by studying the relationship between WWR and human comfort. Results showed that WWR can be maximized up to 0.1 in hot humid climate. Su and Zhang (2010) [7] revealed that the orientation most impacted by the WWR for the study region was the North followed by East and West. These results allowed the South orientation to have the largest WWR ratio with little increase in energy use.

For summer times, windows with lower SHGC are preferable as they allow less heat to enter. Therefore the measures taken for summer are counterproductive during winter times. Large seasonal differences in temperature may require flexible passive design measures, which can take the form of automated systems, as well as simple, manually operable systems. An optimum control of shading devices can limit the use of active energy systems relying purely on passive measures (shading) to control heat gains. This can be effectively implemented using digital control and sensing technologies.

Natural light is another natural resource which can be harnessed through proper passive design. It may consist of a combination of the following three components:

- Diffuse light from the sky dome
- Diffusely reflected light from the surroundings
- Direct sunlight

For regions with all-year round cooling requirements, direct sunlight must exclusively be prevented from penetrating the interior to cause excessive heat gains and glare using suitable external or internal shading devices. Since the daylight component carries little heating effect (around 1W per 100 lumen), it represents a fraction of the heat gains from artificial light fixtures. However, the significant variation in daylight levels over a given day due to the changes in the sky condition as well as the need for light outside sunshine hours mean artificial lighting is required, and a hybrid mode of combining both is needed for achieving adequate light levels in all circumstances.

Albayyaa et al. (2019) [8] studied two types of houses in Sydney, which has a climate profile requiring both heating in winter and cooling in summer and concluded that the integration of passive measures with a high thermal mass envelope produced 58% in energy consumption. Ouedraogo et al. (2012) [9] found that shading strategies was most effective for the region of Burkina Faso, a hot arid country in West Africa, with the simple use of curtains shown to achieve as much as 40% reduction in cooling loads. The part of any building most exposed to direct sunlight is the roof, especially if the roofs are flat (as is typical in Mauritius). Among the various methods available for roofs, the use of reflective and radiative roof strategies is a simple one (Al-Obaidi, 2014b), [10] but being a permanent passive measure, it is not amenable to modulation to regulate heat transfer. Shanshan et al. (2016) [11] showed that a cool roof in Singapore can repay back the investment in only 1.4 months.

To further improve the indoor conditions for occupants, renewal of the indoor air by natural or forced convection is beneficial, both for providing oxygen-rich air and to carry away heat, provided the air velocity remains within acceptable levels, typically less than 1 m/s. The use of stack and cross ventilation has been demonstrated by Hien et al., (2019) [12] in Singapore. The buoyancy effect can also be created in a double skin façade, also known as a ventilated cavity façade. Gooroochurn et al. (2019) [13] proposed a space saving ventilated façade using hollow cavity concrete blocks, where the internal wall surface temperature was found to be lower with the ventilated cavity, with as much as 6°C temperature difference recorded for the west-facing façade in late afternoon due to the settling sun known to cause significant heat gains.

Another on-site natural resource which can be used to promote good indoor thermal conditions is the earth's (almost infinite) thermal capacity. Several researches have been carried out to investigate the potential of ground-coupled heat exchanger systems [14, 15] (Singh, 2018; Vidhi, 2018). Gooroochurn et al. (2020) [16] carried out a preliminary investigation in the tropical context of Mauritius on a 6m buried PVC pipe at a depth of 1.5m, and obtained as much as 3°C drop in temperature, with simulated drop for a 50m pipe length at a depth of 3m reported at 8°C.

The contribution of tall trees and shrubs integrated in a building project is well-known, while promoting biodiversity and purifying air in the surrounding environment. Gómez-Muñoz, et al., (2010)[17] investigated the effect of shading of trees on walls in the city of La Paz in Mexico. They showed that suitable selection of plant species can stop the majority of heat falling on facades. Gooroochurn et al. (2021) [18] simulated the benefit of tall trees using a 3x3 space array in Designbuilder with plant parameters derived from Envi-MET. By rotating the model and varying the transmittance level of the trees, the study allowed to set guidelines for plant selection with respect to orientation of glazing.

Overall, the findings from literature show great potential in reimagining the spaces in the tropical context based on passive solar design which can go a long way to improving thermal comfort and energy efficiency. Furthermore, the complex phenomena involved is amenable to the application of AI and machine learning techniques, paralleling an Industry 4.0 paradigm. This would allow to understand the underlying phenomenon for the natural resource in question and to set control strategies for providing the needed adaptation of these passive measures in the wake of a fluctuating climate, both during a given season or as a result of seasonal changes.

2 Passive design measures for a tropical context

To understand the heat transfer dynamics for the predominantly concrete-based constructions in Mauritius, a 3x3 array of building spaces (see figure 1) was devised, which when rotated by a suitable increment through a full 360° degrees yield configurations which will be encountered in practice for actual building layouts. Through this building model, a baseline case with no passive measures was generated, which allowed to understand the beneficial contribution of the following measures:

- External shading devices
- Internal shading by using curtains
- Pitched roof
- Roof shading

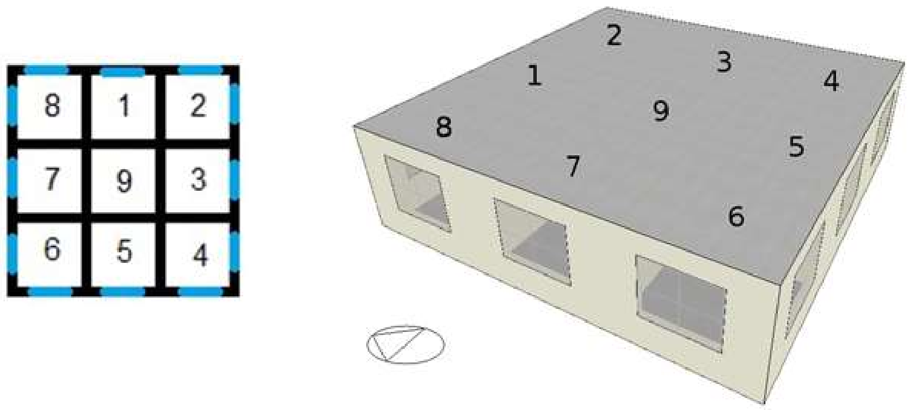

Figure 1: 3x3 space layout used to assess passive measures and controls

The findings of the simulation have confirmed the significant reduction in heat gains with passive measures sized and installed on specific building elements based on their orientations. The results of the simulation have been validated against in-situ experimental data collected for representative layouts in existing buildings. Moreover, dynamic simulations have shown the potential to achieve further improvements in the indoor conditions and energy performance of the building if the passive measures can be modulated to adapt to the prevailing climatic conditions given a specific state of the interior space. The next section describes the work being pursued in this respect for analyzing the automation of building systems, by first placing the work in the context of the literature and then proposing the framework being pursued using the 3x3 array of spaces described above.

3 Building controls to address the limitations of passive design

A variety of building control strategies can be adopted based on the type of building where it is being implemented. Alkhatib et al. (2021) [19] have reviewed different techniques used to control building facades and these have been summarized in Table 1. The complexity of the control systems increases from classical control to hybrid control. The latter combines an intelligent control with a classical or advance control. It can also be two or more intelligent control that have been merged. The increasing use of building controls integrated in new buildings or retrofitted in existing ones can be explained by the benefits provided. Passive design provides a static solution in a dynamic environment and is inherently limited in achieving the highest energy efficiency constantly. Moreover, at different time of the day or at different season, some passive measures can have adverse effect on thermal comfort. The addition of building controls can enable some of those passive measures to dynamically adapt to the prevailing conditions and make the optimal use of natural resources around the building.

Promoting natural ventilation in buildings is an effective way to reduce energy usage while maintaining thermal comfort. The use of ceiling or exhaust fans is a good alternative to air conditioning. In the case of Mauritius for example, natural ventilation from the South East can help with cooling. However, many buildings are unable to harness natural ventilation as they are constrained by their design and characteristics (Elahee 2014)[20]. Table 2 provides an indication of the benefits that daylight control and hybrid ventilation can bring to a building as reported by previous studies. The use of hybrid ventilation, as demonstrated by Meng et al. (2020)[21], is a useful way to reduce energy use for mechanical ventilation while enhancing the thermal environment inside the building by increasing the exhaust speed between 0 m/s to 0.6 m/s. In this case, one possible solution is to use the indoor temperature and the exhaust velocity as inputs in a PID controller to adjust the speed of the exhaust fan. Such a system could eventually be retrofitted in residential buildings, especially where natural ventilation is limited. However, Byon and Jeong (2020) [22]point out that developing countries in the tropics do not have cheap and useful retrofitting methods.

Table 1: Classification of different control techniques adapted from Alkhatib et al. (2021)[19]

Control Type	Technique	Brief Description
Classical	Rule-based	On/Off method to control process within an operating range.
	PID	Uses feedback from sensors to adjust the output. Tuning is required.
Model Free	Intelligent PID	Works like a traditional PID controller but without any model.
Intelligent	Neural Networks	Black-box models consisting of hidden layers that learn the relationship between inputs and outputs.
	Genetic Algorithm	Based on natural selection process where mutation, crossover and selection of the fittest occur. Also known as evolutionary algorithm.
	Fuzzy Logic	Similar to human reasoning where inference is made based on ”gray” information.
Advanced	Adaptive	Changes dynamically to meet the desired output.
	Optimal	Determines the best control by reaching the minimum or maximum of a function.
	Model Predictive	Predicts future conditions and take best course of action.
	Robust	A stable controller under any of its operating conditions.
	Feedback and Feedforward	A combination of both control techniques for better performance.
Hybrid	Advanced + Intelligent Classical + Intelligent Two or more Intelligent methods	

3.1 Machine Learning in Building Controls

It can be very complex to model the exact dynamics of a building which is often required when designing a control system. Approximate and simplified models can be used as substitutes and still provide a good performance. With the advent of increasingly powerful computer hardware the past few years, the use of machine learning in various fields keeps on rising and building control is no exception. Hong et al. (2020) [23] reported that 28% of their search results on the application of machine learning in buildings was related to control and they identified Model Predictive Control (MPC) and Reinforced Learning (RL) as two major approaches. Machine learning models like MPCs can also be approximated as demonstrated by Yang et al. (2021) [24] by using a recurrent neural network (RNN) with a Nonlinear AutoRegressive network with eXogenous inputs (NARX) as shown in Table 3. Additionally, Drgoňa et al. (2020) [25] worked on a unified MPC framework to provide stakeholders a common platform to work better together in order to design and implement MPC for building control.

Table 2: Reported energy saving various for daylight control and hybrid ventilation compared to no control

Application	Energy savings	Description	Reference
Daylight Control	Up to 48.5%	Manual switch On/Off with photosensors controlled dimming	de Rubeis et al. (2018)[26]
	18%	Photosensor centrally positioned (closed loop)	Delvaeye et al. (2016)[27]
	34%	One photosensor per luminaire (closed loop)	
	46%	Photosensor facing outward (open loop)	
	50 to 75%	Shading control with photosensors and dimmable lights	Shen and Tzempelikos (2017)[28]
Hybrid Ventilation	20%	Automated control using set points and sub-routines	Menassa et al. (2013)[29]
	5.3% to 11.7%	412 residential buildings with outdoor and indoor sensors and varying number of devices per room for with different kits	Mancini et al. (2019)[30]

Table 3: Result of implementation of MPC and approximate MPC

Algorithm	Energy savings	Description	Reference
MPC	58.5% (office) and 36.7% (lecture theatre)	The MPC developed is controlling the air-conditioning systems in two rooms.	Yang et al. (2020)[31]
Approximate MPC (NARX RNN)	51.6% (office) and 36.2% (lecture theatre).	The approximate the MPC is copying the behaviours of MPC proposed by Yang et al. (2020) and generates commands 100 times faster.	Yang et al. (2021)[2021]

3.2 Sensor and actuator considerations for building controls

Figure 2 shows the structure of the proposed system to allow collection of data on the specific natural resource in question, while offering the possibility to modulate the related building system to influence the indoor environment by adapting to the prevailing climatic condition with respect to the specific indoor conditions. The set points typically represent temperature, humidity, air quality and lighting requirements of users, defined in comfort zones that characterize the well-being of building occupants.

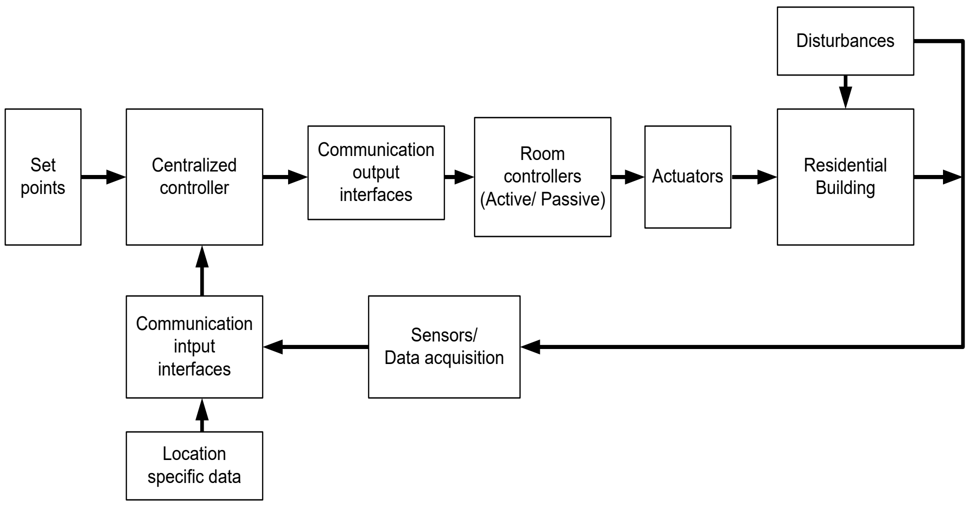

Figure 2: Structure of proposed system

For a building that is already equipped with natural heating, cooling, ventilation and lighting schemes, it is necessary to control these energy sources so as to contribute to user comfort. Because of the high variability in climatic conditions, the passive measures are complemented by active measures, where the main source of energy is derived from the electrical grid. Hence dedicated controllers for individual rooms have been grouped into two categories, namely 'active measure' and 'passive measure' types, respectively. Based on the reference inputs, sensor outputs and location data, the centralized controller dictates the amount of control effort required by the individual passive and active controllers. The aim is to operate within set points and predefined comfort zones, while maximizing energy efficiency and reliance on renewable energy sources wherever relevant. Table 4 lists typical schemes and actuators for each controller.

Table 4: Typical passive and active schemes, and associated controls

	Passive schemes	
Method	**Controllers**	**Actuators**
Cross ventilation by louvers and wind towers	Position controllers	Motor drives
Water-assisted roof cooling/ heating	Flow controller, Timers	Water pump, solar water heater
Daylight-assisted illumination	Position controller	Blinds actuator motors
	Active schemes	
Method	**Controllers**	**Actuators**
Air-conditioning and Indoor ventilation	HVAC controller, Switching devices and speed controllers	Air-conditioning units, Electric fans
Room heating	Temperature controllers	Heaters
Room illuminance	Electronic dimming controller	LED lamps
Indoor air quality	Switching devices and Timers	Air purifiers, extractor fans

Furthermore, a wide range of parameters, including disturbances, state variables, output variables and location-specific data should be processed by the centralized controller to achieve the control objectives. Consequently it is proposed to employ various sensors so as acquire information in real time, as shown in Table 5. The sensing requirements refer to acquisition of indoor, external and location data, depending on the parameter being controlled. Meteorological forecasts and topographic information can also be used by machine learning algorithms to improve the controller performance. Communication interfaces between sensors and the centralized controller are required to ensure reliable data transmission and storage. Similarly, it is proposed to use wireless links between the centralized controller and individual room controllers to minimize wiring requirements.

Table 5: Sensors/data acquisition requirements

Parameters controlled	Data acquisition devices
Thermal comfort	Indoor and outdoor temperature, Relative humidity, Air flow sensors
Light intensity	Illuminance, Room occupancy, PIR and Solar irradiance sensors.
Air quality	Air quality sensors (CO_2 concentration, particulate matter)
Electrical energy usage	Voltage and current sensors, Energy meters

4 Simulating shading control with respect to temperature and illumination level

To show the benefit of automating passive measures, the simulation model described earlier was configured to automate the shading control using the electrochromic shading option provided in Designbuilder software with respect to indoor air temperature and illumination level, where it becomes possible to assess the benefits in terms of improvement in thermal comfort and savings in lighting energy consumption. For the results presented next, the improvement in thermal comfort has been used, for which the cooling degree day (CDD) parameter, defined for hourly temperature values has been used. The cooling degree day is an effective parameter to summarize temperature dynamics over a certain period of time, typically over one year, which enables to capture the summer and winter seasons. The cooling degree day is calculated using a temperature reference value, which for the tropical climate of Mauritius has been chosen as 25°C. Therefore, any temperature less than or equal to 25°C does not contribute to the cooling degree day calculation and any hourly temperature exceeding 25°C contributes to a cumulated sum by that difference.

The simulation model with no shading or lighting control was used as the baseline case. The cooling degree days obtained for the nine rooms are shown in Figure 2 with an average of 4,952 cooling degree days. A switchable electrochromic absorptive 6mm window was selected as the window type and the available shading controls were tested. The shading control with an indoor temperature threshold of 25°C (equal to the reference used for the cooling degree day) yielded the cooling degree days illustrated in Figure 3, which represents a 12.6% reduction. It should be noted that fully shading the window permanently yielded a 15.6% reduction in cooling degree day, showing the potential to harness daylight while blocking unwanted solar gains by implementing suitable controls on the passive design measures.

The measure implemented in the simulation was an electrochromic shading mechanism, but in practice these can take the form of interior blind or curtain control or external fin angle control. The parameter that can be used to assess fully this multi-optimization problem can be the improvement in thermal comfort, e.g. through the cooling degree day in unconditioned spaces or the air-conditioning energy in conditioned spaces and the lighting energy to represent the harnessing of daylight to allow the reduction in use of artificial lighting.

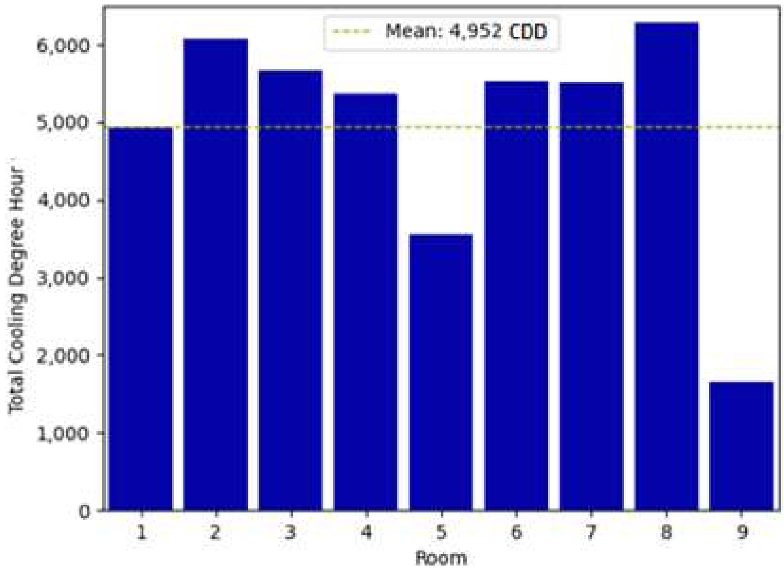

Figure 2: CDD25 for the baseline case with no shading control

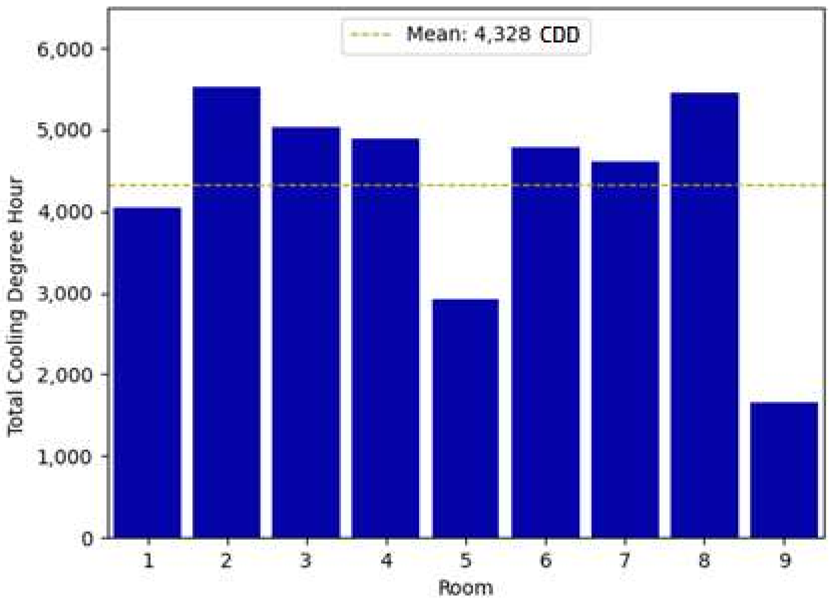

Figure 3: CDD25 for optimized passive design with inside air temperature as shading control

5 Discussion and Conclusion

Despite the useful features of machine learning, there are practical challenges that limit its adoption. Primarily, a large labelled data set is required to train and validate the model and may not be readily available. Secondly, a trained model for a particular building is not directly transferable for use in another one. Wang et al. (2021) [32] further explored the practical issues to apply machine learning in building control system and also how to address them. As more research is carried out in this area, novel techniques and solutions may be developed to enable the application of machine learning in building controls.

With the paradigm adopted in the research work, based on experimental data collected from the proposed system architecture and the simulation works using the 3x3 array of spaces, the data sets needed to create the knowledge base using an AI/machine learning approach becomes possible for a given climate context and building typology, since the heat transfer dynamics, air movement and daylight penetration are heavily affected by these design constraints. As for the assessment of the benefits of passive measures as fixed elements using the 3x3 array methodology, which allowed to quantify the relative importance of selected passive measures, the automation of these building elements to decide when they need to be deployed, and being able to quantify the achievable savings in energy and improvement in thermal comfort will be key as a next step to achieve optimum harnessing of natural resources. While passive measures hold the key to achieving sustainability in the built environment from an energy perspective to tackle the daunting challenge of climate change, the ability to modulate the underlying building systems will provide further flexibility to allow these systems to provide acceptable interior conditions more effectively, and hence provide greater acceptance of passive design as a sustainability measure in green building conception.

Through the simulation results generated for one scenario with shading control with respect to interior air temperature, it was shown how the control of shading can be applied to achieve comparable improvement in thermal comfort as for a fully-shaded window, while offering the possibility to harness daylight, which can be used to reduce the use of artificial lighting while bringing in other benefits such as more healthy and productive work spaces as has been validated by previous research works. Moreover, in line with the artificial intelligence framework proposed in this paper, the ability to predict the effect of the external climatic conditions on the indoor environment through the complex building physics involved can allow to more effectively modulate the passive measures, while capturing the customized phenomena involved. The underlying knowledge about the complex phenomena can be inferred by using data generated through a simulation or experimental approach, and put into practice using innovative technologies such as IoT sensing and actuators.

References

1. https://www.usgbc.org/leed
2. https://www.breeam.com/
3. Tinker and Ghisi. E. (2004). An evaluation of thermal comfort in typical modern low income housing in Malaysia. In Thermal Performance of Exterior Envelopes of Whole Buildings IX.
4. Taleb, H. (2014). Using passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings in U.A.E. buildings, Frontiers of Architectural Research 3, 154–165.
5. Lee, C. and Won, J. Analysis of combinations of glazing properties to improve economic efficiency of buildings, Journal of Cleaner Production, Volume 166, 2017, Pages 181-188, ISSN 0959-6526.
6. Alwetaishi, M. (2019). Impact of glazing to wall ratio in various climatic regions: A case study. Journal of King Saud University - Engineering Sciences, 31(1):6 18, ISSN 1018-3639.
7. Su, X. and Zhang, X. (2010). Environmental performance optimization of window-to-wall ratio for different window type in hot summer and cold winter zone in china based on lifecycle assessment, Energy and Buildings, 42(2):198-202, ISSN 0378-7788.
8. Albayyaa, H., Hagare, D. and S. Saha, S. (2019). Energy conservation in residential buildings by incorporating passive solar and energy efficiency design strategies and higher thermal mass. Energy and Buildings, 182:205-213, ISSN 0378-7788.
9. Ouedraogo, B., Levermore, G. and Parkinson, J. (2012). Future energy demand for public buildings in the context of climate change for Burkina Faso. Building and Environment, 49:270-282, ISSN 0360-1323.
10. Al-Obaidi, K. M., Ismail, M. and Rahman, A. M. A. (2014b). Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: A literature review. Frontiers of Architectural Research, 3(3):283-297, ISSN 2095-2635.
11. Shanshan, T., Zhang, Z. and Yu, H. (2016). Life cycle analysis of cool roof in tropical areas, Procedia Engineering, 169:392-399, ISSN 1877-7058.
12. Hien, W. N., Erna, T. and Sukma, A. A. (2019) Utilization of Natural Ventilation for Hot and Humid Singapore, pages 165-184. Springer Singapore, Singapore, ISBN 978-981-13-7519-4.
13. M. Gooroochurn, H. Shamachurn, B.Y.R Surnam and A. Cadersa, "Experimental and Simulation Analysis of the Performance of a Low Cost and Space Preserving Ventilated Façade for Hot and Humid Climates", The Fourth International Conference on Efficient Building Design (ASHRAE), November 2020, Beirut.
14. Singh, R., Sawhney, R., Lazarus, I. and Kishore, V. (2018). Recent advancements in earth air tunnel heat exchanger (eathe) system for indoor thermal comfort application: A review. Renewable and Sustainable Energy Reviews, 82:2162-2185, ISSN 1364-0321.
15. Vidhi, R. (2018). A review of underground soil and night sky as passive heat sink: Design configurations and models. Energies, 11(11).
16. Gooroochurn, M., Seegobin, B. and Jankee, L. (2020) A preliminary in-situ measurement and simulation of the performance of ground-coupled heat exchanger system in the tropical context of Mauritius, 8th Eur. Conf. Ren. Energy Sys. 24-25 August 2020, Istanbul, Turkey.
17. Gómez-Muñoz, V., Porta-Gándara, M. & Fernández, J., (2010). Effect of tree shades in urban planning in hot-arid climatic regions. Landscape and Urban Planning, 94(3-4), pp. 149-157.

18. Gooroochurn, M., Chooneea, M., Bhoodoo, D. (2021). Development of a Sustainability Matrix for Plant Selection & Analysis of the Use of Landscaping to Promote Energy Efficiency and Thermal Comfort in the Built Environment, 2nd International Conference on Recent Advances in Fluid and Thermal Sciences, iCRAFT2020, BITS Pilani Campus Dubai, UAE.
19. Alkhatib, H., Lemarchand, P., Norton, B., & O'Sullivan, D. (2021). Deployment and control of adaptive building facades for energy generation, thermal insulation, ventilation and daylighting: A review. Applied Thermal Engineering, 185, 116331.
20. Elahee, M. (2014). Energy management and air-conditioning in buildings in mauritius: Towards achieving sustainability in a small-island developing economy vulnerable to climate change [6th International Conference on Sustainability in Energy and Buildings, SEB-14]. Energy Procedia, 62, 629–638.
21. Meng, X., Wang, Y., Xing, X., & Xu, Y. (2020). Experimental study on the performance of hybrid buoyancy-driven natural ventilation with a mechanical exhaust system in an industrial building. Energy and Buildings, 208, 109674.
22. Byon, Y.-S., & Jeong, J.-W. (2020). Annual energy harvesting performance of a phase change material-integrated thermoelectric power generation block in building walls. Energy and Buildings, 228, 110470.
23. Hong, T., Wang, Z., Luo, X., & Zhang, W. (2020). State-of-the-art on research and applications of machine learning in the building life cycle. Energy and Buildings, 212, 109831.
24. Yang, S., Wan, M. P., Chen, W., Ng, B. F., & Dubey, S. (2021). Experiment study of machine-learning-based approximate model predictive control for energy-efficient building control. Applied Energy, 288, 116648.
25. Drgoňa, J., Arroyo, J., Cupeiro Figueroa, I., Blum, D., Arendt, K., Kim, D., Ollé, E. P., Oravec, J., Wetter, M., Vrabie, D. L., & Helsen, L. (2020). All you need to know about model predictive control for buildings. Annual Reviews in Control, 50, 190–232.
26. de Rubeis, T., Nardi, I., Muttillo, M., Ranieri, S., & Ambrosini, D. (2018). Room and window geometry influence for daylight harvesting maximization – effects on energy savings in an academic classroom [ATI 2018 - 73rd Conference of the Italian Thermal Machines Engineering Association]. Energy Procedia, 148, 1090–1097.
27. Delvaeye, R., Ryckaert, W., Stroobant, L., Hanselaer, P., Klein, R., & Breesch, H. (2016). Analysis of energy savings of three daylight control systems in a school building by means of monitoring. Energy and Buildings, 127, 969–979.
28. Shen, H., & Tzempelikos, A. (2017). Daylight-linked synchronized shading operation using simplified model-based control. Energy and Buildings, 145, 200–212.
29. Menassa, C. C., Taylor, N., & Nelson, J. (2013). A framework for automated control and commissioning of hybrid ventilation systems in complex buildings. Automation in Construction, 30, 94–103.
30. Mancini, F., Lo Basso, G., & de Santoli, L. (2019). Energy use in residential buildings: Impact of building automation control systems on energy performance and flexibility. Energies, 12(15).
31. Yang, S., Wan, M. P., Chen, W., Ng, B. F., & Dubey, S. (2020). Model predictive control with adaptive machine-learning-based model for building energy efficiency and comfort optimization. Applied Energy, 271, 115147.
32. Wang, Z., Liu, J., Zhang, Y., Yuan, H., Zhang, R., & Srinivasan, R. S. (2021). Practical issues in implementing machine-learning models for building energy efficiency: Moving beyond obstacles. Renewable and Sustainable Energy Reviews, 143, 110929.