Optimization of Building Façade for Passive Thermal Management: A Machine Learning Based Simulation Study for Kolkata, India

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ABSTRACT

With an ever-increasing population, there is a sharp increase in the demand for residential areas. This has resulted in high-rise residential towers with building façades having balconies that not only serve utilitarian and aesthetic purposes but also provide air circulation and ventilation. Hence balconies become an important passive component to control the heat gain by the building. This paper investigates the effect of the geometry of the balcony and the material used for construction on the heat gain by the internal space, optimizing the cooling load. This study gauges the effect of various designs of building façades in terms of balcony geometry and material using Energy Plus and MATLAB-based neural network modeling. We use a surrogate model to predict simulation results and run various material properties to find the optimum material properties and the geometry of the balcony. We assume the balcony area to be fixed and find an optimum design using surrogate modeling. The results of this research can significantly reduce the energy consumption of high-rise buildings by keeping them cool.

CCS CONCEPTS

• Computing methodologies ~ Modeling and simulation ~ Simulation support systems ~ Simulation tools

BuildSys '22, November 9–10, 2022, Boston, MA, USA

ACM ISBN 978-1-4503-9890-9/22/11...$15.00
https://doi.org/10.1145/3563357.3566139

KEYWORDS

Energy Efficiency, Building Façade Design, Simulation, Optimization, Machine Learning

ACM Reference format:

Souparna Chakraborty, Vinay Arya, Siva Shankar SS, Chirodeep Bakli. 2022. Optimization of Building Façade for Passive Thermal Management: A Machine Learning Based Simulation Study for Kolkata, India. In *The 9th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation (BuildSys '22), November 9–10, 2022 Boston, MA, USA.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3563357.3566139

1. INTRODUCTION

The global population and energy consumption are increasing very fast [1]. In the last 15 years, production wastes have been growing despite increasing efficiencies. Humanity now overspends its biological budget every year. The rate of consumption of natural resources is more than the rate of regeneration of the resources by the planet. Since the area of the earth is constant, the energy received from the sun, the primary source of energy, remains constant[2].

There is an overall energy consumption increase for a lifetime of over 50 years. The operating energy increases in due course of its lifetime and requires repair from time to time[3]. The building energy depends upon the location of the building, mostly the surrounding environment[4]. For a warm and humid climate, there will not be much temperature variation during day and night and during seasons [5]. Whereas for low humidity or dry places, the temperature differences are higher during various times of the day or seasons.

The primary objective of a green building is to reduce energy consumption, which may be achieved by using either active or passive means[6]. Active systems that need continuous human maintenance also need to be monitored daily [7]. For example, Greening the roof by plantation requires continuous watering, weed protection, manure, etc. These systems need separate energy to operate daily, but the energy saved by this system overcomes the energy used. The passive system does not need continuous monitoring; for example, the building envelope is designed during the construction phase itself and does not need any monitoring once the construction is over[8]. For futuristic high-rise buildings, we need passive systems with less maintenance cost. Balconies in high-rise buildings can be used as a passive mechanism to reduce energy consumption and enhance thermal comfort, and the same can be optimized by using tuning the geometry and material of these overhangs.

The design of balconies is imperative for high-rise residential buildings as they are the only source of natural ventilation [9]. Their presence can be a governing factor in the thermal comfort of the building. The addition of a balcony alters the pressure distribution of buildings. Indoor air distribution and room temperature can also change based on the size and geometry of balconies [10]. Previous research for balconies focuses on thermal comfort and case studies for various parameters like pressure on the buildings. Balconies create pressure fluctuations on the wall that protect the buildings against the wind [11]. Results show that the mass flow rate of air increases and velocity decreases in cases of single-sided ventilation. The suction in most areas of the building's surface subsequently yields the enrichment of air conditioning. Balconies also act as passive air conditioners in the building [12] and simulations show an annual electricity saving of 6.7% and 12.3% for the split-type air conditioner in the living rooms facing four orientations with a balcony. It helps natural ventilation by directing and allowing inflow. Proper geometry and orientation of the balcony can shadow solar radiation. A recent study focused on façade material for energy savings [13]. Using good thermal mass in the balcony, we can control the heat transfer due to its thermal bridge character. However, very little comprehensive research has been carried out on the combined effects of façade material and geometry on the passive cooling of the building.

Computer simulations are essential for understanding the wide variety of input parameters[14]. A large quantity of data is required to find the optimum geometric features or material properties. This will mean significant simulation times and computational costs. To circumvent the necessity of these simulations, we use a data-driven technique called surrogate modeling, which constructs a statistical model to predict simulation results based on the initial training dataset[15]. Later, we can use this model to generate large datasets for optimization, risk analysis, or cost reduction. Such models can be based on statistical tools or machine learning. However, in recent literature, there has been a sudden surge in machine learning-based models owing to their simplicity in execution and better prediction of simulation results [16].

2. PROPOSED METHODOLOGY

In this work, we aim to examine the effect of various geometries and materials used in balconies construction on the thermal effect on the room. We simulate a room with various polygonal balconies to train our machine-learning model. Our model takes important material properties like specific heat, thermal conductivity, and density of the construction material along with a number of sides of the polygonal geometry for the training. We use the same as a surrogate model for generating the data for various values of material properties in the range for determining the optimum material properties and geometry. The material properties we use are standard construction materials available. We expect our final optimum material to have properties obtainable by a composite of two or more input materials. We verify the output of our surrogate model by simulating the optimum parameters and obtaining the room temperature.

3. SIMULATION DETAILS

The geometry of the room is 16 ft × 20 ft., and the balcony of different geometry but the same surface area of 10 m^2 has been added to the study. The balcony as a façade overhang can be modeled as a polygon with the geometry altered by varying the number of sides of the polygon. The sides of the polygon are increased from 2 to 18 for our optimization. The balcony is positioned in the south face as sunlight comes from the south direction, and the wind is almost the highest all over the year.

The location for the simulation is chosen as Kolkata, India. The coordinates for the city are 22.57° N, and 88.36° E. The area of Kolkata city is 1886.7 km^2 and location is considered to be warm and humid type. Due to continuous urbanization, the city population is proliferating. The temperature varies from 15°C in Winter to 35°C in Summer (Dry Bulb Temperature). The temperature variation is presented in figure 1.

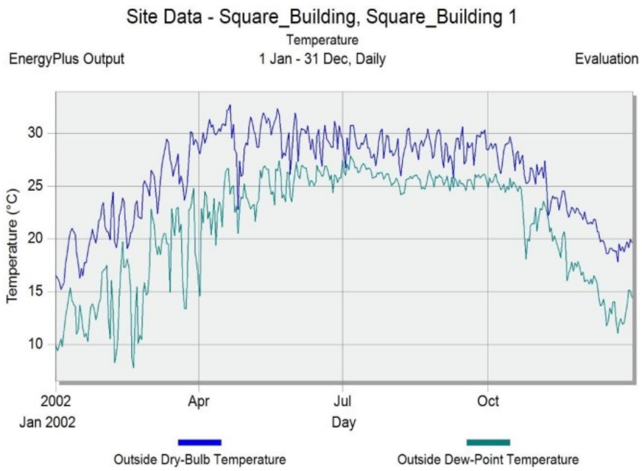

Figure 1 Ambient temperature at the location of the building (Kolkata). Both Dry bulb temperature and dew point temperatures are provided

Thus, the temperature variation is about 20°C in a year which causes a strain on the Heating Ventilation and Air Conditioning (HVAC) system, requiring a vast cooling system and minor heating system to maintain thermal comfort indoors.

The building geometries are drawn in Sketch up Pro 2021 and exported to Energy Plus 9.6 [17] for simulations. Energy Plus calculates the heat consumption of buildings by the heat balance method, which takes into account all balances on outdoor and indoor surfaces and transient heat conduction through building construction. The room and balcony are considered as separate zone. The internal Loads are minimized. No HVAC systems are considered for proper study of the thermodynamic profile of the building and balcony. Different balcony materials (as listed in Table 1) are considered in the simulations. We keep the thickness of the balcony wall constant (8 cm) for the simplicity of the problem. No insulation materials are used in the balcony. The room temperature is calculated from zone temperature.

The heat balance equation [18] for our simulations in Energy Plus is

$$C_z \frac{dT_z}{dt} = \sum_i^N Q_i + \sum_i^N h_i A_i (T_{SI} - T_Z) + \dot{Q}_{sys}$$

where $C_z \frac{dT_z}{dt}$ is the energy stored in the air inside any particular zone, $\sum_i^N Q_i$ is the sum of the convective heat load, $\sum_i^N h_i A_i (T_{SI} - T_Z)$ is the convective heat transfer from surfaces of various zones, and $\dot{Q}_{sys}$ is the air system output.

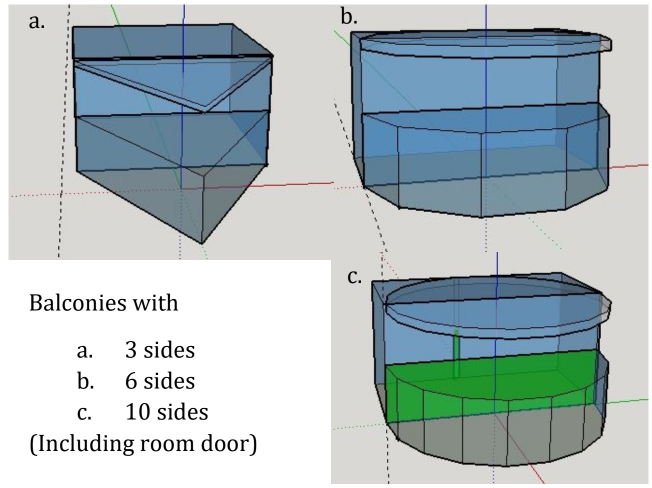

Figure 1 Different Geometries: We begin from a triangular balcony to circular as we keep increasing the number of sides of the polygon while maintaining the same area

We use the temperature at 2.00 PM on 21st May as it is expected that the interior of the building would have a maximum temperature around this time. The current location within the hot and humid zone receives considerable solar insolation during May, with a significant amount of direct/beam radiation. We use a range of building materials for the simulation as listed in table 1.

Table 1 List of different materials and their properties[17]

Sr. No.	Material Name	Thermal Conductivity (W/mK)	Density (kg/m³)	Specific Heat (J/kgK)
1	Clay Brick	0.21	700	1000
2	Fly ash Brick	0.9	1676	840
3	Tiles	0.06	368	590
4	Wood	0.15	608	1630
5	Glass	0.6	2700	883
6	Synthetic Fiber	0.15	1500	1700
7	PVC	0.2	1380	900
8	Aluminum	247	2700	900
9	Paint on Metal	0.57	1162	2835

3.1 Optimization Methodology

We utilize a machine-learning surrogate model to generate data based on the initial simulation results. We use MATLAB's inbuilt neural network code that will serve as our surrogate model. We use the material properties and number of polygon sides as the input to the neural network as depicted in Figure 4. We use two hidden layers for our model generation. Standard backpropagation is used to determine the training dataset's weights and biases.

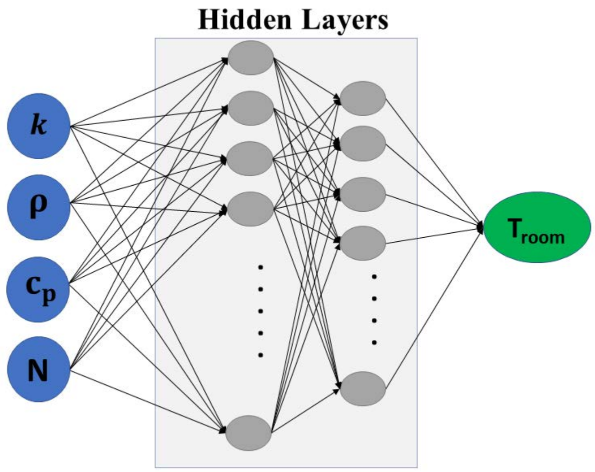

Figure 2 Neural Network Structure with four input neurons, two hidden layers and the room temperature as output neuron. Here k , ρ , c_p represent thermal conductivity, density, and specific heat of the material, respectively, and N is the number of sides of the polygon.

We take 100 input data values for training our model from the simulations and generate output data of 10200 values using the model.

4. RESULTS AND DISCUSSION

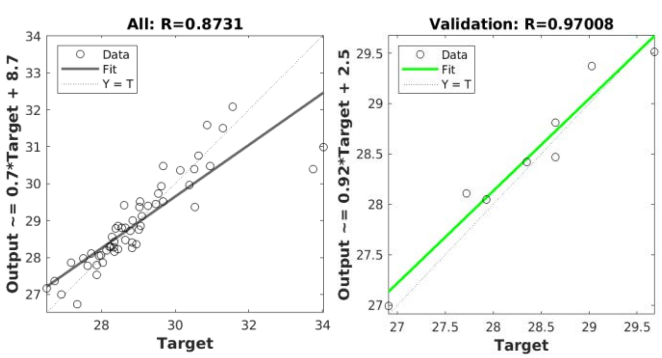

Figure 3 Prediction accuracy of our surrogate model based on the simulation data and the validation plot. Plots show predicted values on the vertical axis and simulation values on the horizontal axis **a)** All data values, **b)** validation dataset prediction. Values close to the straight solid line represent accurate predictions.

It is essential to plot the predicted values versus simulation results, as shown in figure 4, to quantify the model's predicting abilities. The dark line shows the output data, whereas actual data lie in $y = x$ straight line. The deviation of output values from this line represents the error. We observe Mean Square Error (MSE) of 0.0480 for the validation set. In figure 5, we can observe that our surrogate model performs quite well on original data for training, validation and testing. This means if we keep our range of data in a similar range, our obtained results will be very close to actual simulation results and we can use them for further analysis. Upon generation of large amounts of data from the surrogate model, a lot of useful information can be extracted.

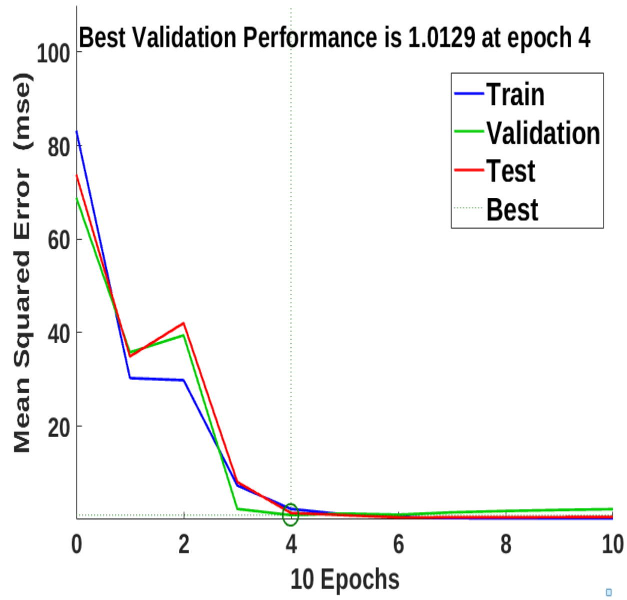

Figure 4 Loss Function Plot of Training the model

The simulation results provide a direction towards selecting of material and the number of sides of the balcony for the construction. As seen in figure 6, we can notice that a large number of sides can reduce the heat gain by the building. We can observe that fiber is the best material for three sides, changing to painted walls for four sides. This establishes that thermal gain by the room from the balcony is an interplay of geometry and building material. The effect noticed can be significant depending upon the size of the balcony. We notice temperature differences up to 5.2 ^{o}C in the simulation. This raises our curiosity if we can further improve this temperature difference by improving upon construction material and balcony geometry.

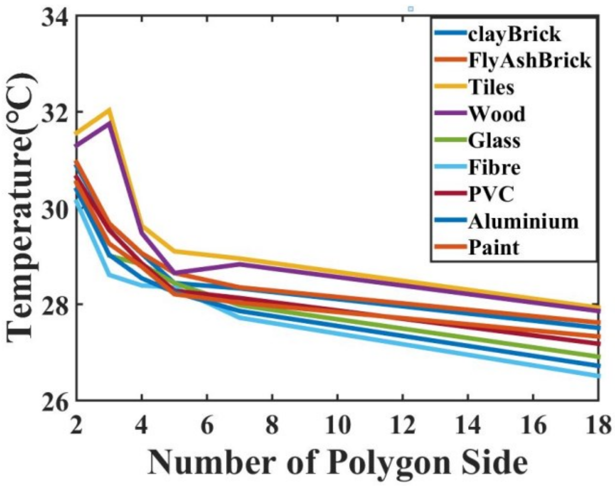

Figure 5 Simulation results showing a decrease in room temperature as we increase the number of sides in the balcony with different materials

The optimum values are obtained by searching the minimum room temperature from the large dataset generated by the surrogate model. We find that the room temperature decreases as we increase the number of sides in the balcony. The effect is so dominant that temperature differences are up to 5-6 ^{o}C. This will result in immense energy savings. Figure 7 shows, for fixed material properties, the effect of increasing the balcony sides up to 20. As we increase the number of sides of the balcony, the room temperature decreases first and then plateaus after 20. This is pretty evident from the surrogate model data. At this point, it practically leads to a circular shape of the geometry for the balcony size under consideration. Also, the room temperature remains the same even for a circular geometric configuration.

We report the optimum material properties in table 2. These material properties do not correspond to the simulations' input materials. However, these provide helpful direction for the material researchers to develop a material with these properties like composites, etc. Using these material properties and circular geometry for the simulation resulted in a room temperature of 25.8 ^{o}C, which is less than all the simulations.

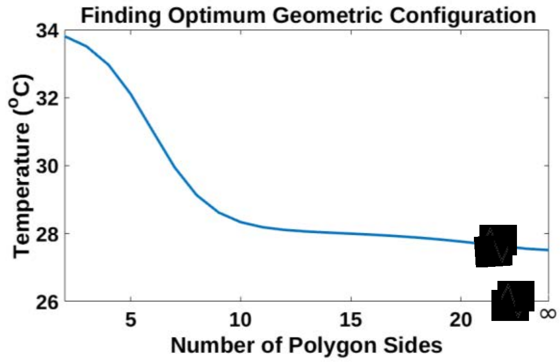

Figure 6 Optimum Geometric Configuration Obtained is with a maximum number of sides of polygon while keeping material fixed, i.e., Circular Balcony

Table 2 Optimum material properties

Thermal Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)
0.186	717.8	926.75

We observe that the best material for the balcony walls should consist of low thermal conductivity, low specific heat, and medium density. Such properties can result from a composite made of two or more materials considered in the study. Also, this provides new challenges for material scientists to develop new materials which give an optimum combination of these properties.

5. CONCLUSION

Intending to find the optimum geometry and best material for the balcony in residential buildings, we run simulations in Energy Plus software. However, considering the computational cost to obtain a full parametric optimization, we resort to Neural Network based surrogate model. We use the model to generate extensive data from all feasible material properties and geometric dimension combinations. We predict a circular-shaped balcony in conjugation with material properties in table 2 as best for minimizing heat input from the outer wall. Though convection to the room's outer wall from the sunspace is high, the heat transfer through conduction is lowest for the circular balcony due to its geometry. We find the optimum properties to be thermal conductivity of 0.186 W/mK, a material density of 717.8 kg/m^3, and specific heat of 926.75 J/kgK. These properties will result in the minimum room temperature. Thermal conductivity is an essential material property, as poor thermal conductivity leads to reduced heat transfer through the balcony. Density is a crucial factor for heat transfer as the dense material adds to the thermal mass of the balcony. However, high-density materials pose a different sort of challenge to the civil structure and material strength for balconies. The data-driven approach used here has proven beneficial for finding the optimum material properties and geometric configurations. Such methods will further prove to be helpful in designing new buildings and significantly impact reducing energy requirements. A simple extension of this study can consider the effect of the height of the balcony, orientation, and surroundings, generating a more robust and practical model.

ACKNOWLEDGMENTS

The authors acknowledge the Science and Engineering Research Board (SERB) of the Department of science and technology (DST), India for financial support vide reference no. IMP/2018/000216 under IMPRINT-II to carry out this work. The authors acknowledge the Apex Committee of SPARC, MHRD, New Delhi, India for financial support through the project Confinement-inducted Dynamics in Nanoscale Phase Transition (IDN_SKI) to carry out this work.

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