ENHANCING BUILDING ENERGY EFFICIENCY ESTIMATION BY INTEGRATING MICROCLIMATE CONDITIONS

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The building sector accounts for over a third of greenhouse gas emissions nationwide and 36% of energy consumption globally. Urban settlements alone are responsible for around 70% of carbon dioxide emissions. Building performance simulation tools (e.g., EnergyPlus) are frequently used to conduct energy calculations which use weather data (obtained from weather stations) as one of the boundary conditions. However, it is hypothesised that the energy calculations are more dependent on microclimatic conditions, leading to inaccuracy in energy estimations. Therefore, a new approach by integrating a microclimate tool (i.e., ENVI-MET) with a building performance simulation tool to enhance the accuracy of energy estimations is proposed in this study. A comparative analysis using computational tools was carried out for a real-scale typical UK residential settlement and it was observed that there is a distinctive difference (around 1°C) caused by the microclimate for both the summer as well as the winter period.

Keywords: building energy; CFD simulation; ENVI-MET; microclimate modelling

INTRODUCTION

With over 50% of the world's population, urban settlements consume between 60 and 80% of total energy consumption. It is responsible for up to 70% of carbon dioxide emissions (Un-habitat, 2016), becoming a significant contributor to climate deterioration. Climate change is causing an enormous risk to the environment and, subsequently, to the health of the population (Guțu *et al.,* 2021). Moreover, rapid urban development has caused a significant increase in urban air temperature (3-5 °C) as compared to adjacent rural areas, resulting in the urban heat island effect, which further contributes to the upsurge in energy consumption (Arshad *et al.,* 2021). All these factors further lead to an increase in human discomfort. To improve the thermal comfort level in a built environment while simultaneously reducing its share of carbon dioxide emissions, it is critical to first design the buildings efficiently, followed by operating them competently once they are built. Currently, designers use various extensively validated building performance simulation (BPS) tools (some examples are- EnergyPlus, eQuest, DesignBuilder, ESP-r, Indoor Climate and Energy, IES Virtual Environment, and TRANSYS) for the prediction of built environment behaviour in terms of energy consumption, emissions, and comfort level of occupants (Loonen *et al.,* 2017). These BPS tools also assist in accelerating and improving the

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design and planning process, optimising building performance, developing building controls, testing new products, and evaluating the market potential of novel concepts, along with enhancing operational performance (Magni *et al.,* 2021).

These computer-based BPS tools are frequently used to access energy-related credit points for various building rating systems, such as the United Kingdom's (UK) founded Building Research Establishment-Environmental Assessment Method (BREEAM) or the United States' (US) founded Leadership in Energy and Environmental Design (LEED) (Schwartz and Raslan, 2013). However, BPS tools require an enormous amount of data to predict the built environment's future behaviour. Occupancy load, occupancy schedule, lighting design, heating, ventilation, and air conditioning (HVAC) design, and lighting schedule are all essential data for BPS tools.

Weather data is also keyed in as one of the boundary conditions in any kind of dynamic simulation that is conducted to predict the energy consumption of a building. The EnergyPlus Weather (EPW) data format is the most used dataset for conducting building simulations (Shashwat *et al.,* 2022). Crawley *et al.,* (1999) first proposed the EPW data format for use in two major BPS tools, EnergyPlus and EPS-r. The EPW format has now become a standard format and is currently being used in over 20 BPS tools (Crawley *et al.,* 2015). Weather datasets are text based, comma-separated data files that contain hourly values for the parameters needed to run the energy simulations, such as dry bulb temperature, dew point temperature, relative humidity (RH), atmospheric pressure, wind direction and speed, global and diffuse horizontal radiation, direct normal radiation, total sky cover, and so on.

Weather stations, such as those in the WMO (World Meteorology Organisation) weather station network, provide the data for creating these standard climate files (Shi *et al.,* 2019). However, it is critical to recognise that buildings operate in distinct microclimate conditions that could differ noticeably from the specified typical weather dataset. Computational fluid dynamics (CFD) simulation is frequently used for analysing microclimate conditions. Therefore, this research aims at developing a new methodology that can enhance the accuracy of building energy estimation by integrating microclimate simulation using CFD tool (ENVI-MET) with building level simulation.

LITERATURE REVIEW

BPS tools can provide an accurate prediction of energy consumption along with maintaining an adequate comfort level for the occupants. Therefore, BPS tools are frequently used by designers and engineers to aid in the decision-making process during the development of building designs. However, it is often seen that the predicted energy performance of a building using BPS tools does not match the actual energy usage of the building, resulting in a performance gap (Hong *et al.,* 2018). According to Shi *et al.,* (2019) the major reasons for the performance gap are oversight of microclimate, occupant behaviour misjudgement, and discrepancies in construction from building design.

The microclimate has distinct environmental factors such as solar radiation, wind speed and direction, ambient air temperature, and many others which may vary drastically, even within a city. The distinct microclimatic conditions around the building are not included in the standard datasets (such as EPW files) as the building site may be located far away from the weather station data, which is commonly used for creating these standard datasets. There are studies which have considered the coupling method for building level and urban level modelling, highlighting the interdependency of building parameters and microclimate parameters (Yi and Peng, 2014, Bueno *et al.,* 2011). Bozonnet *et al.,* (2007) have computed that a difference of over 30% is observed in building energy consumption when outer conditions are considered for the calculation.

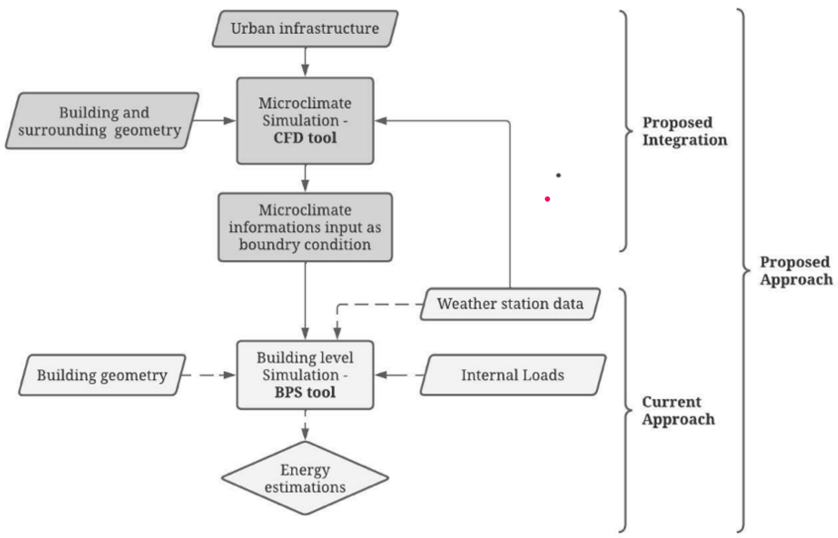
Also, one of the studies has concluded that including urban parameters to perform the coupling method of evaluation with energy modelling will have an advantage in improving the precision of building energy consumption data (Bouyer *et al.,* 2011). Therefore, it is important to investigate the impact of comprehending microclimatic conditions in building energy simulations for improved accuracy as related studies are lacking for the UK's climatic conditions. Existing BPS tools typically do not include the local microclimate while performing building level simulations due to the unavailability of local microclimate data. It is hypothesised that the integration of CFD (which estimates the microclimatic conditions) along with the existing BPS tools would enhance the accuracy of energy estimations.

METHOD

Proposed Approach

As compared to the current approach (Zingre *et al.,* 2015) of energy estimation, the proposed approach of this study consists of two distinctive successive stages (as can be observed in Figure 1). The first stage is to generate the local microclimatic data, which is then used as an input for the building level simulation. Observational methods have long been used for analysing local microclimates. However, with the significant advancement in computation capability in the recent past, digital tools such as CFD are now capable of performing microclimatic simulations (Blocken, 2015).

Figure 1: Proposed approach for enhancing the accuracy of building level energy estimations



The generated urban microclimate dataset (dry bulb temperature, in this study) can then be used (in place of the weather station dataset) in successive stages for conducting building level simulations using the BPS tool. Typically, a three-dimensional building model is developed in the EnergyPlus tool (or imported from a third-party visualisation tool) and weather data is inserted as one of the boundary conditions to conduct the building level simulation. A typical building level simulation needs various additional inputs for conducting the simulation. The first and foremost is the creation of the building geometry with all relevant physical parameters such as walls, roofs, and windows, along with their material specifications. Internal loads, which include occupancy load, lighting load, HVAC load, and their respective operational schedules, must be input into the model. The model is keyed in with the available weather data file which is nearest to the location of the building, and simulation is conducted. In the proposed approach, first a three-dimensional microclimate model is developed, focusing on the building of interest along with the other nearby building blocks.

The model is then populated with various available urban features, such as roads, pathways, and greenery. The model is keyed in with the weather data file and other necessary inputs. The microclimatic level simulation is conducted to generate local microclimatic conditions. This generated microclimatic data should be keyed in as a boundary condition in the EnergyPlus three-dimensional model where only the concerned building geometry is made. Multiple simulations are conducted to analyse the impact of local conditions on microclimate based on the weather data. The 3-D ENVI-MET model is shown in Figure 2, which consists of the residential buildings along with local infrastructure.

Development of ENVI-MET Model of a residential settlement
The proposed approach of this study (i.e., to integrate CFD simulations with building level simulations) was implemented on a real-scale residential settlement (as shown in Figure 2a) by developing an ENVI-MET model. This selected settlement (0.04 km2) represents homogeneous residential architecture across the UK. The settlement is arranged in six rows, with a few units aligned perpendicularly. The typical two-story residential houses are connected by asphalt roads and pavements.

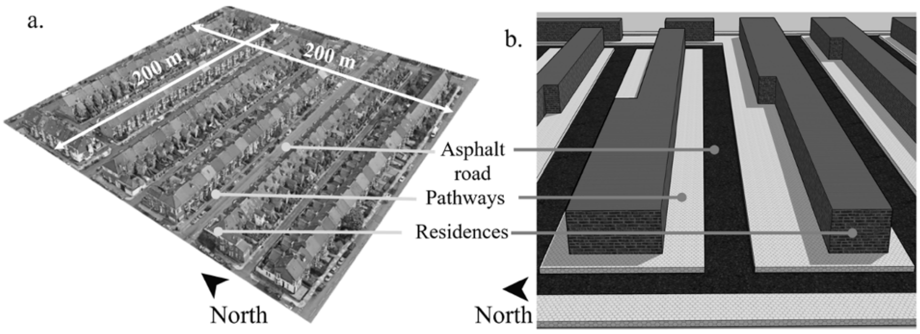


Figure 2: 3-D view of: a) a selected residential settlement in London; and b) birds eve view of the CFD-based model for the residential settlement

The model was further simplified and drawn with flat roof surfaces (as compared to existing sloped roof surfaces) since it will have a minimal impact on the pedestrian air temperature. Table 1 gives a detailed description of the input parameters for the model. The developed model was further simplified by removing the greenery, as this site has limited vegetation. Also, the windows were not modelled, as the small sizes of windows in residential buildings may not have a significant effect as compared to the considerable increase in computational time. The standard distance between the two opposite residential rows was modelled as 20m, and 8m of it was drawn as an asphalt road. The analysis was conducted on the central grid of the model, which lies between the two rows of residences 0.2m above the asphalt road. A sizable area was selected so that results are not influenced by other model elements. The model site was divided into 50 grids in both the X and Y directions, with two metre grids modelled along the Z-axis.

Table 1: Input parameters to ENVI-MET simulations

Parameters	Input Data and Boundary Condition
Site dimension	200 m x 200m
Model dimension	50 m in X-Y direction and 15m in Z-direction
Atmospheric boundary conditions	Meteorological data for wind speed & direction, air temperature, relative humidity, and solar radiation & cloud
Size of grid cell	4 m in X-Y direction and 2 m in Z-direction
Simulation Time-Step	1 Hour
Simulation Period	2 days - representative summer/winter days

Input parameters for ENVI-MET simulations

As shown in Figure 1, the ENVI-MET model requires several inputs such as weather data (shown in Figure 3), thermophysical properties of wall layers (Table 2), and surface radiation properties of model elements (Table 3).

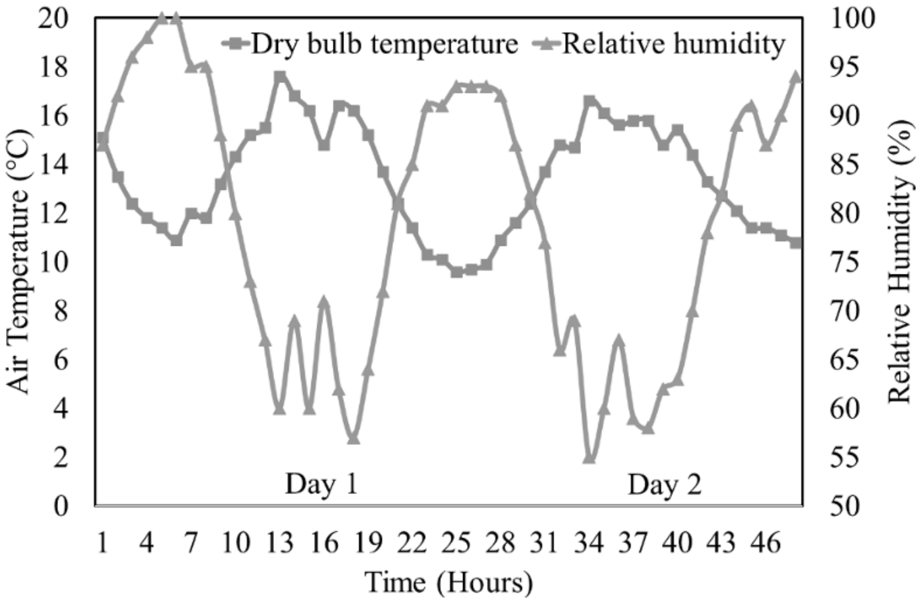


Figure 3: Dry bulb temperature and relative humidity for London, obtained from a typical meteorological year (EnergyPlus, 2022).

Weather data has a significant impact on energy estimates, which are primarily based on current or typical meteorological year weather conditions (Kikumoto *et al.,* 2015). Figs 3 and 4 illustrate the weather conditions for the days that were selected for simulation. Two consecutive days were selected for analysis so that the result reflects the validated trend, and any anomaly (in the case of single day selection) does not drastically influence the results.

The weather data (used in building level simulations) is commonly obtained from the nearest weather station, which is taken at approximately 15 m above ground surface level. The UK has a temperate climate with a mild-to-warm summer period and a cool winter period along with distributed high relative humidity (Ahmadian *et al.,* 2021).

Table 2: Thermophysical properties of wall layers

Layers (inside to outside)	Thermal conductivity (W/mK)	Density (kg/m3)	Specific heat capacity (J/ (kg K)	Reference(s)
Concrete	1.60	2400	850	Shafigh *et al.,* 2018
Polyurethane board	0.03	30	837	Asan *et al.,* 1998
Plaster	0.50	1300	1000	Asan *et al.,* 1998

Table 3: Surface radiation properties of various model elements

Elements	Solar Reflectance	Thermal Emittance	Reference(s)
Road	0.2	0.9	
Pavement	0.5	0.9	Santamouris, 2013
Wall / Roof	0.9	0.9	

The weather data used in this study is for London. The weather data set (refer Figure 3) shows that the daytime dry bulb temperature was relatively warmer with a high relative humidity, especially during the night-time. The solar radiation is also showing a regular pattern (shown in Figure 4) with a slight variation on the second day. Along with these, wind direction and speed were also forced into the simulation model.

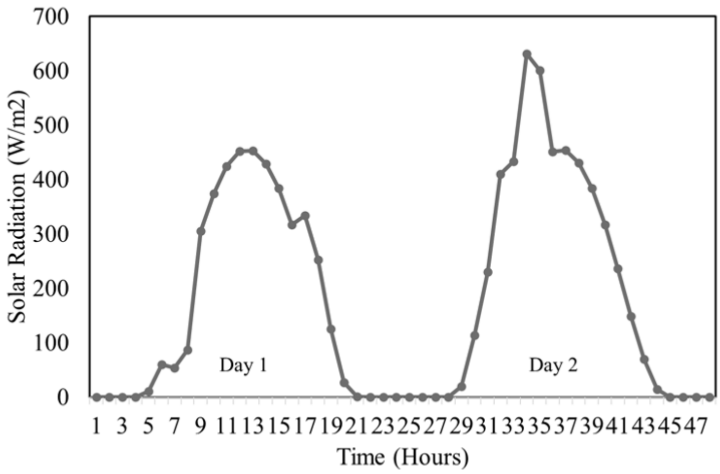


Figure 4: Solar radiation profile for London obtained from typical meteorological year (EnergyPlus, 2022).

FINDINGS

The developed ENVI-Met model (shown in Figure 2) was used to analyse the impact of the UK's local seasonal conditions on the microclimate of the selected buildings. The holistic impact was investigated over a typical 48 hours for the summer and winter periods, as well as the same was conducted for different weather conditions.

Comparison of proposed approach Vs current approach during the summer period

Figure 5 shows the comparison of the air temperature profile for two different approaches. It can be observed that there is a distinctive difference between the microclimatic data when compared to the weather data for the London summer period. For the duration of simulated days, a maximum difference of 2.30 °C is observed.

The effect is observed to be more prominent during the daytime as compared to the night. This could be potentially due to the lower outdoor temperature during the night, as can be observed from Figure 5. The overall average temperature difference (i.e., ΔT) between the simulated microclimate data and the weather data is 0.96 °C. The ΔT of 0.96 °C may appear insignificant, but a study has shown that a 1 °C temperature increase results in an 8% increase in cooling demand (Ortiz *et al.,* 2018).

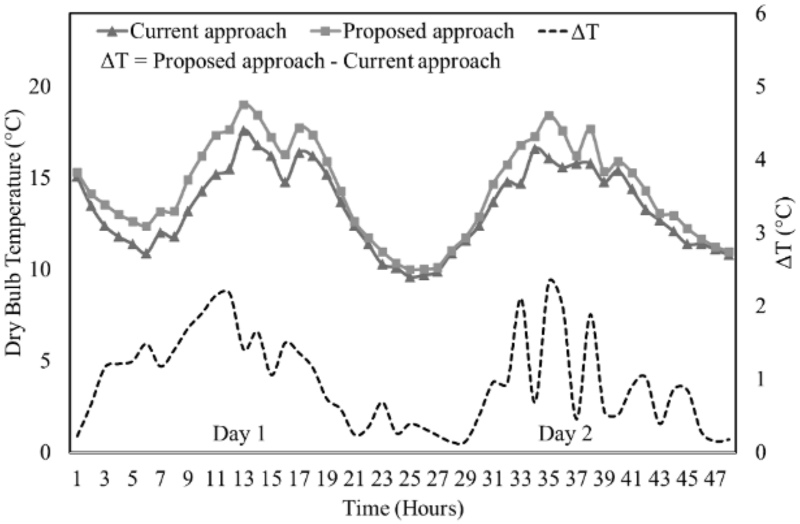


Figure 5: Comparison of estimated air temperature against Weather data for two representative summer days.

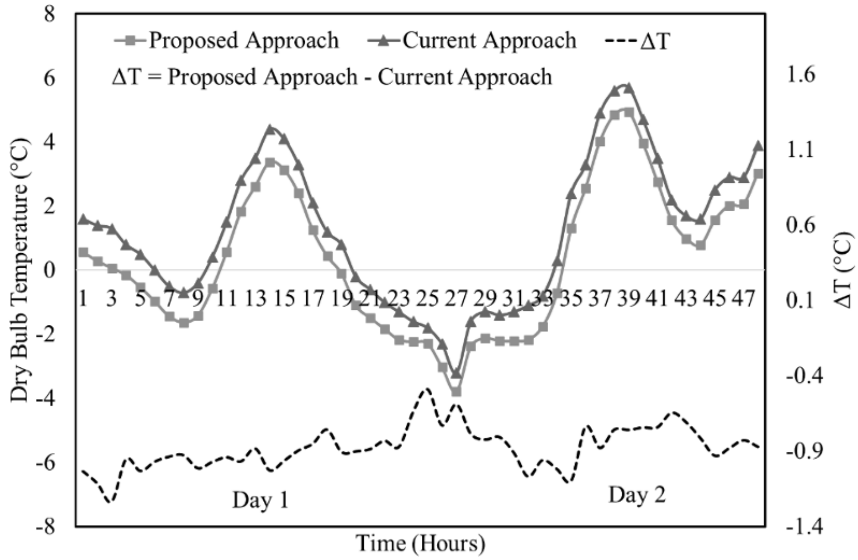


Figure 6: Comparison of estimated air temperature against Weather data for two representative winter days

The microclimate data results for the winter period (shown in Figure 6) also show a distinctive difference compared to the weather data. The absolute average difference for the winter period simulation is 0.88 °C. The maximum difference in air temperature is 1.23 °C. However, unlike the summer period where the weather data (current approach) was lower than the microclimate data (proposed approach), in the winter period the weather data shows a higher value than the microclimate data. The difference in air temperature between the two approaches is higher during the summer period as compared to the winter period. It can be interpreted that the higher the dry bulb temperature, the greater the difference. These results were further verified by conducting another set of simulations by comparing the impact of local conditions between two different weather data sets. A hot climate in Abu Dhabi (Alawadi *et al.,* 2021) was selected for the comparison of the proposed approach with London.

Comparison of proposed approach Vs current approach in different climate conditions

Weather data for Abu Dhabi (EnergyPlus, 2022) was used in the same residential model and a CFD simulation was conducted. The temperature difference between the two approaches for Abu Dhabi is plotted along with that of London's, which is illustrated in Figure 7. As expected, the higher the recorded dry bulb temperature in the weather data, the higher the difference between the two approaches. The average ΔT for Abu Dhabi is 1.17 °C which is higher than the average ΔT for London, which was 0.96 °C. Furthermore, the maximum T for Abu Dhabi is 3.60 °C, which is significantly higher than the 2.30 °C recorded for London. These results show a noticeable difference in the two approaches, and many conclusions can be drawn.

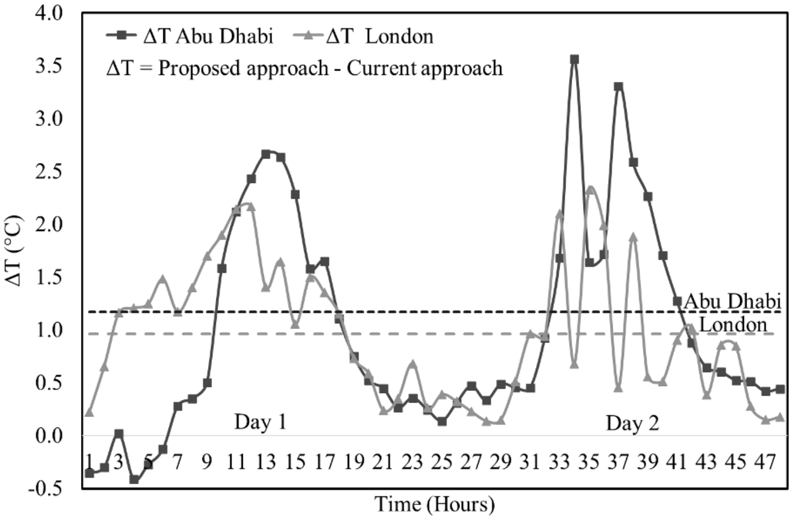


Figure 7: Comparison of ΔT for two different climate conditions - London Vs Abu Dhabi.

CONCLUSION

The proposed approach integrates CFD simulations (using ENVI-MET) with building-level energy performance tools in order to enhance the accuracy of energy estimations. The proposed approach was implemented by developing an ENVI-MET model of a real-scale (0.04 km2) residential settlement in London. The ENVI-MET model was divided into 50 grids in both X-Y directions, whereas the results were obtained at a grid height of 0.2m along the Z-direction. It was observed that there is a distinctive difference between the current approach (weather station data), which is commonly used for energy simulation, and the proposed approach (microclimate data). The difference is visible in both seasons, that is, summer as well as winter climate conditions. In summer, an average temperature difference between the proposed and current approach (i.e., ΔT) of 0.96 °C is observed, whereas in winter, an absolute ΔT of 0.88 °C is observed. For the given model, the variation of weather data and microclimate data is nearly 1°C. Furthermore, simulations were performed for the climate of Abu Dhabi and compared with those of London. It can be concluded from the results that there is a noticeable difference in both the simulated weather conditions performed in this study. In the climate of Abu Dhabi, the ΔT (i.e., 1.17 °C) is higher compared to the temperate climate of London.

Therefore, it is important in the building sector that the impact of microclimate is considered during energy estimations because, based on these estimations (energy modelling output), the building design, selection of construction materials, and selection of active systems (chiller capacity and fan size) and passive systems (U-value of wall/roof) are conducted. The improved energy usage prediction will give engineers and architects the liberty to make an informed decision during the design or retrofitting phase. Exclusion of microclimate consideration may also impact building construction budgets, comfort levels, whole life analysis, and eventually operation and maintenance. The improved accuracy in energy estimation will eventually lead to improved management and easier maintenance of buildings, eventually leading to a reduction in operational costs.

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