Impact of the courtyard on the energy performance of conditioned office buildings in Dhaka, Bangladesh

Urmi Sarkar[1] and Avlokita Agrawal[2]

[1, 2] Indian Institute of Technology Roorkee, Uttarakhand, India
{u_sarkar[1], avlokita[2] }@ar.iitr.ac.in

Abstract: The challenge for building design is to maintain comfort inside while the weather outside changes unexpectedly. Therefore, air conditioning (AC) has become an essential component in office buildings as it provides a comfortable indoor environment while also being the primary source of energy consumption growth. Recent studies have emphasized the application of courtyard as a passive design strategy to reduce building energy use in tropical climates, particularly for cooling demand. Unconditioned buildings usually have a positive impact on courtyard design. This study investigates the effectiveness of courtyard design for a fully air-conditioned and mixed-mode naturally ventilated office building in the tropical context of Dhaka, Bangladesh. A typical office building model was developed using Design Builder software, according to the ASHRAE 90.1 standard. Both scenarios fully air-conditioned building and change over mixed-mode control ventilation (same space in different times) were compared in terms of total end-use to observe how the courtyard affected total energy performance. The courtyard was combined with several passive envelope design strategies, including insulation in the wall and roof, shading on the roof, self-shading over the wall, cavity wall, jaali (lattice) walls, and low-E glass. According to the simulation results, a single courtyard design might not be efficient, but a courtyard that integrates different passive design strategies will be efficient in fully air-conditioned and mixed-mode control buildings in Bangladesh's tropical environment.

Keywords: Humid-tropical climate; courtyard; air conditioned-mixed mode control; energy-efficient building.

1. Introduction

The world of sustainable development is facing an increasing number of obstacles, notably in the sector of building energy efficiency, as environmental and energy constraints become more prevalent(He et al., 2022). Globalization, changing living standards and lifestyles, and growing urbanization substantially increase energy demand (Rahman, 2018). Concern for sustainability has always stemmed from the energy challenges and greenhouse gas emissions caused by the use of active ventilation methods(G C Alozie, 2020). The rise in global temperature has increased the use of air conditioners in workplaces to promote

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comfort and productivity. Air conditioners consume more energy and have a detrimental environmental impact (Aldawoud, 2008).

The preceding issue sparked a desire for passive energy methods for altering the indoor environment. Besides, in the quest for building sustainability and reduced building energy consumption, conditioned buildings have called for alternative means for cooling buildings. However, due to diverse reasons, constructions are now moving toward mixed-mode buildings, using a hybrid method of space conditioning that blends operable windows with mechanical cooling (Ibiyeye et al., 2015). Well-designed mixed-mode buildings can be more comfortable and consume less energy by taking advantage of the strengths of both systems.

Moreover, it is fundamental for the construction industry to place a greater emphasis on energy efficiency by integrating passive solutions from traditional architecture while managing indoor thermal comfort (Tabadkani et al., 2022). The courtyard has proven to improve the thermal comfort of both outdoor and indoor spaces by altering the microclimate in naturally ventilated buildings(G C Alozie, 2020). The incorporation of courtyards into buildings can make a significant contribution to the creation of passive buildings with high energy efficiency (George Chinedu Alozie, 2020).

The integrated design of a building combines envelope design techniques to enhance passive cooling for maximum comfort and energy efficiency. Envelope is an integral part of any building because it protects the structure's inhabitants and has a significant impact on controlling the internal climate. The study includes envelope design strategies as a major passive design component along with courtyard. Bangladesh is a tropical region where the building envelope contributes significantly to solar heat absorption(Rana et al., 2020).

In this study, the effectiveness of courtyard design for a completely air-conditioned and mixed-mode building along with combinations of passive envelope design strategies such as insulation in wall and roof, shade on roof, self-shading wall, jaali wall, cavity wall, and the low-E glass window were investigated for an office building in a tropical context of Dhaka, Bangladesh.

2. Methodology

A two-storied office (Sonali Bank) building has been chosen by a survey-based study which is in Dhaka, Bangladesh. The data on energy consumption in numbers of electricity bills and other required information were gathered. Using the 'DesignBuilder' (version 6.1.0.001) interface on a hypothetical example model with different design parameters, the annual energy consumption was determined. The 'DesignBuilder' is one of the most comprehensive user interfaces for EnergyPlus dynamic thermal simulation engine (Aranda et al., 2017)(Arima et al., 2017). Dhaka has tropical savanna climate according to Koppen’s climate classification which lies in climate zone 1A (ASHRAE, 2020) with the distinct features of a hot, wet and humid tropical monsoon climate. The weather data from Dhaka was used in the modeling process to assess the energy load and specify the activities and construction, opening and HVAC sections.

After performing a simulation of As-is case and its validation, Base case according to ASHRAE 90.1 office standards(S I Rae et al.,2016) has been developed and the courtyard was modified in the layout of base case by running simulation for the both air-conditioned and mixed-mode case. The courtyard case was combined with different passive envelop design features by developing twenty-one ECMs (Energy Conservation Modules) and with forty-two annual simulations in ‘Designbuilder’ to see the impact of courtyard on energy performance with or without these design features. An excel file with the results was organized and utilized for analysis thereafter.

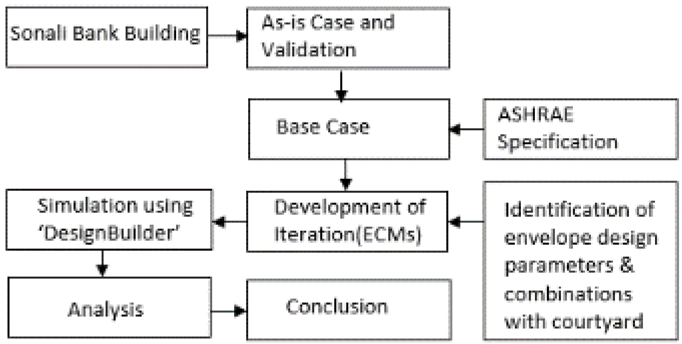

Figure 52: Methodology Diagram

3. As-is case development and validation

The Sonali Bank building is in Kurmitola Cantonment, Dhaka, Bangladesh (23.8103° N, 90.4125° E). It has two floors. The office building model has been established with a total floor area of 1283 m^2. Because the conditioned and unconditioned zones are distinct, the building was divided into major zones and the floor layout for energy simulation. Figure 2 represents different zones of the building.

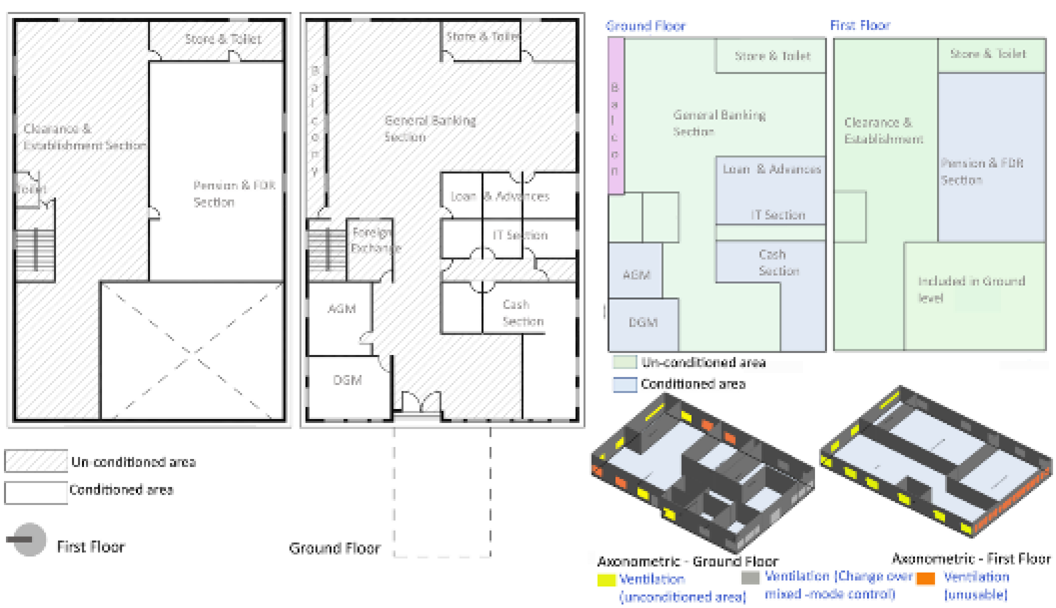

Figure 53: Floor Plans of Sonali Bank Building(left) & layout of plan defined by zone for Design Builder Simulation (right)

'DesignBuilder' configuration template instructs the simulation standard and reference to be straightforward for modelling and altering. Weather data, activity, occupancy, material standards, HVAC and lighting systems were modelled with the building's current state of the situation. According to Dhaka's climate and for work hours as per ASHRAE 90.1 (ASHRAE, 2007) the cooling set back and the heating set back was utilized. Since no natural ventilation was utilized, the conditioned area is assumed to be fully air-conditioned for the purposes of running the As-Is case simulation with a total of 8760 hours.

Table 27: Input for As-is-Case

Features of the Building	Description	Features of the Building	Description
Site:			
Location	Dhaka, Bangladesh	Total building area	1283 m^2
Weather file	BGD_DHAKA_TEJGAON_SWERA	Floor height	5.3 m Ground Floor,3.5 First Floor
Site orientation	90^0		
Activity:			
Occupancy	18.58(sq. m/person)	Computer power density	5 w/m2
Occupancy schedule	9.30 AM-6.0 PM, Sun-Th	Office equipment density	3 w/m2
Construction:			
External wall U-value	1.87 W/m2-k	External floor U-value	0.259 W/m2-k
Roof U-Value	3.954 W/m2-k	Infiltration Flow Rate	0.3 ac/h
Opening:			
U-Value	.778 W/m2-k	Window-wall ratio	30
SHGC	0.8	Shading	0.5m overhang,1^{st} floor
Vt	0.7		
Lighting:			
Lighting power density	7.0 w/m2	Lighting control	No
HVAC:			
System	Split No Fresh Air	Cooling set back temp.	32
Heating set back temp.	13	Cooling system seasonal CoP	3.5
Total energy consumption	120,683 kwh		

As shown in Figure 3, the actual building consumed 80,000 kWh of electricity annually (Source: Principal officer, Sonali Bank). However, the actual building's fully conditioned scenario consumed 120,683 kWh annually.

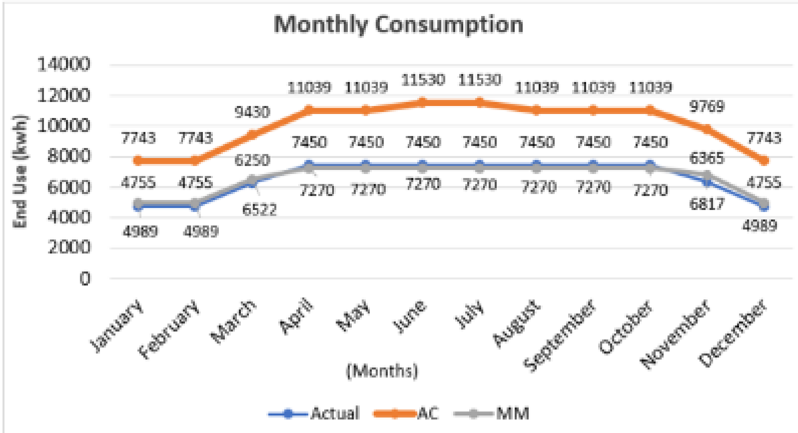

Figure 54: Monthly consumption of actual, AC & MM case

For the validation of As-is case, the model was revised by rearranging the layout into multiple zones to control the HVAC and natural ventilation. All the parameters were kept the same except HVAC. Natural ventilation Mixed-Mode (MM) control was used to see if the results matched the actual consumption to validate the office building model. The yearly consumption of total energy usage of the actual case is 80,000 kwh, which is close to the annual consumption of the As-is case (Mixed-Mode=MM) running control 79,197 kwh. Here the As-is model is validated.

4. Base case development

The As-is case model was modified according to the ASHRAE 90.1(S I Rae et al.,2016) building design energy standard and Dhaka's climate zone 1A categorization to develop the Base Case. By keeping all parameters, same as, As-is case model, only construction, opening and lighting specification were changed for the base case run of the simulation. Two simulations of the ASHRAE base case were performed using the fully conditioned scenario and mixed-mode control. The following Table 2 include the specification between the as-is case and base case models:

Table 28: Specification for ASHRAE As-is Case and Base case

As -is Case		**Base Case**	
Construction:		**Construction:**	
External wall U-value	1.87 W/m2-k	External wall U-value	2.071 W/m2-k
Roof U-Value	3.954 W/m2-k	Roof U-Value	1.540 W/m2-k
External floor U-value	0.259 W/m2-k	External floor U-value	0.259 W/m2-k
Infiltration Flow Rate	0.3 ac/h	Infiltration Flow Rate	0.3 ac/h
Opening:		**Opening:**	
U-Value	5.778 W/m2-k	U-Value	2.70 W/m2-k
SHGC	0.8	SHGC	0.4

As -is Case		Base Case	
Vt	0.7	Vt	0.56
Window-wall ratio	30	Window-wall ratio	40
Shading, Overhang	On 1st floor,0.5m	Shading, Overhang	No
Lighting:		**Lighting:**	
Lighting power density	7.0 w/m2	Lighting power density	10.5 w/m2
Lighting control	No	Lighting control	No
HVAC:		**HVAC:**	
System	Split No Fresh Air	System	Split No Fresh Air
Heating set back temp.	13	Heating set back temp.	13
Cooling set back temp.	32	Cooling set back temp.	32
Cooling system seasonal CoP	3.5	Cooling system seasonal CoP	3.5
Mixed mode:		**Mixed mode:**	
Natural Ventilation	On	Natural Ventilation	On
Control mode schedule control	Mixed-mode temp.	Control mode schedule control	Mixed-mode temp.
Min. outdoor ventilation air schedule	Always 1ac/h	Min. outdoor ventilation air schedule	Always 1ac/h
Airflow control type schedule	Always 0	Airflow control type schedule	Always 0
Total consumption (AC)	120,683 kwh	**Total consumption (AC)**	119883 kwh
Total Consumption (MM)	79,197 kwh	**Total Consumption (MM)**	86,418 kwh

5. Energy conservation module development

The ASHRAE base case has been used to test the impact of the courtyard on the investigated building. A central courtyard as shown in Figure 4 has been modelled with distinct differences in layout, construction, opening, lighting while the activity tab, and HVAC tabs remain the same for each model. Courtyard (C) with one, two, three and four combinations(Table 3) of Insulation in Wall (IW), Insulation in Roof (IR), Shade on Roof (SR), Self-shading of Wall (SSW), Low-E-glass (Low-E-g), Jaali Wall (JW), Cavity Wall (CW) were run with a total forty-two simulations. Following are the twenty-one combinations for the experiment:

Table 29: Energy Conservation Modules (ECMs) courtyard with one, two, three and four combinations:

Strategies/ Courtyard (C)	1.Insulation in wall	2.Insulation in roof	3.Shade on roof	4. Self-Shading of Wall	5.Jaali Wall	6.Low-e-glass	7.Cavity wall	Total
1 Combinations	C+1	C+2	C+3	C+4	C+5	C+6	C+7	7
2 Combinations	C+1+2	C+2+3	C+3+4	C+4+6	C+5+6	C+6+7	C+1+3	7
3 Combinations	C+1+2+6	C+3+4+6	C+3+5+6					3
4 Combinations	C+2+4+6+7	C+1+3+5+6	C+3+5+6+7	C+3+4+5+6				4

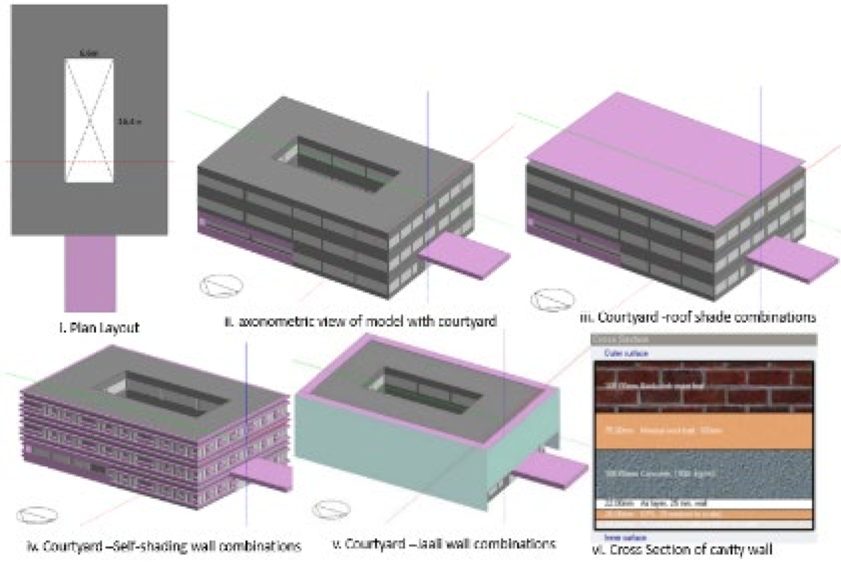

Figure 55:ECMs layout

A central courtyard with (6.6 m×16.4m) was created, as another level was added to equal the total built-up area to compensate for the sacrificed working space by making the courtyard void. As per ASHRAE maximum U-value, wall insulation was used 79.4 mm XPS extruded polystyrene-CO2 blowing, and roof insulation was used 108.60 mm XPS extruded polystyrene-CO2 blowing. The same features were used in ECMs one, two, three, four combination simulation with courtyard.

For all the ECMs combination white coated metal as roof shading material in component block was created as entirely shaded courtyard. Horizontal self-shading walls was created with component block in 'Design-builder'. For making jaali wall, component block has been developed with the maximum transmittance 0.4 for the perforation percentage of existing building's jaali wall. Low-E coated glass (Dbl LoE (e2=.1) Clr 3mm/13mm Air and double-glazed glass are used as window glass type. Cavity has been formed in between the wall according to the cross-section in Figure 4. In all the combinations with courtyard same glass type and cavity wall configuration was used.

6. Result and discussion

The model of courtyard layout with twenty-one combinations has been simulated for both conditioned and mixed-mode controlled buildings with a total forty-two annual simulations. The total energy end-use result was collected and arranged to find out the best case and worst case with the combination of courtyard in different ECM's module. To measure a feature's effectiveness, total annual end-use was counted in the best cases when one, two, three and four envelope design features were combined with courtyard.

Cases	Lighting & Equipment End-use	District Cooling End-use	Total End-use
Base Case (AC)	53,773	66,110	119,883
Base Case (MM)	53,773	32,644	86,418
Courtyard (AC)	35,720	99,749	135,469
Courtyard (MM)	35,547	91,011	126,558

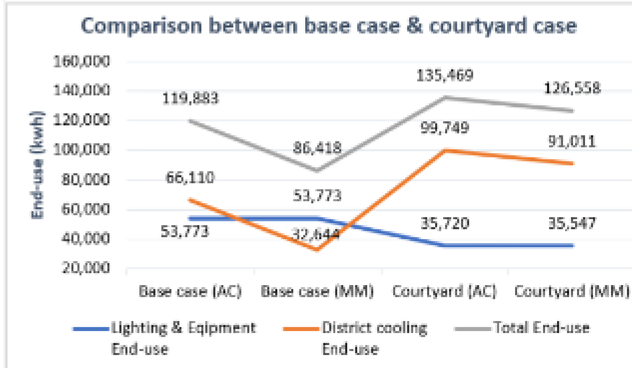

Figure 56 : Base case & Courtyard combinations

The total end-use for the courtyard arrangement were compared to the ASHRAE case AC and mixed mode scenarios. It is evident from Figure 5 that the courtyard is not improving the energy performance of the office building and it has more consumptions than base case because the thermal performance of the building is impacted by solar radiation that is directly received by courtyard surfaces. But the lighting consumption improves with the courtyard.

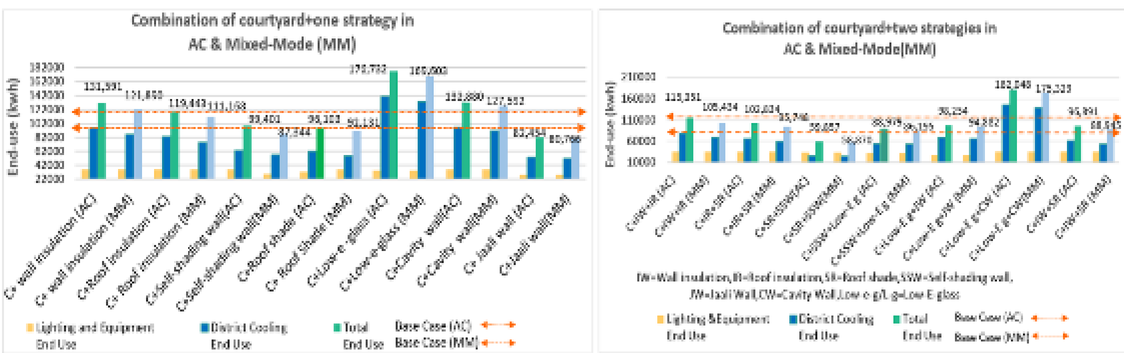

Figure 57:(a) Courtyard +one strategy combination, (b)Courtyard +two strategy combination,

Since the courtyard is not a good alternative for optimizing energy performance in the previously mentioned case, the impact of the passive envelope design with combination of courtyard by developing seven sets ECMs with (courtyard + one passive strategy) has been further evaluated for the both AC and mixed-mode scenarios. The figure 6(a) demonstrates total end-use of the wall's self-shading (99,401 kwh AC;87,344 kwh MM), shade on roof (96,103 AC kwh & 92,131kwh MM) and jaali wall (82,454 kwh AC & 80,766 kwh MM) has the most significant influence when utilizing a courtyard combination. The jaali case's both AC and MM have less energy and lighting end use consumption than base case (119,883 kwh AC and 86,418 MM). Where mixed-mode control scenarios of these cases are more efficient. And energy-efficiency is poor when a courtyard is combined with Low-E glass windows. It has almost reached its maximum end-use in AC 176,732 kwh and in MM 169,603kwh.

While low-e glass double-glazed windows with courtyard combination does not improve annual energy use for this investigation. Another seven sets of ECMs (courtyard + two strategies) were run to test the effectiveness of the Low-e glass windows efficiencies. Figure 6(b) illustrates how a courtyard with a different wall and roof strategy performs better in terms of energy and lighting efficiency. The optimum combination in this case is C+SSW+SR; C+SSW+Low-e-glass and C+JW+Low-e-glass. Mixed mode always performs better than AC scenarios. Here, the worst combination is C+Low-e window -cavity wall. As it has more energy consumption than base case scenarios (Ac & MM). Overall, in this example of Dhaka, shading method is preferable to insulating strategy with the combination of low-e-glass window.

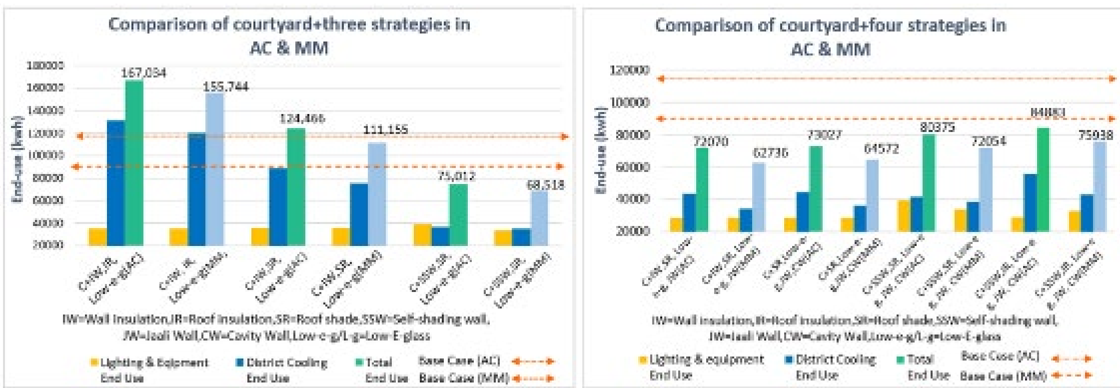

Figure 58: (a) Courtyard +three strategy combination (b) Courtyard +four strategy combination

Figure 7(a) indicates that courtyard with self-shading wall, roof shade and low-e glass performs better for the both AC (Total end-use=75,012 kwh) and mixed-mode (Total end-use= 68,518 kwh) scenarios as it has less energy consumption comparison to base case. Whereas the courtyard, wall insulation, roof insulation, low-e glass has consumed more energy with a total end use of 167,034 kwh (AC) and 155,744 kwh (MM). The results strengthen the findings that shading is the best performing scenario over insulation for the office building.

From previous analysis it was found that mixed-mode scenario of courtyard+ three strategies was working effectively rather than AC. Hence, another eight simulations were run to see if courtyard +four strategies can work better for the both AC and mixed-mode scenarios. Figure 7b) shows the courtyard when implemented in conjunction with four techniques that have the greatest impact on lowering overall end-use consumption for both AC and mixed mode scenario in comparison to both base case scenarios in AC and MM.

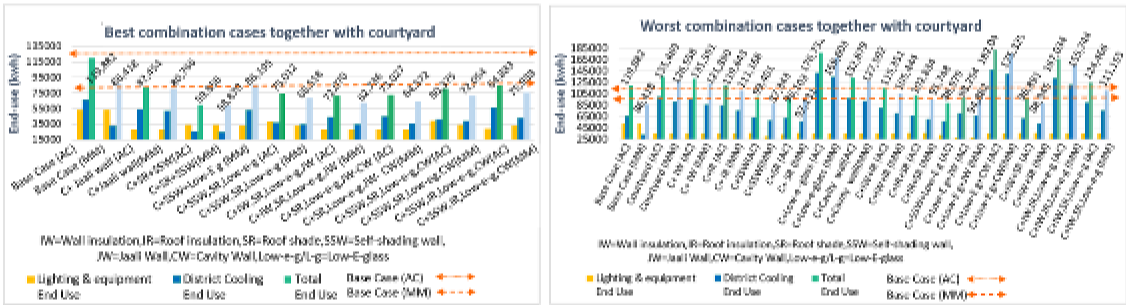

Figure 59: All best-worst case together AC &MM

Figure 8 depict both the best-case and worst-case scenarios for a courtyard with air conditioning and mixed mode. The C+1 strategy has consumed more energy than the C+2, C+3, and C+4 strategy combinations. When courtyard with walls or only the roof is combined, it uses a lot of energy. With the combination of the wall, roof, and low-E glass, courtyard is overall efficient. Courtyard with self-shading wall or wall insulation with roof shading is the ideal option for energy optimization. However, the worst alternative in this case is the single or double combination of low-e glass and cavity wall with courtyard. Because it reaches the highest consumption (Figure 8) in compare with the base case. It was determined in the office building of Dhaka that mixed-mode control using a single roof and wall approach was better than a completely air-conditioned building.

7. Conclusion

Twenty-one energy-conservation modules have been studied in this study, and the effects of courtyard when combined with passive envelope energy-efficient building design strategies have been explored. Because the courtyard plan increases the surface area exposed to direct sunshine, it is not a possible best option for this office building. The courtyard and double-glazed Low-E glass windows also exhibit the poorest performance. On the other hand, to reduce heat gain from the outside, ECM modules were developed with alteration of envelope design layout. While applying the techniques, ECM of courtyard-self shading over wall -roof shading (total end-use =59,856 kwh in AC; 58,870 kwh MM) and courtyard-jaali wall-roof shading-low-E glass (total end-use =72,070 kwh in AC; 62,736 kwh MM) combinations produced the most improved outcomes from individual simulations than the base case (119,883 kwh AC and 86,418 MM). In addition, it was found that in Dhaka the mixed-mode management using a combination of courtyard with a wall and roof system is the best choice as opposed to an air-conditioned building. This study lays the framework for identifying the need for mixed-mode control structures that combine passive building design strategies to maximize energy performance.

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