Energy

Numerical Simulations Methods for Sustainable Planning

Seminar report
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1. Introduction

This paper deals with numerical simulations of energy efficiency strategies in the built environment. Therefore, a six-story office building in Lagos, Nigeria, serves as a case study. Here, active and passive design approaches are investigated. The two main objectives that inform the design are minimizing heat gain into the building and promoting heat loss. All calculations are performed with Ladybug Tools for Rhino Grasshopper.

2. ASHRAE climate zone

2.1. Energy efficient building design for Nigeria

Lagos is in ASHRAE climate zone 1 which is hot and humid. It is recommended to insulate the buildings adequately and provide air sealing to reduce the infiltration of the air. The selection of materials and building skin components contributes to reducing heat gains by conduction, convection, and radiation, controlling humidity, and promoting thermal loss. Materials' physical properties (color, thermal mass, conductivity) are critical for good thermal performance. Thermal comfort is the condition of the mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. This feeling of satisfaction is achieved when the heat generated by human metabolism is allowed to dissipate, thus maintaining thermal equilibrium with the surroundings (ANSI/ASHRAE Standard 55). [1]

For the case study, several strategies of the Building Energy Efficiency Guideline for Nigeria will be adopted.

2.2. Base case office building

For all energy simulations, the weather file from the airport of Lagos, Nigeria, will be used. As the office building is located within ASHRAE zone 1, a typical wood-framed construction set will serve as a base case - the first simulation has shown that this performs slightly better than the construction set with massive bricks. In previous daylight simulations, a generous window-to-wall ratio of 60 % as well as a shading overhang of 1.3 m have turned out to meet LEED v5 daylight criteria. In this paper, detailed energy simulations will deal with these parameters critically. When taking a closer look at the monthly energy demands of the base case, it becomes clear that the main focus should be on reducing the cooling loads (see Figure 1). Annually, these are relatively high with 168.9 kWh / (m^2 * a), compared to 15.8 kWh / (m^2 * a) for interior lighting, and 37.1 kWh / (m^2 * a) for electric equipment (both values resulting from medium-sized office program). Unsurprisingly for the constantly high outdoor temperatures, there is no heating demand.

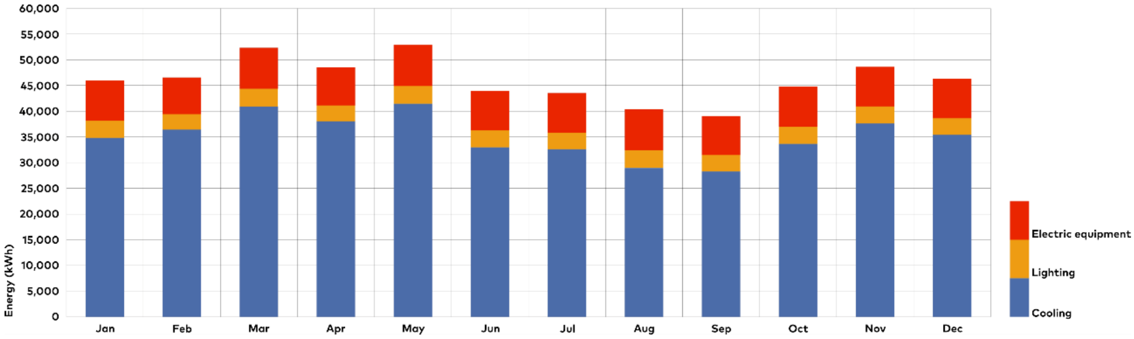

Figure 1: Base case monthly energy demand

3. Iterative energy optimization

3.1. Construction

As a first step in reducing the annual cooling demand, the exterior wall construction was optimized. Therefore, the generic insulation of the timber-framed wall was exchanged with wood fiber insulation with a specific heat load capacity of 2,100 J / (kg * K) – mineral wool is around 1,000 J / (kg * K). Moreover, a humidity-regulating clay board with a high density of 1,450 kg / m³ was added as the inner layer of the wall construction. Besides, the added thermal mass can also reduce interior heat peak loads when combined with effective night ventilation. With this low-tech strategy, the annual cooling demand could be slightly reduced from 168.9 kWh / (m² * a) to 167 kWh / (m² * a). Next, the window glazing was optimized. Also here, the window construction of the base set was already pretty good with a solar heat gain coefficient of 0.23. This was only lowered to 0.2 since further reduction can lead to significant losses in daylight supply. This led to a cooling load of 161.7 kWh / (m² * a), with the highest reduction in the hottest month of May (see Figure 2).

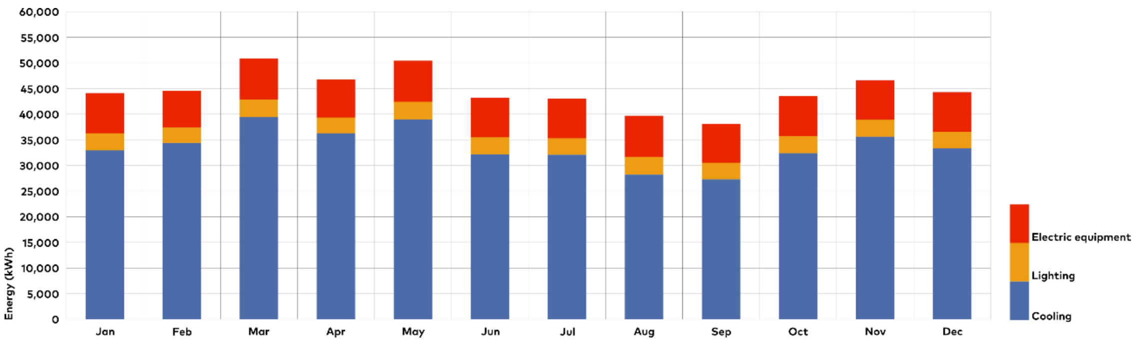

Figure 2: Wall and window construction optimized monthly energy demand

Besides, lowering the window-to-wall ratio from 60 % to 40 % would lead to a cooling load decrease of around 13%. Yet, no compromises for interior daylight supply should be made, so for all simulations, the aperture remains 60%. The most important finding here was that choosing a specific double-glazed window with a much lower thermal conductivity dramatically increased the annual cooling demands. This is due to the lack of natural ventilation at this point, which will be added next.

3.2. Façade ventilation

Based upon the need for air ventilation, further investigations were made regarding the cooling potential of operable (one out of three) windows. On the one hand, simulations showed that automatic night ventilation needs almost 70 % less cooling compared to office workers opening the windows during highly occupied working hours. Night cooling thermal mass is useful in hot climates by absorbing heat that has accumulated inside the building, storing it, and releasing it during the cooler night [1]. On the other hand, increasing the number of operable windows during the night also increased the cooling demand in case of night ventilation (see Figure 3).

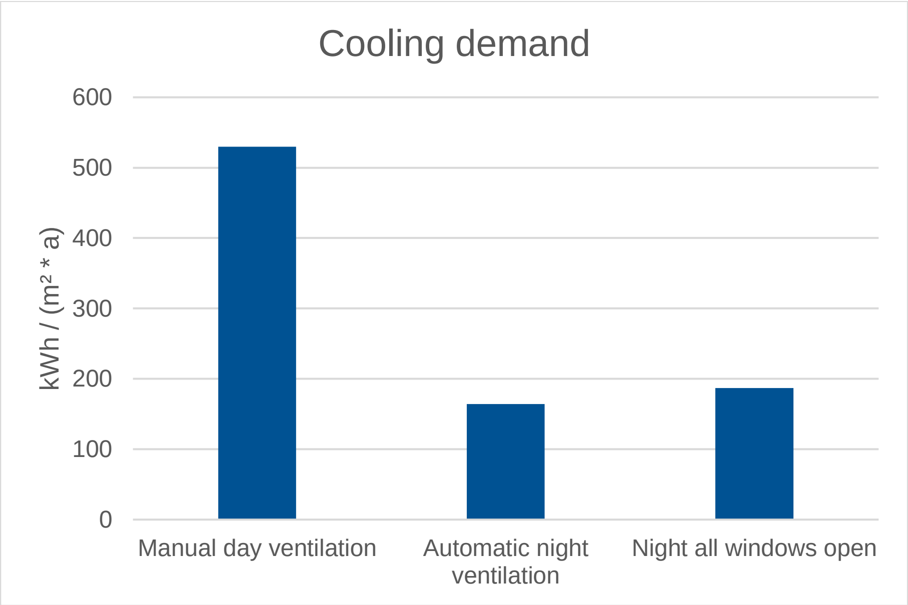

Figure 3: Wall and window construction optimized monthly energy demand.

This leads to the conclusion that the outdoor air temperature entering the office rooms directly is too high and should be preconditioned by the ideal air system that has been used in the simulations so far.

3.3. (H)VAC concept

Since the natural ventilation failed to further reduce the overall cooling demand, a mechanical solution was opted for. In the category of energy-efficient dedicated outdoor systems (DOAS), a far-reaching iterative simulation process revealed the variable-refrigerant-flow (VRF) system to be the most successful in cooling. Generally, in DOAS cooling is separated from ventilation. In principle, a VRF system moves the conditioned refrigerant directly to each zone's indoor unit, while sensors measure the (heating and) cooling load for each zone [2] (see Figure 4).

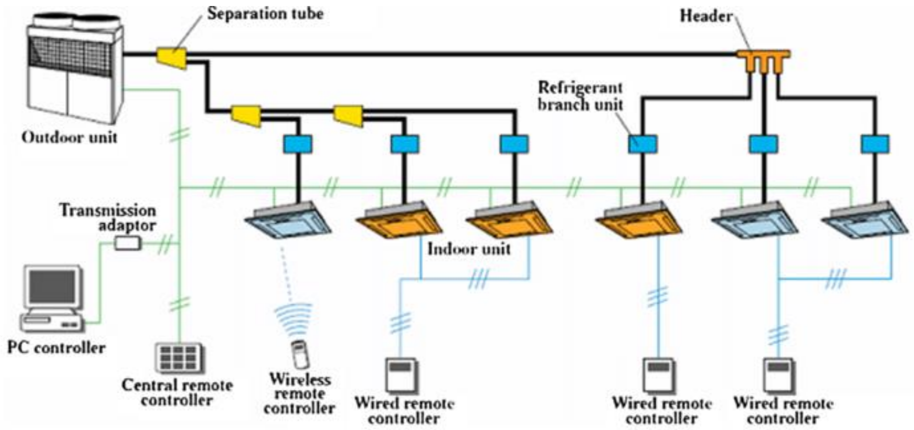

Figure 4: VRF system principle

More precisely, the units' outdoor compressors can be adjusted to meet the indoor units' set points. This results in a coefficient of performance (COP), which varies from 3 to 3.5 for VRF units. For comparison, the COP of split AC systems lies around 2.5 [1]. While its sensory heat recovery was set to 81 %, the latent heat recovery was set to 0 %. If needed, energy recovery ventilation (ERV) systems can be integrated within a DOAS VRF system to recover both sensible and latent heat from the exhaust air stream. The energy recovery ventilation unit is used to supply fresh air. The fresh air is preconditioned with the exhaust air via a heat exchanger, which minimizes energy losses. The unit perfectly complements the ventilation requirements in VRF [3]. This way, the annual cooling load significantly dropped down to 34.2 kWh / (m² * a). From this point, a combination with natural window ventilation slightly improved the cooling effect. So automatically opening windows can be installed for additional passive night cooling. The overall results will be shown in the next chapter.

4. Energy demand analysis

After all design strategies were implemented in the energy simulation, a big energy saving potential of 60 % compared to the base case could be achieved (see Figure 5).

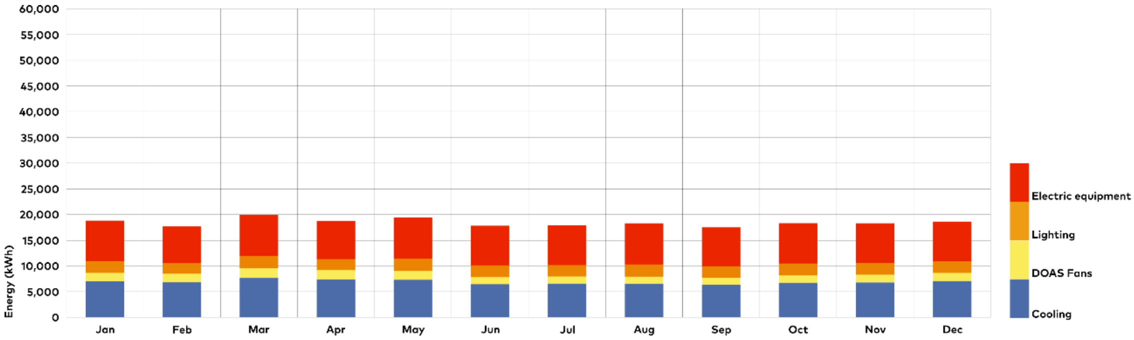

Figure 5: Final design of monthly energy demand

A study in 2013 commissioned by GIZ on energy consumption in seven office buildings in Nigeria suggested that office air-conditioning (VAC) accounted for 40-68% of electrical consumption, with the other important uses being lighting (13-37%) and office equipment (12-25%) [1]. In the case study, additional illuminance sensors reduced the interior lighting demand by more than 30 %. Overall, the total energy consumption lies at around 88.9 kWh / (m² * a). To better understand the decisive cooling load reduction process, a waterfall diagram is provided (see Figure 6).

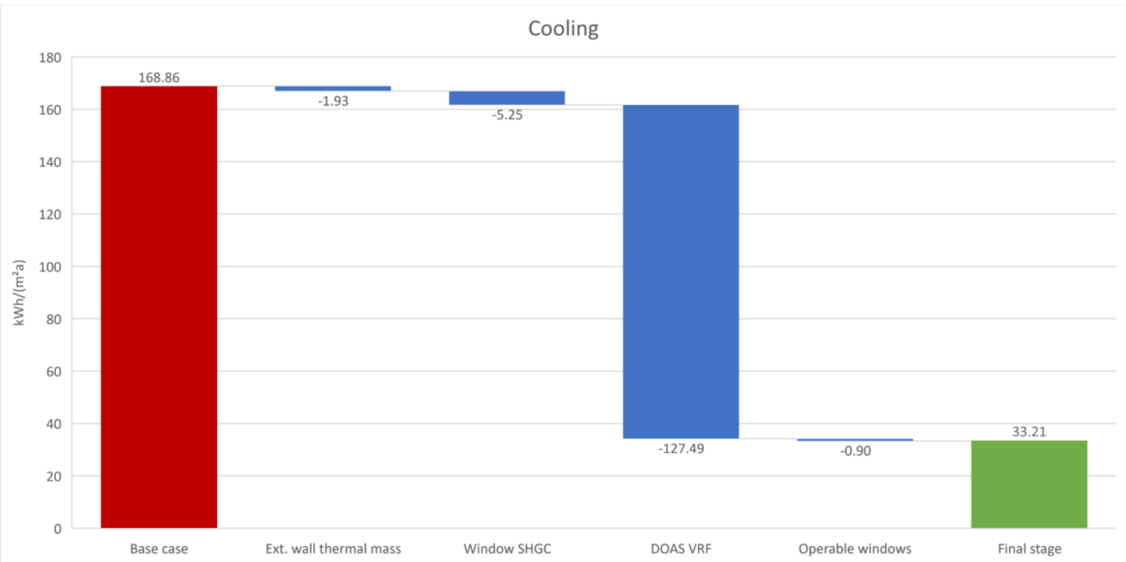

Figure 6: Gradual cooling load reduction

5. Annual carbon footprint

Finally, the annual CO_2 emissions during building operation are calculated. Therefore, the electricity mix in Nigeria is considered [4] With 0.4396 kg CO_2-eq. / kWh, the electric supply is almost 25 % higher than in Germany with 0.354 kg CO_2-eq. / kW, mainly because of natural gas and oil [5]. After considering the PV yields of 54,294 kWh / a (14° tilt), the remaining 523,988 kWh / a is powered by the Nigerian electricity mix. This leads to a total global warming potential of 230,345 kg CO_2-eq. / a. To visualize this number, the total emissions are in the range of cutting down ~0.3 ha of Nigerian forest (above-ground biomass) every year, which stores 550,000 to 1,100,000 kg of CO_2 [6].

6. Conclusion

Overall, climatic design measures could be found to effectively reduce the energy loads of the office building. After iterative energy simulations, further investigations can be made regarding the relatively high aperture. As (passive) cooling load reduction turned out to be the biggest challenge, some compromises could be made in interior daylight supply. Here, the illuminance sensors with a comparably low energy demand could compensate for the illuminance losses. But other psychological factors like increased mental health and well-being due to a higher sky view factor from people's desks can outweigh energy efficiency. When it comes to natural ventilation, the high office standards could not be reached without the additional VRF system. Here, automatic night opening of the windows can only play a complementary role. Adding an energy recovery ventilation (ERV) system with latent heat recovery to the DOAS VRF could improve the energy efficiency of the system and thus reduce cooling loads. On top of that, it improves humidity control and overall indoor environment quality.

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7.2. List of Figures