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Development of whole building energy models for detailed energy insights of a large office building with green certification rating in Singapore

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Abstract: Detailed insights on energy use are missing for the building stock in Singapore which may aid with energy consumption reductions through a targeted approach. Therefore, we created two whole building energy models for a large commercial office building in the tropics; representing a fully glazed and a concrete façade. We used Singapore's current building codes, which includes compliance with local green rating system, and collaboration between two entities with first-hand experience with design, construction, and operation of buildings in the tropics to define the models. The models provide a first step towards a set of standardized inputs and assumptions for office buildings in the tropics. The results show an energy use intensity of 146 kWh $m^{-2}\cdot a$. The three highest energy consumers are air conditioning and mechanical ventilation (43%), lighting (29%), and plug loads (21%) while the two main sources of cooling loads are ventilation (29%) and conduction and radiation through windows (20%). Finally, we evaluated the effects of exterior shading on the fully glazed energy model to demonstrate the use of the models to building stakeholders.

Introduction

Buildings account for 30-40% of global primary energy consumption and 30% of annual greenhouse emissions in OECD countries.[1] In Singapore, over 50% of the generated electricity is used in buildings and most of this electricity is being produced with imported natural gas and contributes to annual GHG emissions.[2] The Inter-Ministerial Committee on Sustainable Development (IMCSD) established a goal that 80% of Singapore's building stock achieve Green Mark Scheme certification and a 35% reduction in energy use intensities from 2005 levels by 2030.[3]

The first step in achieving a reduction of energy use in a building is often to gain insight of how much and where energy is being consumed with current design, construction, and operational practices. There are multiple methods to calculate energy use of buildings which include engineering, statistical, and machine learning techniques.[4,5] Each of the methods has their own advantages and disadvantages. Some can be simple to implement with few inputs while others are complex and have many inputs to define. It is desirable that models give high fidelity results, flexibility in modeling different systems of the building, and flexibility in output options. These traits can be accomplished with whole building energy models. However, developing representative models is challenging because inputs can be difficult to define properly as many strongly depend on common design practices in any given location. Shahrestani, Yao, and Cook (2014) offer three categories in which data can be collected to develop representative building energy models: 1) inputs from real buildings; 2) inputs based on small-scale surveys; and 3) inputs based on large-scale representative national surveys.[6] It is obvious that large-scale surveys have the potential to inform inputs to benchmark models to ensure that they are representative of a large portion of a building stock. However, they are time consuming and resource intensive and as such are not commonly available. This is most likely the reason why there are few reported instances where countries developed representative building benchmarks using large-scale surveys.[6] In other cases, researchers conducted smaller surveys of current designs, building codes, and/or other building statistics to define models for a specific building type.[7–9]

Standardization and accurate representation is a key component of many building energy simulation studies. This allows for straightforward comparison of energy saving potential across different technologies and operational strategies. Whole building energy models have been used in a variety of ways that include evaluation of energy efficiency measures (EEMs)[10], decision making support for early building design[11], and policy effects at the state[12] and federal level in the USA[13] and in the European Union.[14]

In this study, we developed a whole building energy model that is representative of a large commercial office building with minimum local green rating certification as none is currently available. This energy model quantifies typical energy end-use consumption in Singapore's tropical climate with mandatory green building rating system. Building stakeholders can determine where and how much energy is being used to develop appropriate designs in new construction or adequate EEMs in existing buildings to reduce and optimize energy consumption. The model serves as a first step in creating a common reference point for energy savings potential

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assessments for newer technologies being developed to help reach IMCSD's aggressive goals. The whole building energy model input data files can be downloaded from the supplementary online material.

Methods

We established an iterative process illustrated in Figure 1 with Singapore's government agency that oversees the development and regulation of the built environment (Building and Construction Authority (BCA)) and a private mechanical engineering firm with experience in designing buildings in the Asian-Pacific climates (Beca), to develop a representative whole building energy model. The energy model represents characteristics of a typical large commercial building in Singapore that complies with requirements BCA's Green Mark (GM) Scheme version 4.0 at Certified Level.[15] We relied on Singapore's building codes and standards, an extensive literature review pertinent to Singapore's building stock, and communication with the two entities mentioned above to define parameter inputs and reasonable assumptions for an office building in the tropics.[16–19]

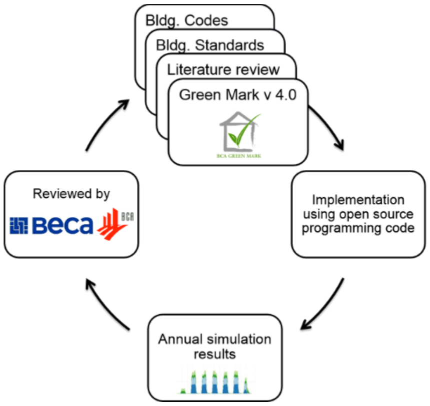

Figure 1: Overview of iterative process to create whole building energy model. We started with a literature review to define energy model inputs, proceeded by implementing inputs into input data files using open source programming software, simulated models, and discussed results with partnered entities. We repeated this process eight times until reaching consensus on results.

The GM Scheme was first established in 2005 as a voluntary environmental sustainability building rating program but then became a mandatory requirement in 2008 for new construction and major retrofits greater than 2,000 m^2.[20] To comply with GM, buildings need to meet certain criteria in energy and water efficiency, environment protection, indoor environment quality, and other green features. Each of the five criteria contains points that can be earned depending on the performance of the building similar to other green rating programs like Leadership in Energy and Environmental Design (LEED) established in the USA and the Building Research Establishment Environment Assessment Methodology (BREEM) in the UK.[21–24] GM version 4.0 became effective in December 2010. GM version 4.0 prescribed the minimum performance requirements for cooling systems in existing buildings and raised the energy efficiency standard by 10% for new construction and major retrofits from the previous version 3.0.[15,25]

We took the US Department of Energy's (DOE) large commercial office building with ASHRAE 90.1-2010 for Miami's climate as the starting point for the model in this study.[26,27] We modified the input data files for the energy model using open source software and packages discussed in the method section below. This made the work repeatable and easy to change, as decisions were often not final due to lack of clear evidence to support one viewpoint or the other.

Weather data and indoor design conditions

Singapore has a hot and humid climate. We used ASHRAE weather file SINGAPORE-SGP IWEC Data WMO#=486980 which is approved for energy modeling by BCA. ASHRAE weather files are compiled from historical weather data to represent a typical year.[28] The daily average for outdoor dry-bulb temperature, dew point temperature, and relative humidity found in the weather file are 27.5 °C, 24.3 °C, and 84%, respectively. Rim, Schiavon, and Nazaroff (2015) provide additional weather statistics and indicate the relative consistent weather conditions.[29]

The cooling design day dry-bulb and wet-bulb temperature is 33.3 °C and 27.8 °C, respectively. We defined six design days throughout the year to account for yearly solar variation. We used the 21st day for months February, April, June, August, October, and December, which will prevent the energy modeling software from undersizing cooling requirements due to orientation and sun position on any one design day of the zone.

Per building code requirements, the operative temperature in occupied zones shall be maintained between 24 °C and 26 °C.[19] To comply with this requirement, we set the mean air temperature setpoints to 24 °C and 23 °C for core and perimeter zones, respectively. The perimeter zones need lower setpoints since the high glazing of the building will increase the overall mean radiant temperature which in turn increases the operative temperature. Air-conditioning and mechanical ventilation (ACMV) system does not directly control relative humidity at the zone level. The air handler modifies humidity at the system level through the supply air temperature setpoint and chilled water plant parameters. We observed zone outputs to confirm relative humidity was below 65% during occupied hours.

Building description

BCA has oversight on the planning, permitting, and construction process of buildings in Singapore. Therefore, this agency became our resource for information on the models' geometrical specification that included aspect ratio, number of office and car park floors, and window-to-wall ratio (WWR).

We modeled a square, 28,000 m^2 building with 20 floors (each 1,400 m^2). Floors 1-3 are modeled as car parks with the rest, floors 4-20, modeled as open plan office floors. The car park is divided into four perimeter zones (180 m^2 each) and one core (1,220 m^2). Every office floor is divided into seven thermal zones: four on the perimeter (150.2 m^2 each), one core (689.2 m^2), one staircase (60 m^2), and one restroom (50 m^2). Office floor perimeter zones have a depth of 4.6 m. We did not explicitly model internal partition and other office furniture. Instead, we defined internal mass objects to account for thermal mass effects in interior zones. We used wood material properties to define the interior mass as recommended in Raftery et. al (2014).[30] The total exposed surface area of interior mass for core and perimeter zones is 1,378 and 300 m^2, respectively, representing 182 $kg\cdot m^{-2}$ of internal mass for both zone types. We set most inside zone boundaries to an EnergyPlus (EP) object that transforms solar radiation energy (shortwave radiation) that is incident on the surface to longwave radiation. It allows core zones to engage in the longwave radiation exchange with perimeter zones. The exceptions are in the restroom and staircase zones where we used brick material properties.

The building envelope is an all-glazed façade with 59% WWR for floors 4-20. Floor-to-floor height is 4 m including a 1.2 m return plenum. We applied selective window treatments based on façade orientation to ensure compliance with GM minimum thermal transfer value (ETTV) of 50 $W\cdot m^{-2}$ and used established methods for calculation.[31] North and South façade windows are tinted single pane glazing with a U-value of 5.7 $W\cdot m^{-2}\cdot K^{-1}$ and SHGC of 0.5. East and West façade windows are clear double glazed with titanium reflective coating windows with 2.2 $W\cdot m^{-2}\cdot K^{-1}$ and SHGC of 0.2. Argon gas fills the void between the two glass panes. The façade includes 0.6 m horizontal overhang shading for all orientations. Figure 2 shows a visualization of the model. We used a zone multiplier for the middle floor to recreate the other 14 floors to reduce geometry complexity and simulation time. The exposed surface area between the gaps where the other floors would have been and seen visually in Figure 2 are defined as adiabatic surfaces. The DOE benchmark office models take the same approach as actual heat transfer between floors is assumed negligible since intermediate floors have similar conditions.[32] The U-value of the exterior wall, floor/ceiling, and roof construction assembles are 0.4, 3.5, and 0.6 $W\cdot m^{-2}\cdot K^{-1}$, respectively. Supplementary online materials provide more details on the layers and their respective thicknesses.

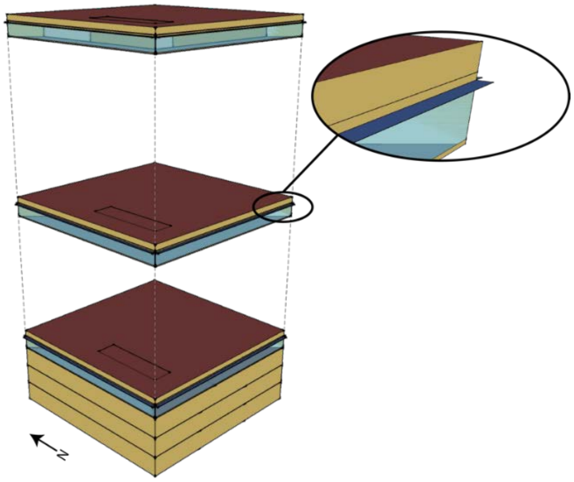

Figure 3: Singapore benchmark building with close-up on horizontal overhangs.

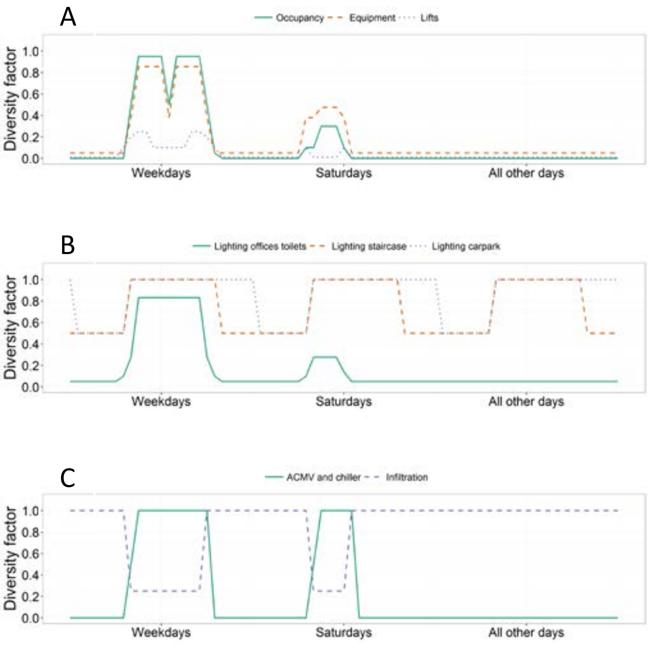

Figure 2: Schedules defined in the whole building energy models for three different week day types (excluding design days) for (A) office occupancy, equipment, and lift; (B) lighting power demand; and (C) ventilation and infiltration.

Internal design loads and schedules

The design internal heat gains are shown in Table 1 and various schedules are shown in Figure 3. Figure 3 uses continuous lines though these diversity factors are discrete at each hour. Schedules are used to show fractional use from the design value at each timestep. We assume occupancy hours on weekdays from 8:00 to 18:00, 8:00 to 13:00 on Saturdays, and closed on Sundays and public holidays which is typical for a commercial office building. The activity for people in this model is "moderately active office work" with a combined sensible and latent heat output of 130 W per person.[33]

Table 1. Internal design loads in energy model.

Internal load	Value 1	Value 2	Value 3	Value 4
Occupancy	10 m^2 per person	-	-	-
Interior lighting	15 $W\cdot m^{-2}$ for office	6 $W\cdot m^{-2}$ for staircase	10 $W\cdot m^{-2}$ for restroom	15 $W\cdot m^{-2}$ for car park
Exterior lighting	4 kW for exterior	17.85 kW for façade	-	-
Office equipment	14 $W\cdot m^{-2}$ for office	270 kW for lifts	-	-
Misc. equipment	12 kW for mechanical room	16 kW for electrical room	2.93 kW for pumps	-
Ventilation	Maximum of 5.5 $L\cdot s^{-1}$ or 0.6 $L\cdot s^{-1}\cdot m^{-2}$	-		-

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Infiltration	0.2 ACH	-	-	-

We did not implement automated daylighting and occupancy controls in the model, as these are not yet commonplace in Singapore. We calculated power demands for exterior lights from the assumption that they illuminate an area of 800 m^2 and we took 5% of the total demand from lights in the building to calculate façade lighting.[16] Exterior lights activate from 19:00 to 7:00 and façade light illuminate from 19:00 to 24:00.

The selected design level for office equipment is lower than what is reference in GM documents for energy models (16 $W \cdot m^{-2}$) and which is based on an ASHRAE 1989 standard.[34] However, we determined 14 $W \cdot m^{-2}$ to be more reasonable design level through consensus with the two partnered entities. Office equipment has become more energy efficient by occupants using LCD versus CRT monitors or opting to use laptops instead of full size desktop computers. This figure is still significantly higher than in the USA where DOE engineering judgment puts the figure at 7.54 $W \cdot m^{-2}$.[32] One possible explanation is the higher occupant densities found in Singapore. We assumed six lifts with motors rated at 45 kW each; from the assumption that each lift has the capacity for 24 people and a rated speed of 4 $m \cdot s^{-1}$. Figure 3 (A) shows the schedules used for office equipment.

We aggregated other miscellaneous building equipment into few modeling objects to avoid excessive complexity related to components about which we had almost no information other than anecdotal evidence or engineering estimates and rules-of-thumb. Pumps used for domestic water and drainage operate 24 hours a day at an average power demand just under 3 kW. The mechanical ventilation for the mechanical room operate on the same schedule as in the cooling system shown in Figure 3 (C). The electrical room has a higher peak because it is temperature controlled and its ventilation system is set to operate continuously throughout the day, but at only 75% of the peak load.

Ventilation rates in the energy model comply with Singapore standard SS 553.[18] We modeled a fixed pressure difference across the outdoor air damper through a modulating return air damper. This assumption, approved by the two partnered entities, will maintain a constant minimum outdoor airflow rate during occupied hours when fan speed varies with changing cooling loads. An important note is that the minimum outdoor airflow rate will not vary with occupancy because the strategy is not common in Singapore. We assumed that the building is slightly pressurized during occupied hours. Thus, the maximum infiltration will be observed when the ventilation system is off and only a quarter fraction when the ventilation system is on during occupied hours. This is based on the approach used in the DOE's large commercial office building. Schedules for ventilation and infiltration are shown in Figure 3 (C).

Mechanical system and operation

The cooling system is a water-cooled chilled water plant serving air-handling units (AHU) at each floor. AHUs then serve variable-air-volume (VAV) terminals with no reheat at the zone level, which is a mandatory design feature in Singapore VAV terminals.

The cooling system has two variable speed chillers rated capacity of 1,400 kW (398 refrigeration tons (RT)) each and two variable speed pumps rated at 16.9 kW each. Chillers operate at a lead-lag system. The rejection system consists of two cooling towers rated at 1,758 kW each and two constant volume pumps rated at 17.2 kW. The cooling towers' fans have a total power of 33 kW at the design water flow rate. The rejection system is designed to remove heat 1.25 times the capacity of the chillers and we obtained its properties for modeling purposes from commercially available cooling towers (SKB-645, Kuken Kogyo Co. LTD, Japan). Supplementary online materials show additional design properties for the two systems mentioned above.

The main AHU fans have a combined power draw of 177.8 kW for a maximum combined airflow rate of 108.5 $m^3 \cdot s^{-1}$ for perimeter and core zones. EP calculated design values based on design day loads, pressure rise of 1,000 Pa, and total fan efficiency of 61% in each of the 17 office floors. We assumed fans to be a draw-through variable frequency drive (VFD) fan with the motor in the air stream. We also assumed a minimum airflow rate for fan power at 50% which is to prevent the fan's VFD from dropping below 30 Hz, which is a common practice in Singapore. It is worth noting that this is not common practice in the USA where modern VFDs on large air handling units often run at speeds below 20% without issues. Significant energy savings could be obtained by the implementation of this common practice. The VFD fan system curve was based on a plenum airfoil fan static pressure drop of 170 Pa.[35] All individual component efficiencies for the ACMV system are better than the baseline efficiencies.[16,18] We calculated an efficiency of 0.70 kW per RT for the chiller plant, which includes chillers, cooling towers, chiller pumps, and condenser pumps, meeting GM requirements.

Concrete façade energy model

We modified the completed energy model to create a second model suitable to implement strategies that require a concrete façade buildings. We used a survey of Singapore buildings in the central business district to serve as a guideline for a reasonable concrete façade construction.[36] The construction layers of this construction with a calculated a U-value of 5.6 $W \cdot m^{-2} \cdot K^{-1}$ is shown in Table 2. An insulation layer is not defined since it is not common practice in concrete based constructions in Singapore. We retained the same window assemblies as in the all-glass façade energy model, in which we will now refer it to as model-A, but we reduced the WWR to 35% to meet the 50 $W \cdot m^{-2}$ ETTV criteria. This is in line with the survey where WWR for the first and third quartiles are 35% and 50%, respectively for 16 concrete buildings. The rest of input parameters remained identical to those in model-A. We designated this new derived model as model-B.

Table 2. Exterior opaque construction assembly used in model-B with layers listed from outside to inside

Layers	Thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$]	Density [$kg \cdot m^{-3}$] (Specific heat [$J \cdot kg^{-1} \cdot K^{-1}$])	SR [a]
Cement_Sand_Plaster_20mm	0.53	1568 (991)	0.45

Concrete_150mm	1.44	2400 (832)	0.45
Cement_Sand_Plaster_20mm	0.53	1568 (991)	0.45

[a] Solar reflectance.

Comparison to Singapore’s building stock

We used Singapore’s inaugural report on national benchmarking to provide a frame of reference for the energy models developed in this study.[37] It is important to note that it will not be a direct energy comparison. The report includes both GM and non-GM certified buildings. In 2014, about 25% of the total gross floor built-up area of Singapore was GM certified and a smaller percentage is certified to the higher energy efficiency requirements outlined in GM version 4.0.[38] Therefore, we expect the energy consumption results from the benchmarking report to be higher than the resulting energy consumption obtained from the energy models developed in the current study. Nonetheless, the statistics provided offer a frame of reference to put model-A results into perspective. In addition, BCA shared data for GM certified office building where energy consumption is reported in a metric called energy efficiency index (EEI). It provides more normalization by considering vacancy rate and normalizing the buildings’ operating hours to 55 hours per week.[39] We analyzed and subset the data into two smaller sets of buildings to provide as close to a direct comparison with model-A as possible. The first requires buildings that have the same GM version, the second further requires buildings to use the same type of energy efficient water-cooled chilled water plant ACMV system. The more energy efficient ACMV system is required by GM for building that have cooling loads of 500 RT or more, which are likely to be seen in large buildings.

Case study

We provide a simple example on the potential use to a variety of building stakeholders of the energy models developed in this study. We evaluated the effects of exterior shading on model-A’s overall energy use and cooling loads. We modified the shading devices on all windows in model-A. We selected two projection angles, ϕ, and a range of lengths, P, for simple overhang shading devices to achieve shading coefficients (SC) from 0.94 to 0.4 as calculated from the established methodology.[31] The lower the SC value, the more solar radiation the shading device will block and have the potential to increase energy savings in buildings. The height of the window, H, remained the same as in model-A at 2.3 m.

Software

We used EnergyPlus (EP) because it offers modular and structured code that has a range of flexibilities to model many different scenarios found in buildings and uses the ASHRAE heat balance method.[40] We used simulation engine version 8.10.009. We modified the initial input files using open source programming language called Python version 2.7.10 in conjunction with a Python package called eppy version 0.4.6.4a.[41,42] Python along with eppy allowed for quick selection of specific EP objects and field for modifications. We processed raw EP outputs using R, a statistical computing and graphics software version 3.1.2.[43] Processing data usually involved the addition of hourly values for a given year and calculating percentages. In some cases, we apply equations to the direct outputs of EP and in those cases, we present the equations before showing the results.

Results and Discussion

The results from the model-A yield an EUI of 146 kWh·m^{-2}·a^{-1}, excluding the car park area. Figure 4 shows the energy breakdown. ACMV includes the chillers, fans, chiller and condenser pumps, and cooling towers. Lighting refers to lighting in office floors 4-20. It does not include car park, façade, and exterior lighting which are included in the auxiliary category along with car park ventilation, miscellaneous domestic water pumps, and lifts. The plug load category includes equipment use in office floors 4-20. The total ACMV energy consumption is 62.8 kWh·m^{-2}·a^{-1} and breaks down into 59%, 28%, 10%, and 4% for chillers, fans, pumps, and towers, respectively.

The Singaporean commercial office building stock has an average energy utilization index (EUI) of 253 kWh·m^{-2}·a^{-1} and a median of 218 kWh·m^{-2}·a^{-1}.[37] The building in the top quartile consumes 164 kWh·m^{-2}·a^{-1} or less while the bottom quartile is at more than 280 kWh·m^{-2}·a^{-1}. EUI represents actual energy use divided by the total gross floor area (GFA), excluding car park area, with no other correction factors or adjustments. Hours of operation and occupant density are unknown factors that can be important to explain energy consumption and group similar buildings for proper comparison. For example, we did not include a datacenter in the model-A, which yields a lower EUI than one would expect in measured data from most modern office buildings. For this reason and fact that only about 25% of the building stock is GM certified, it is reasonable that the developed model-A in this study performs towards the top quartile reported above.

Table 3 describes results from analyzing data shared by BCA. We expect the EEIs in Table 3 to be slightly lower than model-A since the data only includes GM Gold^{Plus} and Platinum rated buildings. Note however, that we also expect all simulation results to have a lower EEI than measured data from real

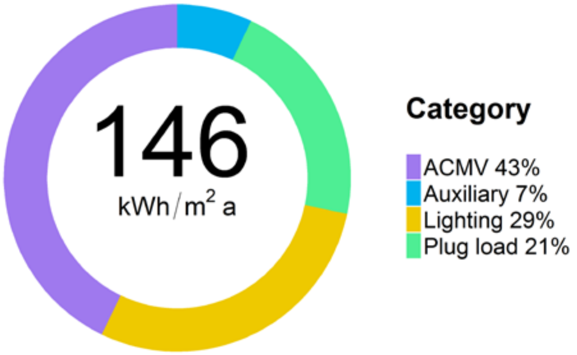

Figure 4: Annual EUI for model-A and percentages broken into four categories.

buildings, such as those presented in the national benchmarking report. The primary reason is that the simulation results do not account for any faults in the building; the simulation assumes that controls and operation are ideal. Faults typically increase energy consumption in an ACMV system by more than 20% and in extreme cases up to 85% depending on the climate, severity, and combination of faults.[44,45] Another reason is that the model does not include any unexpected or unpredictable energy consuming devices that are found in real buildings. Model-A only includes energy-consuming devices that the authors considered relevant and commonplace for a typical office building.

Table 3. Summary of GM Gold^{Plus} and Platinum certified buildings.

Surveyed buildings	Median EEI [kWh·m^{-2}·a^{-1}]	N
Gold^{Plus} & Platinum	145	33
Gold^{Plus} & Platinum since 2010	138.5	18
Gold^{Plus} & Platinum since 2010 & >20,000 m^2	136.3	15

For context, if we assume faults occur in model-A according to the 20% estimate noted in other literature, the result would change from 146 kWh·m^{-2}·a^{-1} to 157 kWh·m^{-2}·a^{-1}. Furthermore, for reference with Table 3, we also calculated the EEI of the model, according to the standard calculation methodology, as 139 kWh·m^{-2}·a^{-1} and 167 kWh·m^{-2}·a^{-1} if we include faults.[39] Both results are within the range of what we expect given information in the BCA benchmarking report and the other considerations noted above. We determined that an EUI value of 146 kWh·m^{-2}·a^{-1} is reasonable and representative of a large office building at GM Certified level.

The main contributors to the cooling load in model-A are shown in Figure 5. The cooling load is rejected through the ACMV system. The detailed analysis of the cooling load provided through the energy model, otherwise difficult, if not impossible, to measure in real buildings, offer building stakeholders with insight to effectively target the major sources of cooling loads to reduce ACMV energy use. We obtained most of the results shown in Figure 5 directly from EP outputs. The two exceptions are latent and sensible heat for the ventilation category. We used Equation (1) and (2) to calculate latent and sensible heat, respectively.

$$\dot{Q}_l = L_v \dot{m}_{oat} \Delta x \quad (1)$$

$$\dot{Q}_s = c_p \dot{m}_{oat} \Delta T \quad (2)$$

where L_v is the latent heat of vaporization for water, c_p is the specific heat for air, $\dot{m}_{oat}$ is the mass flow rate for outdoor air, Δx is the difference in absolute humidity ratio between the outdoor air and return air, and ΔT is the difference in dry bulb temperature between outdoor air and return air. We performed these calculations at each floor and then summed the resulting energy for the overall building. Ventilation air heat gains are essentially the thermal energy removed to cool and dehumidify so it would be at the same conditions as the zone air. We assume L_v and c_p to be constant for the calculations with values of 2,466 kJ/kg and 1.005 kJ/kg·K, respectively.

Figure 5 shows clearly that ventilation is the most significant cooling load source entering the building with 29% of the total. Furthermore, the ventilation bar shows dehumidification to be the predominant driving factor of energy use. The breakdown is 85% for dehumidification (latent) and 15% for sensible. The breakdown is consistent with previous studies.[29]

Windows are another area to focus attention. We selectively placed different types of windows in the model. We defined better windows on the East and West façades because these orientations receive direct solar radiation during the morning and evening, respectively. In other hours of the day, the sun has a high altitude which allows solar radiation to be blocked through effective exterior shading. Model-A only used simple horizontal projection shading. Research for an effective integrated fenestration system is warranted to decrease heat gains through

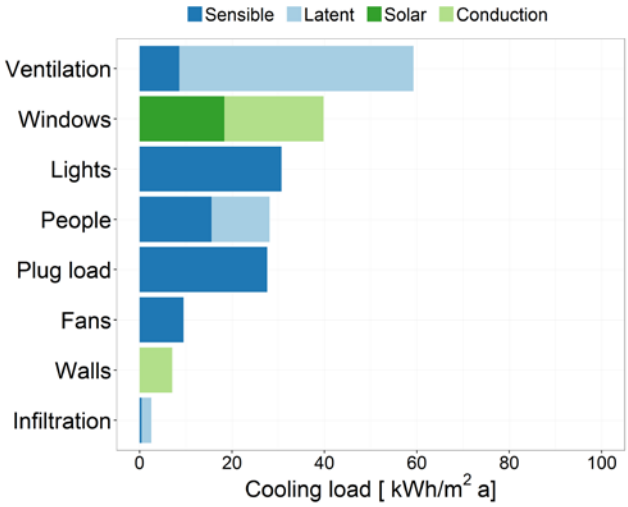

Figure 5: Total cooling load breakdown by type for occupied hours in model-A.

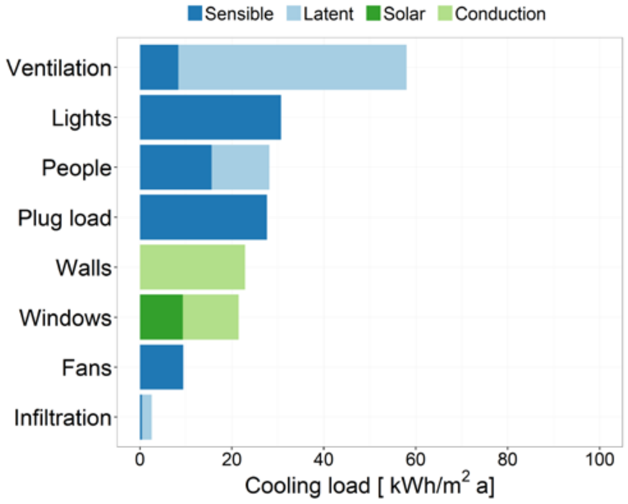

Figure 6: Total cooling load breakdown by type for occupied hours in model-B.

windows and still allow daylight and views to the outdoors.

Cooling loads emitted from people, lights, and plug loads are similar. The fan cooling load category accounts for the temperature rise of the supply air due to motor and fan inefficiencies. Lastly, wall and infiltration are the two lowest cooling load contributors.

It is important to clarify that the cooling loads shown in Figure 5 are not the electrical energy being consumed by each of the components; these are the thermal energy, caused by that source, that must be removed to maintain comfortable conditions. For this reason, components like lighting, plug loads, and fans will be seen in electrical energy and cooling load plots. These components have a direct contribution in the overall building energy consumption but they will also have an indirect effect on the ACMV system electric consumption through the release of thermal energy. The chillers' coefficient of performance (COP) is the reason cooling loads can be much higher than the electrical energy consumed by the ACMV system.

Indoor air simulation outputs show that zone air temperature and relative humidity stay within limit of the prescribed setpoints. The median temperature for occupied periods is 24 °C for core and 23 °C for perimeter zones. The median relative humidity for occupied periods is 50.1% and 52% for core and perimeter zones, respectively. The interquartile range for both values is narrow indicating that temperature setpoints are consistently met. Supplementary online materials show boxplots for temperature and relative humidity for both core and perimeter zones.

The ETTV proved to be an effective simplified metric to compare two different construction assemblies' building envelope cooling loads in the Singaporean climate. The ETTV equation shows an appropriate relationship between conduction and solar loads in hot and humid climate. The total envelope cooling loads for model-A and model-B were very similar. Figure 6 shows the cooling loads for model-B. The biggest difference is in the amount of each type. That is, window cooling loads decreased by 46% while wall cooling loads increased by 220% in model-B. Model-A's cooling loads through the envelope are 18 $kWh{\cdot}m^{-2}{\cdot}a^{-1}$ for solar and 29 $kWh{\cdot}m^{-2}{\cdot}a^{-1}$ for conduction while 9 $kWh{\cdot}m^{-2}{\cdot}a^{-1}$ and 35 $kWh{\cdot}m^{-2}{\cdot}a^{-1}$, respectively, for model-B. These results are reasonable since there is a higher U-value for the exterior wall in model-B and less WWR for solar loads to enter through glazing. For these reasons, the sizing of ACMV components did not have to change and the ACMV energy consumption breakdown by component do not show significant differences. There was a slight difference in total annual energy consumption in model-B (144 $kWh{\cdot}m^{-2}{\cdot}a^{-1}$) due to the higher heat capacity of concrete walls. The concrete stores more energy, some of which will be transferred from the indoor to the outdoor environment during hours when the ACMV equipment is off. This is particularly the case for West facing zones.

The development of the two whole building energy models provides a starting point for researchers and other building stakeholders to assess energy consumption in Singapore buildings in its tropical climate. We provided an initial comparison to the limited available data from current buildings in Singapore. The next steps would be to specifically collect detailed data from GM office buildings and their systems to further improve and verify parameters that we have used to defined the models in this study. In doing so, building stakeholders can have increased confidence when comparing the performance of compliant prescriptive building designs to proposed designs that go beyond mandatory requirements.

We performed a parametric analysis on exterior shading as an example of the use of the energy models developed in this study. Exterior shading is an effective way to further reduce and control solar radiation.[46–48] Exterior shading blocks solar radiation before entering the building thus avoiding an increase in cooling energy. Figure 7 demonstrates the energy savings and heat gain reduction potential of a simple overhang shading device on all windows in model-A. The results show that heat gains through the windows can be reduced substantially as the SC decreases with increasing overhang length which can lower the variation and maximum values of both indoor air and mean radiant temperature in the indoor built environment leading to an increase in thermal comfort for occupants.[49,50] The cooling plant will also work less with higher heat gain reductions and that is why we see a decrease in overall energy consumption as overhang length increases. Finally, reduced heat gains may also require lower cooling capacity in the plant thus savings on capital costs for building owners in new construction. Figure 7 only represents one type of shading device. There are more types of shading devices that are more effective than others. Further analysis will be needed to determine which is more effective for the building type and occupant comfort needs. The results presented here do not include the potential savings from the availability of daylight in the space but the energy model has the functionality to add daylighting controls to assess the impact of daylighting.

Finally, it is important to note that these energy models are one possible reference GM model for Singapore that the three involved parties came to an agreement upon given the

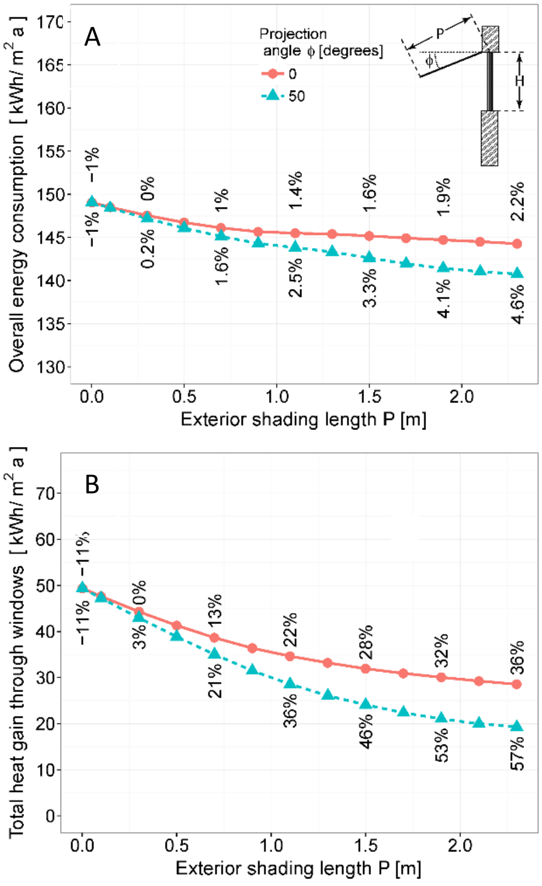

Figure 7: Model-AI's (A) overall energy consumption for different exterior shading length, P, and projection angle, ϕ; (B) Heat gains through windows for different exterior shading length and projection angle. The height of window, H, in model-A is 2.3 m.

information available. The absence of statistically representative measured data about the population of Singaporean GM certified large commercial office buildings and the expected diversity of designs within that population, means that other reference models may also be valid choices. Nonetheless, current mandatory reporting of Singapore's building stock energy consumption along with additional detailed surveys have the potential to develop benchmarks that represent larger portions of the building stock and fit into Shahrestani, Yao, and Cook (2014)'s category three of benchmarks.

Furthermore, this GM energy office building model, like any other energy model, does not represent actual energy usage of a specific building. It is an estimate of energy consumption given a specific set of performance requirements established through policy and current design practices in Singapore. It is intended to provide a standardized baseline in which building stakeholders in Singapore can consistently assess a variety of different building technologies and strategies. Therefore, the change in energy as a percentage from the baseline energy consumption due to upgrades in the envelope, cooling system, or other desired proposed design analysis in the energy model is a more useful result than absolute differences in energy.

Conclusions

We have created a whole building energy model to represent a typical large commercial office building in Singapore which meets the local green rating program. We followed an iterative process to ensure that assumptions were reasonable for the context of a large office building in Singapore, and model inputs values were approved by a government agency and a private consulting firm. Nevertheless, we could improve these assumptions with more detailed information about the built environment in Singapore. For example, plug loads can vary depending on the occupancy density of the building and we found very little information regarding its value for a commercial office building in Singapore.

The models allowed us to look at results pertaining to energy consumption in detail that is otherwise difficult to obtain from direct building measurements. The energy use intensity (EUI) is 146 $kWh \cdot m^{-2} \cdot a^{-1}$. Breaking down the EUI results in the air conditioning and mechanical ventilation (ACMV) system contributing 43% of the total annual electricity consumption followed by lights and plug loads at 29% and 21%, respectively. Ventilation is the most significant source of cooling loads for the building with 29% of the total, windows contributing 20% in model-A and 11% in model-B, and lights, people, and plug loads contributing 15% each to the total cooling loads. The cooling load through the wall is quite low in the all-glass façade building (model-A) contributing only 3% but is equal to the window cooling loads in the concrete façade building (model-B) at 11%. This type of breakdown is useful for researchers and other building stakeholders in determining a plan of action for future development of energy efficiency measures.

The detailed results also showed that fenestration systems are a component that researchers should focus on, especially in all-glass façade buildings. Windows provide daylighting that can help reduce electric lighting in buildings but can also introduce a major percentage of cooling loads into a fully glazed facade building in the tropics. As the efficiency of electric lighting systems increases, the value of daylighting decreases from a purely energy perspective. However, views to the outside have many other benefits to occupants. The correct balance between window-to-wall ratio, shading, and glass types for different orientations of the building will help lower cooling loads and still provide daylighting and views to the outside. Another area for researchers to focus on is reducing the energy associated with ventilation. This could be done with demand control ventilation or by increasing temperature setpoints.[51,52] Significant energy savings can be realized by supplying outdoor air based on actual occupancy. Excess outdoor air is eliminated that does not need to be cooled and dehumidified. Fan energy savings are also possible with demand control ventilation and the use of the wider range of variable frequency drive settings.

The process of deriving model-B showed that ETTV can be an effective simplified metric to compare the heat flow through the envelope with different wall construction assemblies in a hot and humid climate. The all-glass façade building showed almost the same total envelope cooling loads as in the concrete façade building. The minor discrepancy between the total was because of thermal mass differences. However, the distribution of conduction versus solar changed significantly.

Finally, building stakeholders can use this freely available energy model as an additional tool, representing a typical large commercial office building model in Singapore, to test innovative energy efficiency measures, analyze policy changes in energy code, and other building related studies.

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