Explore the cooling demand change in a residential district under typical meteorological year and extreme hot year based on an OB LoD modelling framework

Hanyun Wang¹, Yi Wu², Jiaqian Chen¹, Da Yan*, Mingyang Qian²

¹ State Grid Zhejiang Electric Power Co., Ltd. Huzhou Power Supply Company, Huzhou, China
² Building Energy Research Center, School of Architecture, Tsinghua University, Beijing, China

*Email of the corresponding author: yanda@tsinghua.edu.cn

Abstract

In recent years, with the development of urbanization, the ownership of residential air-conditioning and the cooling energy consumption increased significantly. Various occupant air-conditioning (AC) behavior has led to nearly ten-fold discrepancy in energy reported by IPCC. It is critical to further investigated the cooling energy used by occupants. Recently, with the increasing occurrences of extreme hot weather events, it has led to an obvious increase in residential AC usage and thus, the energy consumption. It is especially necessary to evaluate the influence of extreme hot year (EHY) on occupant AC behavior and their cooling demand changes to quantify the impact and provide mitigation measures. Current studies have devoted to generate proper EHY data and adopted existed building performance simulation (BPS) tools to simulate the energy performance. Yet, the changes in cooling demand of a district has seldomly been investigated and evaluated facing various engineering applications using corresponding performance indicators. Therefore, this study detailedly explored the cooling demand changes in a certain district under typical meteorological year (TMY) and EHY by proposing indicators including: total cooling load, peak cooling load, load duration curve and typical daily curve four aspects. Based on the previous proposed occupant AC behavior level-of-detail (LoD) modelling framework, it is feasible to simulate the cooling demand changes thoroughly and accurately. Based on the results, the extent of cooling demand changes is calculated and the performances of various LoDs are concluded to provide the appropriate modelling approach under the target indicator and achieve potential mitigation under EHY.

Highlights

- Explore the cooling demand of a residential district under extreme hot weather
- Adopt and determine the appropriate level-of-detail air-conditioning behavior model facing different engineering applications
- Provide a overall simulation framework of district cooling energy under typical meteorological year and extreme hot year

Introduction

Building sector accounts for about 30% of global energy consumption, as reported by IEA(IEA 2019). Meanwhile, with the rapid development of urbanization and rising rate of air-conditioning (AC) equipment ownership, cooling energy consumption in buildings is increasing significantly, indicating a great potential for energy conservation. Meanwhile, apart from the energy shortage situation, the increasing cooling demand also leads to more greenhouse gas (GHG) emissions, accelerating the problem of global warming and climate change (Shourav et al. 2017). The fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) reported that the indisputable warming of the earth’s surface is up to around 0.9 °C since the late 19th century (Pachauri et al. 2014). Along with the climate change, the occurrences of extreme weather events, most notably unprecedented heat waves, are increasing obviously and posing great threats to energy infrastructure and people’s life. In 2017, a Florida nursing home experienced a three-day loss of AC supply because of the power system failure during a hot summer, resulting in 12 patient deaths for the overheated indoor room temperature (Reisner et al. 2017).

Therefore, it is critical to pay attention to the extreme hot weathers and their impact on building energy consumption, especially cooling. Plenty of scholars have devoted into related studies and proposed potential measures to mitigate the problem. Tobi et al. (Morakinyo et al. 2019) estimated the impact of extreme heat events on cooling energy demand in Hong Kong and they adopted cooling degree days (CDD) as the index to analyze weather trend and quantify the impact of extreme heat events. Kim et al. (Kim et al. 2022) proposed a novel index to define heat wave and its intensity based on future weather data, and using Pearson’s method to calculate the correlation between extreme high temperatures and electricity demand in Korea. Sherman et al. (Sherman et al. 2022) put forward a simplified equation using webbulb globe temperature to estimate AC demand, and further analyzed the AC demand increasing trend till 2050 in future based on the CMIP6 weather dataset (Eyring et al. 2016). Sheng et al. (Sheng et al. 2023) selected an extreme heat wave weather using the previous indexes (Ouzeau et al. 2016)and simulated the thermal environment of an assisted living facility by three resilience metrics, and then evaluated the effects of potential mitigation measures including improving building envelope, adding natural ventilation, using ceiling fan, etc. during the heatwave.
From above studies, to evaluate the impact of extreme heat weathers on AC energy consumption, it generally requires two steps: proper methods to define and generate extreme hot weather, and then establish AC usage model to reflect or simulate the weather impact. To determine the extreme hot weather, previous studies have proposed simple indexes using threshold temperatures (Möller et al. 2022) and combined metrics considering multiple environment parameters, such as standard effective temperature (SET) (Gonzalez et al. 1974), heat index (HI) (Awasthi et al. 2022), etc. When simulating the AC usage, researchers have considered that AC cooling demands are usually fixed by giving a stable AC on/off status schedule. In recent years, considering the stochasticity of occupant behavior, researchers have already developed various types of stochastic occupant AC behavior models, including logit regression model with outdoor temperatures as input (Schweiker and Shukuya 2009), markov chain model using indoor temperatures as triggers (Yamamoto and Hagishima 2005) and three-parameter weibull model driven by indoor temperatures (Ren et al. 2014; Wang et al. 2016), etc.

Based on the reviewed studies, many scholars have studied effective methods to generate EHY data using future weather datasets. And existed studies have put forward various AC behavior models to simulate AC usage with weather parameter as inputs. Yet, the spatial scale of current studies usually focus on a single building and there is no consensus on the level of detail (LoD) to describe AC behavior model in district cooling energy usage simulation under extreme hot weather. Therefore, this study focused on the impact of extreme hot weathers from the district level. By defining different OB LoD models, quantitative simulation analysis was conducted to investigate the change of cooling demands between the extreme hot year (EHY) and typical meteorological year (TMY). Meanwhile, based on the simulation results, proper LoD of OB models could be recommended and mitigation measures were further discussed.

The paper is organized as following. Method section introduces the four steps of the overall technical approach. The Result section demonstrates the comparisons of different AC behavior LoDs models under TMY and EHY weather. Then, in the discussion, proper AC behavior LoD is suggested and potential mitigation strategies are putforward. The conclusion part summarizes the overall research.

**Methodology**

The research technical framework is shown as Figure 1. There are four primary parts, including weather data generation, OB LoD model establishment, district cooling demand simulation and model performance evaluation. The detailed steps to conduct the simulation are introduced in the following section.

**Weather data generation**

**AC behavior LoDs**

**Building performance simulation**

**Key performance indicator definition**

**Figure 1: Technical approach of this study**

**Weather data generation**

The study adopted fifth-generation reanalysis product released by the European Centre (ERA5) as the weather data source, covering hourly dry bulb temperature (°C), wet bulb temperature (°C), wind speed (m/s) and direction, solar radiation (W/m²), etc. from 1950 to present (Hersbach et al. 2020). The reliability of dataset has been validated and widely applied in climate research fields (Urraca et al. 2018; Gil Ruiz et al. 2021; Soukissian et al. 2021).

When generating the weather data in this study, we used ERA5 as the multiple historical database and the CSWD method in previous research (Wu et al. 2023a) was adopted to generate TMY data. Existed studies (Cui et al. 2017) have validated that CSWD method could reflect the average weather conditions of the historical AMY in multiple climate zones in China, thus confirming the validity of CSWD method and the method is widely acknowledged in China. The time span of historical database was from 2006 to 2020, including fifteen years. TMY data of Hangzhou is generated and utilized in this study for the simulation to represent the condition during average weather.

As for the generation of EHY, the selection method in Guo’s study (Guo et al. 2020) was adopted, where EHY is selected using the index of CDH35. The equation of CDH35 is shown as Equation (1).

\[
CDH_{35} = \sum_{i=0}^{8760} (t_i - t_{base})^+ \tag{1}
\]

Where \(t_i\) represents the air temperature at the \(i^{th}\) hour (\(i = 0, 1, \ldots, 8760\)) and \(t_{base}\) is the threshold temperature, which is 35 °C herein. \((\cdot)^+\) means accumulating when \((t_i - t_{base})\) is positive.
By calculating CDH35 of each year from 2006 to 2020, one continuous year with the highest CDH35 was selected out as the EHY data.

**OB LoD model establishment**

The study defined and followed four different LoDs for occupant AC behavior models according to the previous study (Wu et al. 2023b). Based on the definition of OB LoD framework (Malik et al. 2022b), it has defined 10 attributes of OB models while the attributes considered in the proposed four LoDs to distinguish the different kinds of AC behavior models in this study are illustrated herein, as shown in Table 1.

Table 1: Four LoDs for AC behaviour models

<table>
<thead>
<tr>
<th>LoD</th>
<th>Representation</th>
<th>Occupancy</th>
<th>Decision-making models</th>
<th>Heterogeneity</th>
<th>Collective</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-0</td>
<td>Average occupant</td>
<td>Fixed</td>
<td>Fixed</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>O-1</td>
<td>Average occupant</td>
<td>Stochastic</td>
<td>Probabilistic OR stochastic</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>O-2</td>
<td>Group of occupants</td>
<td>Stochastic</td>
<td>Probabilistic OR stochastic</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>O-3</td>
<td>Individual</td>
<td>Stochastic</td>
<td>Probabilistic OR stochastic</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

The LoD O-0 is defined as the fixed-schedule model, which is one of the traditional OB modelling techniques in BPS tools. From LoD O-1 to LoD O-3, they are stochastic models. LoD O-0 represents average occupant but with stochasticity. LoD O-2, containing several typical patterns, can represent different groups of occupants with various cooling demand levels. LoD O-3 is completely individual model representing each household user himself/herself. The stochastic model for AC behavior simulation from LoD O-1 to O-3 is the three-parameter Weibull method proposed in Wang’s study (Wang et al. 2016) and the calculation method is as demonstrated in Equation (2).

\[ y = \begin{cases} 1 - e^{-\left(\frac{x-u}{\tau}\right)^{k}}, & x > u, \text{turn on when feeling hot} \\ 0, x < u \end{cases} \]  

Equation (2)

Where \( u \) is the threshold for the uncomfortable domain controlling the beginning of the turn-on action. \( L \) indicates the range of function variables, and \( k \) describes the shape. \( \Delta \tau \) refers to the time step of the data, and \( \tau_c \) is the time constant.

**Building performance simulation**

DeST, a building performance simulation tool, is adopted in this study, which is a whole-building energy modelling program developed by Tsinghua University, China (Yan et al. 2022). As for the occupant behaviour modelling, the study used the module embedded in DeST which contains occupant movement based models on the algorithm of Markov Chain (Wang et al. 2011) and the AC behaviour model based on three-parameter Weibull method (Wang et al. 2016).

The studied residential district in this study was a housing estate including 400 households in Hangzhou, China and the cooling season is defined from May 1st to August 31th. The floor plan of one single household is displayed as Figure 2, and the residential household model is also established using DeST software.

**Figure 2 Floor plan of single household**

**Key performance indicator selection**

When investigating the impact of EHY on district cooling demands, various analysis purposes require different KPIs. Considering common engineering applications in district cooling simulation, four KPIs are put forward in this study to in-depth demonstrate the simulation results under TMY and EHY data using four OB LoD models.

The four KPIs include district total cooling load (kWh/m²), peak cooling load (kW/m²), cooling load duration curve and typical daily cooling load curve. Total cooling load can represent the overall cooling demand of all the 400 households under a typical and an extreme hot cooling season. Peak cooling load is an indicator widely-used in the design of district cooling device and critical to the urban power grid. Cooling load duration curve indicator reflects the hourly demand distribution of the whole district, which is a common index in the designing of thermal storage system. Moreover, the typical daily curve is an effective index to demonstrate the load fluctuations in one day. Therefore, detailed comparison analysis is carried out based on the four KPIs.

**Result**

**Results of TMY and EHY**

Based on the existed studies (Guo et al. 2020; Wu et al. 2023a), TMY and EHY data for Hangzhou city was generated and EHY was selected as 2013 from 2006 to 2020. The comparison of air temperatures between TMY and EHY data are demonstrated as shown in Figure 3. It can be noticed that during the summer season, the selected EHY data demonstrates higher temperatures.
Figure 3: Air temperature comparison between TMY and EHY

Moreover, the CDH35 index of TMY is 323.15 hours and CDH35 of EHY is 1272.7 hours. The two weather data files are further used as the meteorological input in the following simulation.

Results of cooling usage change

The change of cooling usage of 400 households in the district is further investigated, and cooling use duration is calculated as the indicator to reflect occupants’ AC use behaviour. The distributions of cooling use duration of different LoDs under TMY and EHY and the cooling use duration deviation between TMY and EHY are demonstrated as Figure 4. Given that LoD O-0 is a fixed schedule model, the cooling use duration under TMY and EHY is 1399 hours, which is the same of two simulations, thus not demonstrated in the following.

From Figure 4(A), it can be noticed that the distribution of simulated cooling use duration by LoD O-3 under TMY is flatter and more dispersed than the distribution under EHY, and the peak occurs at relatively lower intervals, which means that when the weather becomes hotter, occupants will tend to use AC for a longer time and the variances among users are reduced because for those users who do not turn on AC during TMY will turn on AC during EHY, leading to a more concentrated peak of cooling use duration under EHY. As shown in Figure 4(C), LoD O-2, using five typical patterns to represent the whole population, also simulated similar trends with the results of LoD O-3, showing a more concentrated peak under EHY. Yet, the distribution scale and the shape of LoD O-2 results is narrower and non-continuous due to the limited types of occupants. While in Figure 4(E), it can be noticed that LoD O-1 do not simulate the tendency for the peak of cooling use duration distribution to become more concentrated under EHY. The two distributions under TMY and EHY by LoD O-1 are quite similar, except that the overall shift is to the right, which infers that only use one type to represent all households in the district cannot reflect the diverse of occupants and their behaviour change.

Figure 4 (B),(D),(F) displays the deviation of cooling use duration between TMY and EHY using different LoDs. The deviation simulated by LoD O-3 distributes from -200 hours to 400 hours while the deviation by LoD O-2 distributes from -50 to 150 hours. And the distribution of LoD O-1 is from -100 to 200 hours.

Results of four KPIs

After calculating the four proposed KPIs to analyse the various LoDs under TMY and EHY, the total cooling load results are demonstrated as Figure 5. It shows that using LoD O-1, LoD O-2 and LoD O-3 can derive similar total cooling load results and the deviations between TMY and EHY data, which is 2.9, 3.3, 3.5 (×10^4kWh/m²) separately. Yet, the results of LoD O-0 is obviously higher than other LoDs and the deviation between TMY and EHY is also smaller than other LoDs. The reason is that LoD O-0 is a fixed model, not reflecting the environmental-related features of occupant AC behaviour. The increased cooling load is all due to the change of weather in LoD O-0 results, but the increase loads of other LoDs are resulted from both increase of outdoor temperature and the change of AC behaviour caused by the rise of indoor temperature.

Figure 5: Total cooling load results under various OB LoDs and weather conditions

As for the district peak load simulation, the results of peak load demonstrate similar trend with the total cooling load. Results of LoD O-0 are significantly higher than other LoD results. For the other three LoDs, under TMY weather input, the peak load result of LoD O-1 is slightly higher than LoD O-2 and LoD O-3, the result of LoD O-3 is the lowest and the LoD O-3 result is around the medium. Meanwhile, under the EHY weather input, LoD O-3 is the highest among the three OB LoDs. The
deviations between TMY and EHY of LoD O-3 and LoD O-2 are similar to each other, but the results of LoD O-1 displays a relatively smaller deviation.

Figure 6: Peak cooling load results under various OB LoDs and weather conditions

When calculating the load duration curves of the simulation results, the results of two different weather inputs are separately demonstrated as Figure 7.

From Figure 7, it can be seen that through LoD O-0, the fixed model, the district cooling load will be calculated quite high and the cooling load curve is not continuous both under TMY and EHY weather conditions, inferring that fixed-schedule model is not suitable for analysing the cooling demands of district, especially when studying the district cooling load distribution. With regards to the other three LoDs, the results of LoD O-1 seems higher than LoD O-2 and LoD O-3 in the TMY while the three LoDs are quite similar in the EHY. This phenomenon indicates that in TMY, when the outdoor temperature is not quite high, only using one type of AC behaviour model to represent all users will over-estimate the cooling load because occupants are different from each other. Some occupants may not open the AC until the indoor temperature reaches 29°C or even higher. One model could not reflect the feature. LoD O-2, with five typical patterns, can represent different cooling demand levels of occupants to a large extent, therefore resulting in a similar load duration curve with LoD O-3.

But in EHY, the outdoor temperature is high enough for most of users to open AC, meaning that the effects of diversity and stochasticity of occupants now are reduced comparing with the TMY. Therefore, the load duration curves of LoD O-1, LoD O-2 and LoD O-3 are similar to each other and obviously higher than those in TMY.

Figure 7: Load duration curves of various OB LoDs under TMY and EHY

When observing the typical daily load curve, July 9th is selected as the specific day because the maximum air temperature exceeds 35°C. Meanwhile, July 9th of TMY data is also screened out. The daily load curves of the typical day in TMY and EHY are shown in Figure 8. It is obvious that similar to previous KPIs, the fixed schedule model, LoD O-0, demonstrates great deviation from other LoDs in both TMY and EHY. In Figure 8 (A) the TMY results show that simulations by LoD O-2 is quite close to the results of LoD O-3, which indicates that the five typical patterns of occupant behaviour and their corresponding proportions, defined in LoD O-2, can generally represent the district cooling demands of 400 distinct users. However, in TMY, LoD O-1 shows large discrepancy, meaning that single type of occupants is not able to represent the whole population.

As in Figure 8(B), despite that curves of LoD O-2 and LoD O-3 are closer to each other, the three curves from LoD O-1, LoD O-2 and LoD O-3 become more similar than those in TMY. The phenomenon infers that using one average stochastic OB model now can represent the whole population, and it is consistent with the conclusions drawn in the analysis of load duration curves that due to the increase of outdoor temperatures, most users would turn on AC during that time, therefore reducing the impact of occupant diversity in cooling load simulation.
Limitations

The study presents the overall simulation of the cooling loads on a district level during TMY and EHY. Yet, there are still several limitations to be improved. Firstly, the selection method of EHY is based on historical weather. With the future weather datasets have been put forward and applied in wide researches, such as CMIP6, etc. Further studies can be conducted to construct EHY based on future weather and evaluate the demand change between current TMY and future EHY (Eyring et al. 2016). Secondly, considering the cooling demand is primary focus in this study, occupant AC behaviour is the main focus and the various LoD settings are primarily concentrated on the AC behaviour during the simulation. While for the occupant movement module, the study has simplified and assumed that all the movement patterns of occupants are the same. Given that most occupants demonstrate leaving in the morning and back home at evening in previous surveys (Liu et al. 2023), all the movement patterns are set as the worker’s schedule in the existed research (An et al. 2017), which does not exactly reflect the real condition. Therefore, further improvements could be implemented to refine this study.

Conclusion

The research investigates the impact of extreme hot weathers on occupant AC behavior in a residential district. Considering that no consensus on the LoDs of AC behavior models, four different levels of granularity of models are considered in this study to determine an appropriate LoD in district cooling simulation under extreme hot weather facing various KPIs. The study followed the defined four AC behavior LoDs in previous studies and selected two meteorological years, TMY and EHY data, as the district load simulation input. Based on the result analysis, primary conclusions are drawn as following:

1. When investigating the cooling usage change of each household in the district, the results of LoD O-3 demonstrate that cooling use duration under EHY distributes more concentrately and the deviations are nearly ranging from -200 hours to 400 hours. Yet, other LoDs did not demonstrate similar results. This indicates that when the analysis target is at household level, it is necessary to use LoD O-3 with the detailed information for 400 users.

2. In terms of two KPIs, i.e. total cooling load and peak cooling load, it is demonstrated that except the results of LoD O-0 is quite large, other three LoDs derive similar simulation results under both TMY and EHY, which indicates that when analyzing from the district level and concerning about the single gross indicators, it is feasible to apply LoD O-1, which is the simplest.

3. When analyzing the load duration curves, the results of LoD O-0 deviates from the other three curves quite a lot, thus unrecommended in the simulation of load duration curves. Moreover, it is discovered that when the weather is TMY, LoD O-1 also deviates from the other two LoDs obviously, but when using EHY as the meteorological input, the results of three LoDs become consistent more. It is because in EHY, the outdoor temperatures are high enough leading to high indoor temperatures, causing most occupants turn on AC. In such situation, the influence of occupant diversity is not obvious as that in TMY, leading to similar results among LoD O-1 to LoD O-3. Therefore, when analyzing the load duration curve under EHY, LoD O-1 is also feasible with the simplest model settings.

The study proposed a simulation framework of district cooling under extreme hot weather using various LoDs of AC behavior models. Future studies can further...
investigate a proper way to determine the AC behavior LoD when studying the impact of heatwave on a district energy consumption. Moreover, the generation of extreme hot weather data could be more generalized to fit the future weather changing trends.

Acknowledgement

The research is supported by Research on key technologies for building power system integrated “photovoltaic, DC, and flexibility” and zero carbon building. (Contract No.: SGZJHU00FZJS2200028)

References


