Comparative study of using periodic daily and long-term weather data for cooling system sizing and impact of thermal mass

Seyed Shahabaldin Seyed Salehi[2*], Jarek Kurnitski[1,2,3], Martin Thalfeldt[1,2]
[1]FinEst Centre for Smart Cities (Finest Centre), Tallinn University of Technology, 19086 Tallinn, Estonia
[2]Department of Civil Engineering and Architecture, Tallinn University of Technology, 19086 Tallinn, Estonia
[2]Department of Civil Engineering, Aalto University, 02150 Espoo, Finland
* *Corresponding author: shahab.salehi@taltech.ee*

Abstract

The energy efficiency of buildings is increasing due to energy performance requirements, and the basis for reaching high energy performance is a well-designed and insulated building envelope. Therefore, office buildings' cooling needs depend primarily on solar and internal heat gains, whereas outdoor temperature has a significantly smaller effect. Furthermore, the highest cooling capacities may occur in spring or autumn when the solar angles are smaller. For that reason, the cooling systems of office buildings are required to be sized based on dynamic building performance simulations. Most of such designs in Northern Europe are performed using IDA ICE simulation software, which uses the ASHRAE Fundamentals heat balance method by default. The design calculations are carried out using a periodic steady-state method which consists of repetitive simulations of selected hot days until the building is not heated up from day to day using the final designed cooling capacity. The process of heating the space by thermal loads in buildings with high thermal mass and well-controlled solar heat gains takes a longer time than in traditional buildings. Thus, the effect of building thermal mass on reducing the design cooling loads might be underestimated.

In this paper, we analyze to what extent the ASHRAE Fundamentals method underestimates the effect of the building thermal mass. For this purpose, the cooling system sizing with a focus on a zonal level according to the ASHRAE handbook is compared to the system sizing results of a 30-year simulation using IDA ICE simulation software. A hypothetical office building with four offices toward North, West, South, and East is developed and used for the simulations. The building body comprises four alternatives A to D, which can also be called: very light, light, heavy, and very heavy. The study showed that the current method of cooling design did not significantly underestimate the thermal mass effect in buildings with heavy construction. The thermal mass impact was at its maximum in the southern office, resulting in 5 W/m2 or approximately 20% difference between structures A and D's cooling capacities using both simulation methods. The difference between results from simulation methods is negligible. However, the simulations for more accurate cooling system sizing with criteria related to the operative temperature need to be done using specific weather files developed for simulations in longer periods.

Introduction

Recent years have seen increased interest in buildings with net-zero or near-zero energy usage. The energy performance requirements are in place to help cut down the amount of energy used in buildings (Eleonora, Frey, & Rizzi, 2013). A well-insulated and well-designed building envelope is the foundation for high energy efficiency in buildings. Passive solutions for decreasing cooling and heating demand, implementing renewable energy systems, and using more efficient HVAC (active) systems are the primary design considerations for such structures. Some passive solutions, including shadings, natural ventilation, passive façade design, high thermal mass, etc., can be utilized to remove or decrease some of the heat gains for effective cooling design (Oh, et al., 2017).

In highly insulated buildings, the thermal load from higher outdoor temperatures is reduced, and the share of contribution by internal heat gains and solar gains to the thermal loads and cooling system sizing is increased. Therefore, in the countries with higher latitude, specifically colder climates in Europe, the highest cooling capacities may occur in spring or autumn when the solar angles are smaller. This is, however, limited to the north-faced and south-faced offices. (Thalfeldt & Kurnitski, 2014) As a result, office building cooling systems must be sized using dynamic building performance simulations. Most of these simulations in northern Europe are conducted using IDA ICE simulation software, which uses the ASHRAE Fundamentals heat balance approach (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2017) by default. (EQUA, 2013) The approach uses a periodic steady-state method that consists of repetitive simulations of selected hot days until the building does not become overheated from day to day when the final designed cooling capacity is used, at which point the design calculations are completed. Structures with high thermal mass and well-controlled solar heat gains take longer to heat than buildings with low thermal mass and lower solar heat gains. As a result, it is possible that the impact of building thermal mass on reducing the design cooling loads has been underestimated.

This research focuses mainly on identifying and possibly quantifying how much the steady-state method for cooling sizing underestimates the impact of thermal mass. Regardless of how much building materials can contribute to cooling, they may store heat and release it when the temperature difference is large enough. (Sarbu & Sebarchievici, 2018) The key influence of thermal mass is the so-called "peak shifting," which implies that at the peak periods of cooling demand, storage can supply some of the demand to minimize strain on active cooling systems that may lead to smaller HVAC systems. (He, 2004)

This article aims to determine the extent to which the ASHRAE Fundamentals method underestimates the influence of building thermal mass. To do this, the cooling system sizing results from a 30-year simulation using IDA ICE simulation software (EQUA, 2013) are compared to the cooling system sizing results from a zonal level based on the ASHRAE handbook. The simulations are conducted using a generic office building with four offices facing North, West, South, and East. The structure's body is composed of four distinct components, referred to in this study as very light, light, heavy, and very heavy.

Methods

In this paper, two types of simulation methods are called long-term simulation (30 years simulation) and steady-state method (ASHRAE method).

The main steps for this study are summarized below.

1- A generic office building model is developed with four offices. Each office has its windows in one direction, South, East, West, and North
2- The variables of this study are building body and window sizes/glazing. The building body types are four alternatives, A, B, C, and D. The Windows types are also four alternatives, small and Big windows, with and without shadings.
3- For each variation, a specific model is generated and then simulated using long-term (30 years) Simulation and ASHRAE steady-state method.
4- The cooling system capacities were then compared to reflect the amount of cooling sizing underestimation by the steady-state method.
5- Latterly, the operative temperature of two selected cases is analyzed to check if they satisfy EN 16798 standard. The criterion is to have a lower operative temperature than 26°C in 97% of the occupied hours during cooling seasons. (EN 16798-2, 2019)

Figure 1 depicts different alternatives for building bodies with the same architectural layout, and Table 1 shows the two alternatives' windows specifications used in the simulations. The general plan view of the offices is shown in Figure 3, and the three-dimensional view of different windows and shading alternatives is shown in Figure 4.

Four types of structural profiles comprised of walls, floors, and ceilings have a thermal mass difference, which is indicated in Figure 1. Thus, we produced 16 different case studies using a combination of two window sizes, two shading strategies, and four structural profiles for each. The simulation results from the ASHRAE method and long-term simulation using a 30-year climate file are compared.

Several parameters were determined based on EN 16798-1 (European Standard, 2019) or assumptions to facilitate the study. These parameters were as follows:

- The number of occupants in each office was 10, and the installed power of equipment and lighting was 12 W/m^2 and 6 W/m^2, respectively,
- The supply air temperature was 18 °C,
- The offices and the staircase had a Constant Air Volume flow of 1.4 l/(m^2·s) during working hours with one hour margin. The flow outside of the working hours is the minimum amount (0.21 l/(m^2·s)) to take into account the ventilation of toilets, cleaning equipment room, etc. ventilation working on part load.
- The windows had internal blinds drawn when the incident solar radiation on the outside of the glazing exceeded 100 W/m^2. The specifications are mentioned in Table 1,
- The room temperature setpoint was 25°C,
- Internal walls were the same in Three types of structures, A, B, and C. The layers were: 30mm of light insulation and 52mm of gypsum. The internal wall for the D type is just a layer of concrete of 300mm in width.
- The office is located in Tartu, Estonia.

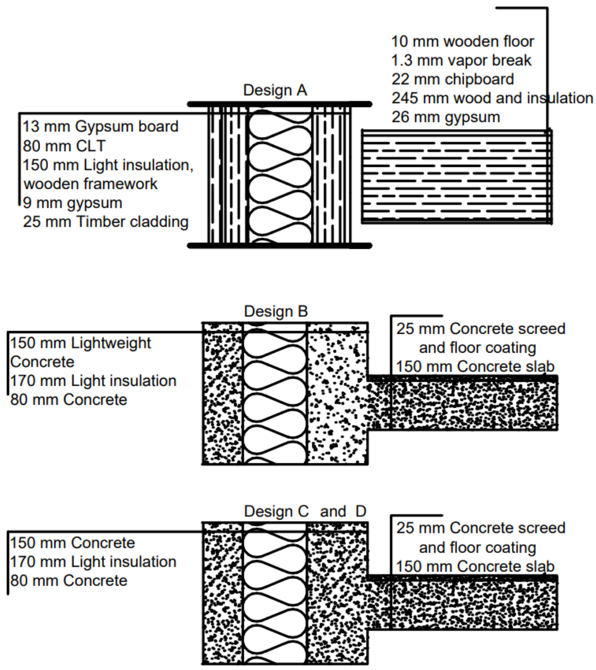

Figure 1: Structural design types of the case studies.

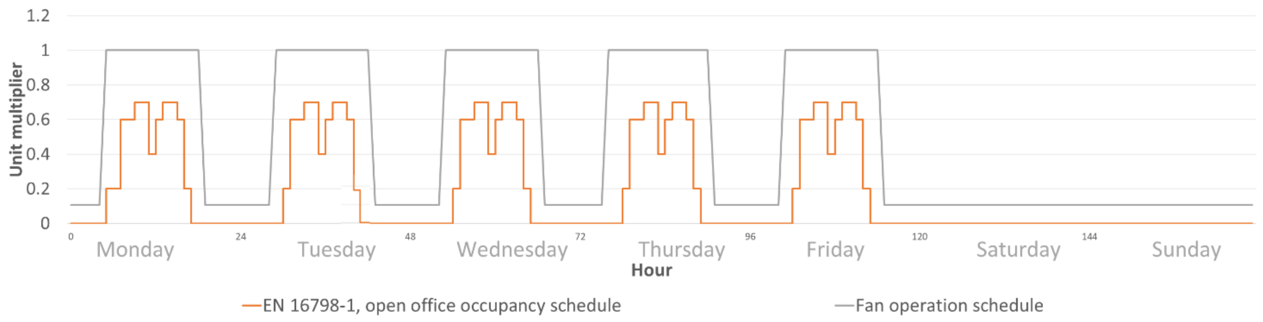

Figure 2: The occupancy and fan operating schedules used in this study.

Table 1: Windows and internal blinds specifications.

Windows group	1 (small)	2 (big)
Width m	1.8	2.1
height m	1	1.9
Area	1.8	3.99
WWR	0.25	0.58
Total windows per office	7	7
Number of layers	3-pane	4-pane
Solar heat gain coef. (SHGC)	0.49	0.32
T. Solar transmittance	0.41	0.28
Visible transmittance	0.71	0.59
Glazing U-value	0.6	0.6
Internal emissivity	0.837	0.837
External emissivity	0.837	0.837
Internal blind solar gain factor	0.65	0.65
Internal blind short-wave shading coefficient	0.16	0.16
Internal blind U-value multiplier	1	1

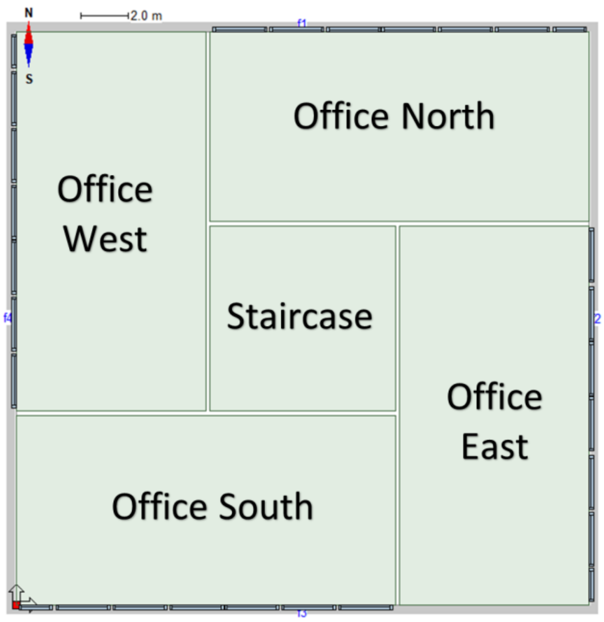

Figure 3: General office plan, 24.5m x 24.5m.

The layout includes four offices with dimensions of 16m x 8m and a total space of 128 m^2. The offices were 3m high. The office used in this simulation is neither on the ground floor nor under the roof. It is a floor in the middle of an office building. This means the model does not have a roof connecting to the ambient air and a floor slab connecting to the earth.

The Simulation process for comparing the results using the periodic steady-state method and long-term simulations can be listed below:

1. A 30 years climate file from 1990 to 2020 is created for the simulations based on historical weather data from the weather station in Tartu, Estonia.
2. Multiple simulation models were created based on building bodies, windows, and shadings variations.
3. The design cooling capacities for each zone were calculated using the steady-state method and long-term simulations using the climate file for each building model.

The simulation, according to the ASHRAE method, needs the identification of design day parameters. By default, the design day parameters can be found for a year, and one set of parameters is used together with the hottest month to size the cooling systems. In this study, we generated the strictest minimum and maximum temperatures for each month according to the ASHRAE handbook and simulated all cases for every month. The minimum and maximum temperatures for the 30-year period according to ASHRAE are listed in Table 2. The maximums are 0.4 percentile of the maximum temperature data points for each month in 30 years.

Table 2: Temperatures for periodic method design days.

Month	Minimum °C	Maximum °C
Mar	13.4	16.8
Apr	20.1	24.9
May	19.5	27.7
Jun	19.7	28
Jul	20.5	28.5
Aug	19.6	28.3
Sep	19.2	27.6
Oct	16.8	18.8

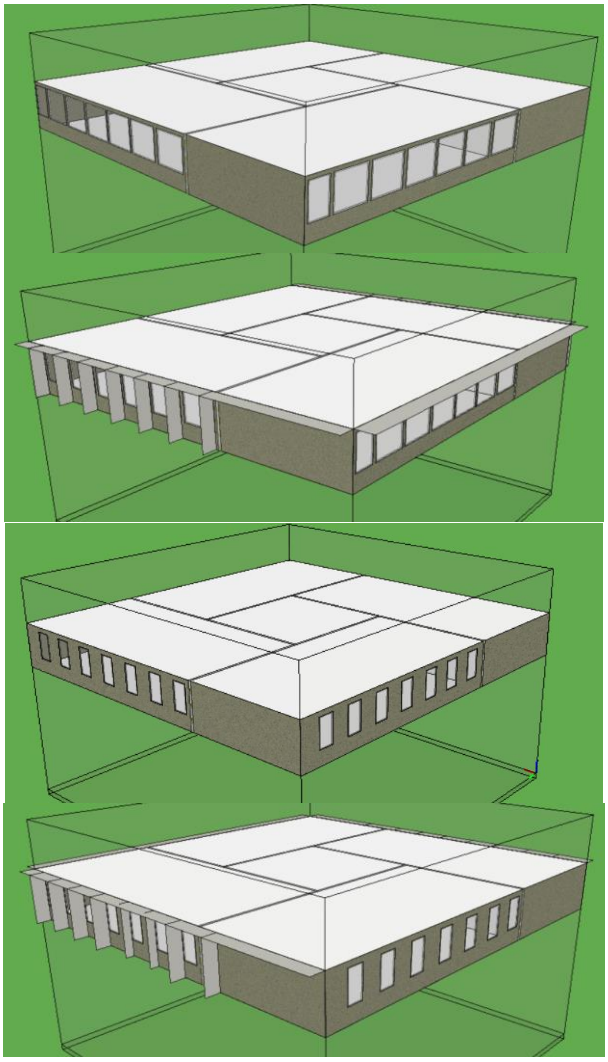

Figure 4: 3d view of the models with two different Window to Wall Ratio (WWR) and shading.

Results

The results are summarized in Figure 5. The largest design cooling capacities occurred in Southern and Eastern offices, proving the importance of solar radiation in efficiently built office buildings. The results from the periodic steady-state method by ASHRAE had the same pattern as long-term simulations. The steady-state method estimated a lower or higher value than the long-term simulation depending on the case study variables. This difference ranges between 1 – 4 W/m^2 for all designed cooling capacities, while it can also be seen that thermal mass does not have a significant impact, as the design cooling capacity difference between structures A (the lightest) and D (the heaviest) levels ranged between 1 – 5 W/m^2 for all cases. The thermal mass impact is at its maximum in the southern office, resulting in 5 W/m^2 or approximately a 20% difference between structure A's and structure D's cooling capacities using both simulation methods. Moreover, the duration curves visible in Figure 8 reflects that the higher the thermal mass, the lower the average operative temperature during cooling periods. The number of hours with an operative temperature higher than 26°C was also higher in buildings with lower thermal mass. Therefore, the overall thermal comfort was better in case studies with higher thermal mass.

The general trend of the results shows that occasionally the long-term simulations resulted in higher cooling capacities. This trend is at the highest for offices with bigger windows without external shadings. This was due to the fact that solar irradiance had much more effect on the sizing of the cooling system using the periodic steady-state method by ASHRAE, which assumes a clear sky for the sizing process. In contrast, in long-term simulation, the sky can be cloudy.

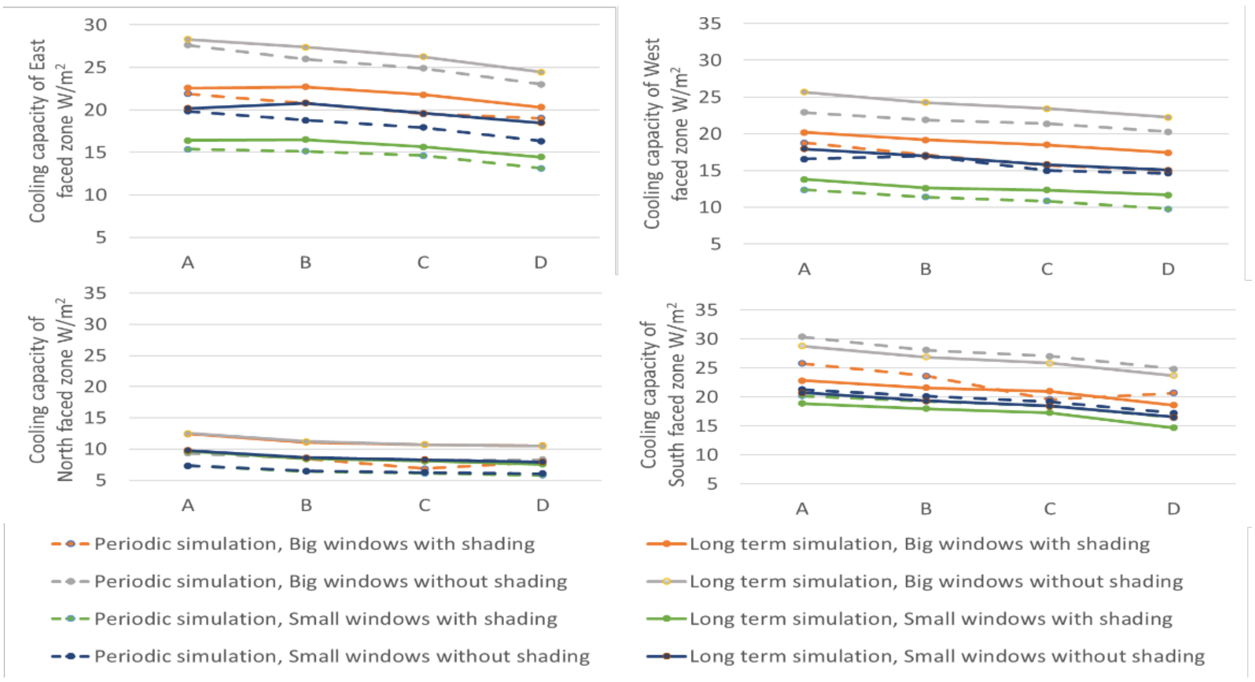

Figure 5: the cooling design capacities for different building bodies, window sizes, and shadings.

https://doi.org/10.1051/e3sconf/202236206002

The window sizes do not affect the cooling capacities for north faced office, indicating the lower impact of solar irradiance in that office. The critical months for determining the cooling system capacity with the steady-state method were in June, July, and August for North, East, and West offices, while for the Southern office, September was the critical month. This is due to the solar radiation effect in such efficiently built offices. Solar radiation has a lower angle during September compared to the summer months; therefore, solar loads were higher in autumn in the office toward the south. To analyze the results in detail, two selected cases are compared. The Big window, no shading settings, and the east and south offices are chosen to have the maximum effect of the sun in the detailed analysis. For structure, a heavier structure body (type D) is selected to include the minor thermal mass effect in the analysis as well. In long-term simulations with actual weather data, the day that the cooling system size peak occurred for office east was the 6th of July 2009, and the date for the Southern office was the 9th of September 2019. The radiation and temperatures of the specific days are presented alongside periodic synthetic climate parameters in Figure 6 and Figure 7.

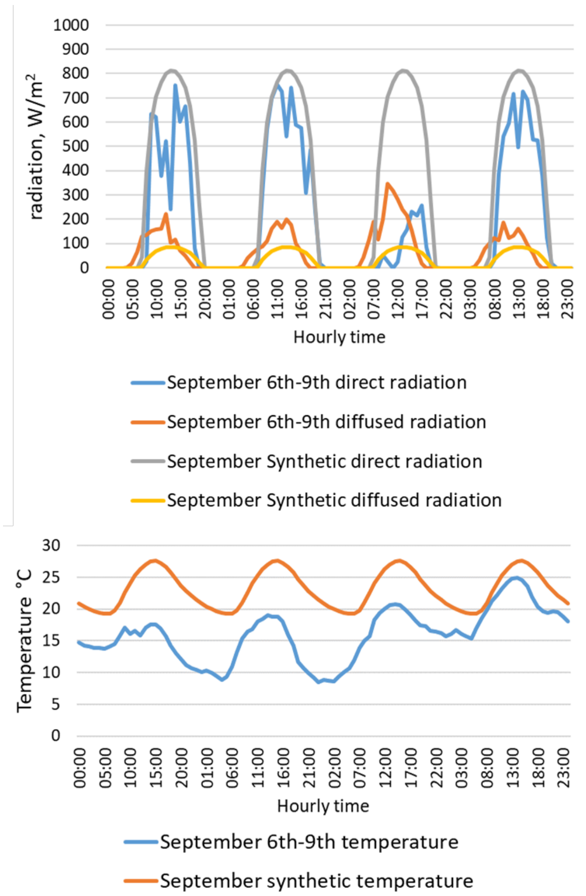

Figure 6: Comparative climate parameters curves for Simulation results in September for both long-term (6th to 9th of September 2019) and periodic (Synthetic climate) simulations

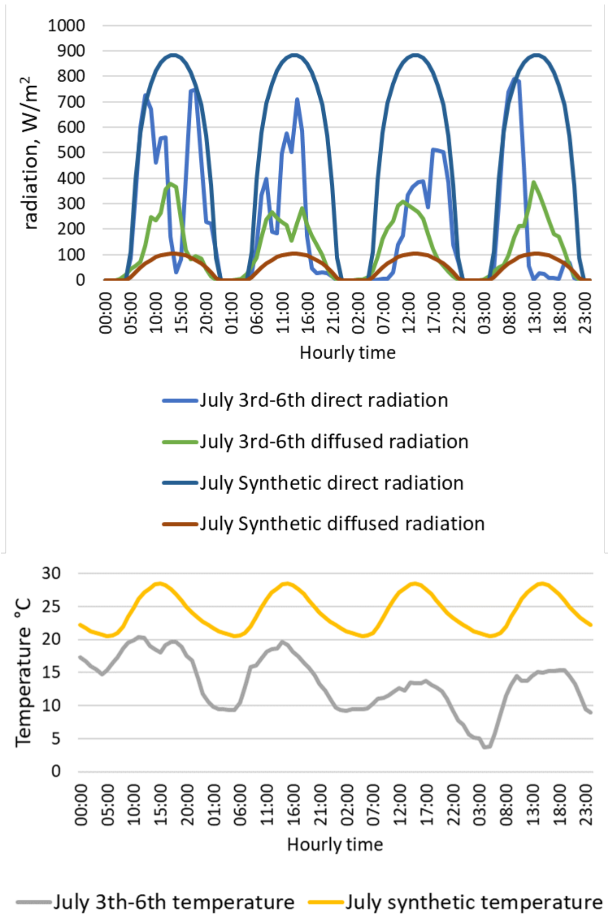

Figure 7: Comparative climate parameters curves for Simulation results in July for both long-term (3rd to 6th of July 2009) and periodic (Synthetic Climate) simulations.

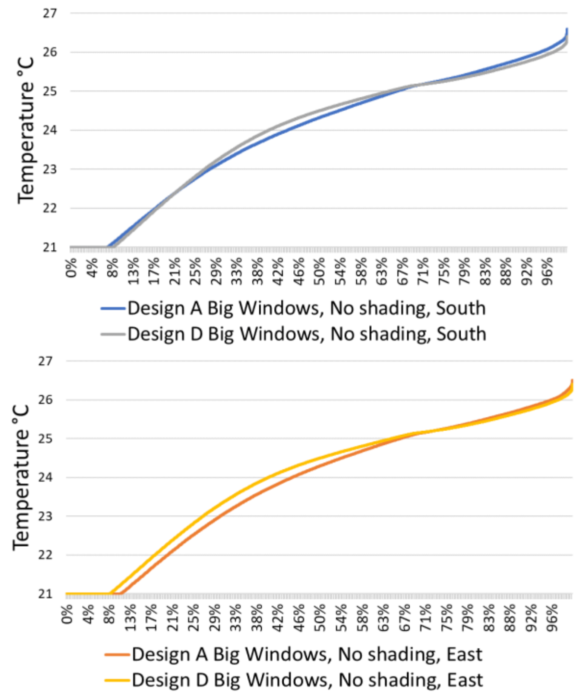

Figure 8: Duration curve for operative temperature in selected cases and offices, temperatures higher than 21 °C are presented only for difference magnification.

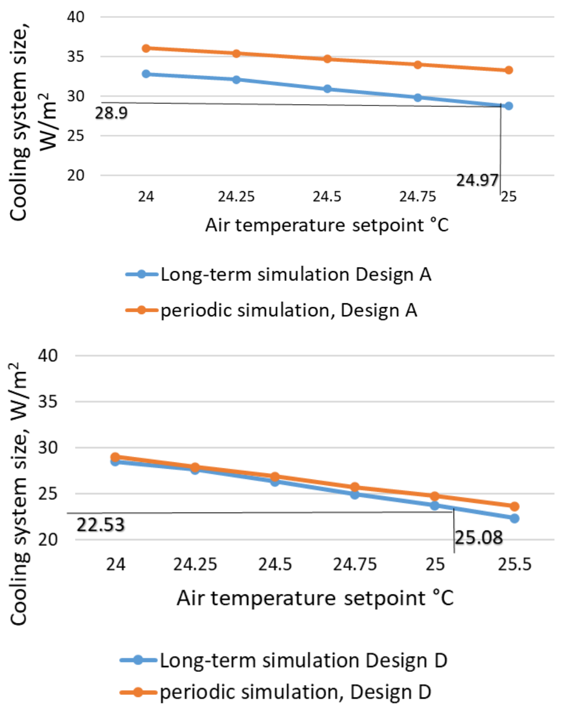

Figure 9: Cooling capacities for different air temperature setpoints for selected cases, A and D for the southern office without shading.

The adjusted setpoints for two selected cases, design A and design D for office south, are 24.97 °C and 25.08 °C, respectively. This means that to compare the two cases considering the operative temperature criterion from EN 15798-1, design A and design D should be simulated with an air temperature setpoint of 24.97 °C and 25.08 °C, respectively. The results are shown in Figure 9. The differences are small, but the difference for designed cooling system size is more in long-term simulations after adjusting the set point. It means that the importance of thermal mass can be more than what is assumed in ASHRAE periodic design method.

Discussion

The long-term simulations resulted in smaller system sizes for offices in the south and bigger capacity for offices in other directions compared to the periodic steady-state method. For calculating the design day, the strictest category, 0.4 percentile of the descending temperature data points, is used as maximum temperature. This can be further studied to what extent the cooling system sizes and thermal comfort is impacted if other percentiles are used for cooling sizing. Additionally, conducting 30-year simulations is not feasible in practice, and further work is needed to determine the weather conditions for dimensioning the room cooling units.

By looking at the results, sizing using air temperature setpoint _the common practice_ without consideration of operative temperature becomes controversial since, according to EN 16798-1:2019 (European Standard, 2019), the number of occupied hours with an operative temperature higher than 26°C should be limited to less than 3% of the total occupied hours during the cooling period. In the future, simulations can be done using adjusted air temperature setpoints to satisfy the operative temperature requirement by the standard to have a more objective comparison of the system sizes.

Moreover, the study can be done with varying building types, orientations, and ventilation strategies (e.g., night cooling) to determine if the underestimation/overestimation happens in all other cases. The geometry difference studies can start with an office layout of 8 offices, 4 in one direction and 4 in a mixed direction on the edge of the layout.

Conclusion

This article aimed to determine the extent to which the ASHRAE Fundamentals technique underestimates the influence of building thermal mass. To do this, the cooling system sizing results from a 30-year simulation using IDA ICE simulation software is compared to the cooling system sizing results from a zonal level based on the ASHRAE handbook. The simulations are conducted using a hypothetical office building with four offices facing north, west, south, and east. The structure's body is composed of four distinct components, referred to in this study as very light, light, heavy, and very heavy. The study found that the current cooling design approach does not significantly underestimate the influence of thermal mass. The thermal mass impact was at its maximum in the southern office, resulting in 5 W/m^2 or around 20% difference between structures A and D's cooling capacities using both simulation methods, and the difference between results from simulation methods is negligible. However, simulations for more precise cooling system size considering operative temperature requirements should be conducted using weather files built for long-term simulations.

Acknowledgement

This work has been supported by the Estonian Ministry of Education and Research, European Regional Fund (grant 2014-2020.4.01.20-0289), the Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE (grant 2014- 2020.4.01.15-0016) funded by the European Regional Development Fund, by the European Commission through the H2020 project Finest Twins (grant No. 856602) and the Estonian Research Council grant (PSG409).

References

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (2017). *ASHRAE® Handbook - Fundamentals (SI Edition) - 18.6.2 Overview.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE).

Eleonora, A., Frey, M., & Rizzi, F. (2013). Towards nearly zero-energy buildings: The state-of-art of national regulations in Europe. *Energy, 57*, 125-133.

Retrieved from https://www.sciencedirect.com/science/article/pii/S0360544212009188

EN 16798-2. (2019). *Energy performance of buildings - Part 2: Interpretation of the requirements in EN 16798-1.* Brussels, Belgium: CEN.

EQUA. (2013). *IDA ICE - Indoor Climate and Energy.* Stockholm, Sweden: EQUA. Retrieved from http://www.equaonline.com/iceuser/pdf/ice45eng.pdf

European Standard. (2019). *EN 16798 - Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.* European Standard.

He, B. (2004). *High-Capacity cool thermal energy storage for peak shaving - a solution for energy challanges in the 21st Century.* KTH, Superseded Departments, Chemical Engineering and Technology, Stockholm. Retrieved from https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A9633&dswid=357

Oh, J., Hong, T., Kim, H., An, J., Jeong, K., & Koo, C. (2017). Advanced Strategies for Net-Zero Energy Building: Focused on the Early Phase and Usage Phase of a Building's Life Cycle. *Sustainability, 12*, 2272. Retrieved from https://www.mdpi.com/2071-1050/9/12/2272

Sarbu, I., & Sebarchievici, C. (2018). A Comprehensive Review of Thermal Energy Storage. *Sustainability, 10*(1), 191. Retrieved from https://www.mdpi.com/2071-1050/10/1/191

Thalfeldt, M., & Kurnitski, J. (2014). External shading optimal control macros for 1- and 2-piece automated blinds in European climates. *Building Simulation, 8*(1), 13-25.