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# Impact of Indoor Environmental Quality Standards on the Simulated Energy Use of Classrooms

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**Abstract:** The effect of indoor environment parameters specified in national and international standards on simulated energy use of an educational spaces were assessed. Standards considered included those of EN, ISO, ASHRAE and ISHRAE. Eight different climatic locations were considered. Energy use to maintain IEQ parameters according to the highest category, Cat. I, is two times greater for Category II of the same standard, while the difference is only 15% when category changes from II to III and from III to IV. On the other hand, when the category of a particular standard is shifted one level down, requirements for IEQ parameters are relaxed. If parameters are set to comply with Category II instead of the Category I, operative temperature stays within the range specified for Category I 30% less time, while indoor air quality in terms of the $CO_2$ concentration remains within the Category I requirements 60% less. It is less energy expensive to improve IEQ parameters by moving from setpoints of the Category III to Category II than from Category II to Category I.

**Keywords:** IEQ, standards, classrooms, energy use, thermal comfort, air quality

## 1. Introduction

The energy needs of buildings account for 20–40% of the total energy use in developed countries, more than either industry or transportation sectors in the EU and USA (Perez-Lombard L., 2008). Worldwide, the building sector consumed 20% of the total delivered energy in 2016 (U.S. Energy Information, 2016). In addition, buildings contribute significantly to global $CO_2$ emissions, up to 36% in the EU (Directorate-General for Energy, 2017). Generally, design of buildings is guided by a combination of international IEQ standards developed by organizations such as ISO, EN, ASHRAE and national IEQ standards that define the acceptable quality of indoor environment assuring at least the minimum requirements for occupants' well-being and health. Standards categorize IEQ parameters and specify ranges of acceptable values for each category. Specifying a narrow range of acceptable values can result in increased energy demand (for example, as a consequence of high ventilation rates). In the effort to reduce energy use in buildings, it is crucial to focus on maintaining an acceptable quality of the indoor environment and comfort of occupants, and design buildings first to serve the needs of occupants. It is expected that buildings having strict IEQ criteria may consume more energy, which should be quantified through parametric analysis of the relationship between IEQ parameters and actual energy use.

IEQ control in buildings and the resulting energy use are affected by many parameters. Generally, the concentration of carbon dioxide ($CO_2$) as an indicator of ventilation and operative temperature as an indicator of thermal comfort are used to assess the quality of the indoor environment. Adequate air quality and thermal environment are maintained by heating, ventilation, and air-conditioning (HVAC) systems, which are one of the main energy users in buildings. For instance, the energy used by HVAC systems accounted for 11% of the total electricity use in the EU in 2007 (Knight, 2012).

This work compares the energy use of two classrooms designed to meet various IEQ standards using a dynamic building simulation tool. Simulations were performed using the criteria for heating and cooling setpoints, ventilation rates, humidity levels and illuminances for each category in the standards such as EN 15251:2007 (CEN, 2007), ISO 17772-1:2017 (ISO, 2017), ISO/TR 17772-2:2018 (ISO, 2018), EN 16798-1:2019 (CEN, 2019), EN/TR 16798-2:2019 (CEN, 2016), ASHRAE 55-2017 (ASHRAE, 2017), ASHRAE 62.1-2016 (ASHRAE, 2016), and ISHRAE 1001:2016 (ISHRAE, 2016). Some of the criteria were identical across standards, and some of them were not, thus, a unique combination of heating and cooling setpoints, ventilation rates, humidity levels, and illuminances were used. The simulations were performed for eight different locations around the world covering such climates as cold, temperate, arid, and tropical.

The energy use of HVAC depends on multiple parameters such as desired IEQ, climatic zone, building envelope properties, occupancy, and internal heat gains such as appliances and lighting. The energy required for heating, cooling, domestic hot water production, air and water distribution by fans and pumps, and lighting contribute to the total energy needs of each modelled building. To compare the influence of each end-use, energy use of classrooms was categorized and analysed as a total and per category. Overall, the parametric study aimed to correlate energy use and IEQ level based on the requirements of different standards for classrooms.

## 2. Standardized requirements

The energy use and IEQ parameters of the specified building were compared for different categories on international and national standards presented in Table 1. A detailed overview of different standards is provided in a review article (Khovalyg. D., 2020). While some standards contain requirements for all IEQ parameter inputs required by the simulation model (*i.e.* temperature, ventilation rate, relative humidity, and illuminance), other standards contain only the requirements for a specific parameter. For instance, ASHRAE 55 defines only thermal comfort parameters, and ASHRAE 62.1 specifies parameters for ventilation only. Therefore, when ASHRAE standards were considered, values for illuminance were taken from EN 15251.

Table 1: Overview of the IEQ standards

<table>
<tr><th>Standards</th><th>Referred in the paper as</th><th>Thermal environment</th><th>Ventilation rate</th><th>Relative humidity</th><th>Illumi-nance</th></tr>
<tr><td>EN 15251:2007 (CEN, 2007)</td><td>EN 15251</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>ISO 17772-1:2017 (ISO, 2017),<br>ISO 17772-2:2018 (ISO, 2018)</td><td>ISO 17772</td><td rowspan="2">✓</td><td rowspan="2">✓</td><td rowspan="2">✓</td><td rowspan="2">✓</td></tr>
<tr><td>EN 16798-1:2019 (CEN, 2019)<br>CEN/TR 16798-2:2019 (CEN, 2016)</td><td>EN 16798</td></tr>
<tr><td>ASHRAE 55-2017 (ASHRAE, 2017)</td><td>ASHRAE 55</td><td>✓</td><td>×</td><td>✓</td><td>×</td></tr>
<tr><td>ASHRAE 62.1-2016 (ASHRAE, 2016)</td><td>ASHRAE 62.1</td><td>×</td><td>✓</td><td>✓</td><td>×</td></tr>
<tr><td>ISHRAE 10001:2016 (ISHRAE, 2016)</td><td>ISHRAE 10001</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
</table>

Specific requirements for the ventilation rates, carbon dioxide concentration increase above the outdoor level, relative humidity, and operative temperature setpoints are listed in **Error! Not a valid bookmark self-reference.**2. As reference setpoints, requirements of EN 15251 Cat II. were used. Requirements for illuminance specified in ISO 17772 and EN 16798 are 500 lux, while EN 15251 and ISHRAE 1001 specify 300 lux for "normal" classrooms for children's education.

Table 2: Setpoints for IEQ simulations

| Standard | Category | Total ventilation rate[a] [L/s, m²] | $CO_2$ concentr. [ppm][b] | Relative humidity [%] | $T_{op}$ setpoints[c] [°C] |
|---|---|---|---|---|---|
| **EN 15251**[d] | I | 1.0-6.0 | 350 | 30-50 | 21.0 – 25.5 |
| | II | 0.7-4.2 | 500 | 25-60 | 20.0 – 26.0 |
| | III | 0.4-2.4 | 800 | 20-70 | 19.0 – 27.0 |
| **ISO 17772, EN 16798**[e] | I | 1.0-6.0 | 550 | 30-50 | 21.0 – 25.5 |
| | II | 0.7-4.2 | 800 | 25-60 | 20.0 – 26.0 |
| | III | 0.4-2.4 | 1350 | 20-70 | 19.0 – 27.0 |
| | IV | 0.3-2.0 | >1350 | <20, >70 | 17.0 – 28.0 |
| **ASHRAE 55, 62.1**[f] | acceptable | 0.3-1.55 | n/a | < 65 | 19.3 – 26.3[g] |
| **ISHRAE 10001**[h] | A | 7.42 | 350 | 20-70 | 19.0 – 27.0[i] |
| | B | 5.19 | 500 | | |
| | C | 3.25 | 800 | | |

[a] – maximum flow rate is determined for fully occupied room, and the minimum flow rate is defined by the building components emissions only, [b] – concentrations above outdoor level, [c] – minimum for heating (winter season) and maximum for cooling (summer season), [d] – two air volumes have to be delivered before the occupancy, [e] – one air volume have to be delivered before occupancy, [f] – ASHRAE 55 provides setpoints for temperature and ASHRAE 62.1 for ventilation rates, [g] - indoor thermal environment requirements are given as PMV limits, and criteria for the operative temperature were determined from the criteria for PMV, [h] – original requirements are given as maximum $CO_2$ concentration above the ambient level (Cat. A - 350ppm, Cat. B. - 500 ppm, Cat. C – 800 ppm), [i] – if air speed is less than 0.2 m/s.

## 3. Methodology Description

IEQ indicators and energy use of the specified classrooms were compared using the dynamic building performance simulation software *IDA Indoor Climate and Energy* (IDA ICE). The software was validated using the tests specified in ASHRAE 140-2004 (Equa Simulation AB, 2010), EN 15255-2007 and EN 152565-2007 (Equa Simulation Finland Oy, 2010).

### 3.1. Climatic zones

The Köppen-Geiger climate classification (Essenwanger, 2001) was used to select the climate zones for building energy simulations. Since IEQ standards used in this work are normative in Europe, USA, and India, certain locations, the most densely populated ones, representing each region were selected. Climatic zones selected are listed in **Error! Reference source not found.**3. For the simulations in IDA ICE, Test Reference Year (TRY), ASHRAE IWEC 2 and EnergyPlus weather data were used.

Table 3. Climatic zones of the selected locations

| # | City | Country | Climate zone | Abbrev. |
|---|---|---|---|---|
| 1 | Copenhagen | Denmark | Temperate/without dry season/warm summer | Cfb |
| 2 | Tromsø | Norway | Cold/without dry season/cold summer | Dfc |
| 3 | Athens | Greece | Temperate/dry summer/hot summer | Csa |
| 4 | Beijing | China | Cold/dry winter/hot summer | Dwa |
| 5 | Mumbai | India | Tropical/savannah | Aw |
| 6 | New Delhi | India | Temperate/dry winter/hot summer | CWa |
| 7 | Abu Dhabi | UAE | Arid/desert/hot | BWh |
| 8 | Miami | USA | Tropical/Monsoon | Am |

### 3.2. Building construction code

Building envelope characteristics in this study were based on the national Danish Building Regulations from 2015 (DBR1995) without tailoring to the local building codes for locations outside of Denmark. Therefore, the building envelope, which was optimized for the heating-dominated Danish climate, was not optimized for other climatic zones (for instance, cooling dominated climates), as a result, calculated energy usage is expected to be greater compared to actual buildings in some regions. Nonetheless, a uniform building envelope across all climatic zones enables a comparison of the effect of the requirements imposed by different standards, which is the main goal of this work.

### 3.3. The building model

Two classrooms 50 m$^2$ each with a height of 2.5 m were simulated, the overall dimension of the building was 4.0 (w) x 2.5 (h) m. One room faced North and the other one faced South as shown in the plan in Figure 1. The classrooms located in a multi-story building, therefore, the only heat loss or gain was through the façade. All other walls and the floor and ceiling were internal and considered as adiabatic.

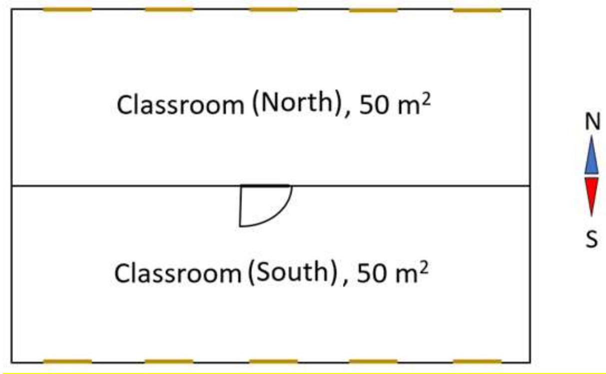


Figure 1. Floor plan of the classrooms

***Wall characteristics*:** To define external walls, design thermal transmittance (U-value) and heat losses across external walls of buildings with at least three floors specified by DBR were used. The building code DBR2015 required U=0.19 W/m$^2$K for opaque surfaces. Internal walls consisted of a double layer of gypsum on each side, 3 cm of insulation in the middle, and an air gap on each side of the insulation. Internal slabs between floors consisted of, from top to bottom, 0.5 cm of floor covering, 2 cm of lightweight concrete and 15 cm of concrete. Thermal bridges were set to the values corresponding to the classification "typical" per DBR2015.

***Window characteristics*:** The building model had one window per 2.5 m of façade width according to the DBR2015 requirement that the glazing area in non-residential buildings be no more than 10% of the floor area when the light transmittance is at least 75%. This resulted in 5 windows 1.05 m x 1.25 m in each classroom. The requirements for the U-value of windows was 0.6 W/m$^2$K. Shades were integrated with windows and closed at solar heat gains of 100 W/m$^2$. Windows were not operable. As in the case of the opaque envelope, windows were not optimized for a particular climatic zone since the primary goal of this work was to compare the energy use of buildings according to the requirements of different standards.

***Occupancy*:** The occupant density was taken from EN 15251 and EN 16798, and was 2 m$^2$ per person in classrooms. The clothing insulation of the occupants was set to 0.75 ± 0.25 clo. The activity level of the occupants was set to 1.2 met. The schedule of occupancy presented in Figure 2 was taken from EN 16798.

***Internal loads:*** The heat load from appliances for classrooms was set to 8 W/m$^2$ according to EN 16798. For the criteria of illuminance 500 lux, a lighting power density of 12 W/m$^2$ was used. A 3/5 of 12 W/m$^2$ for the illuminance of 300 lux was used. The lighting was assumed to be LED, so the luminous efficacy was set to 60 lm/W (Toepfer, 2017) (DIAL, 2016). The values for daily, weekly, holiday, and total usage time and heat load from appliances were based on EN 16798 recommendations. It was assumed that there were no holidays; therefore, the total usage time was 2868 hours per year. The schedule of daily occupancy of classrooms and the use of appliances and lighting are shown in Figure 2. The operation of equipment and lights was controlled by the occupancy only. Lights had an additional setpoint control – they were switched ON when the illuminance was below the set minimum level and switched OFF when the illuminance was above the set maximum level.

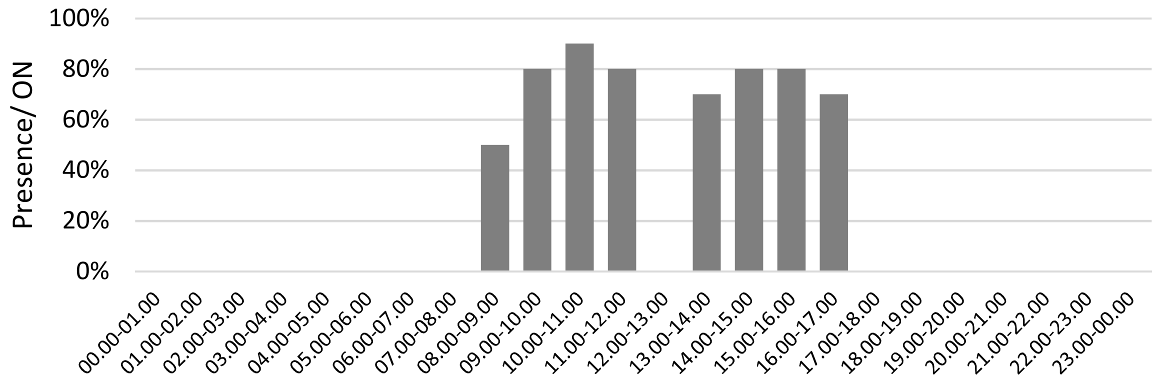


Figure 2. Presence of internal loads (occupants, appliances, lighting) throughout a day (in %)

***Building services:*** The classrooms were mechanically heated, cooled and ventilated. Each room had one terminal unit to compensate for the heat losses or heat gains, no specific type of the unit was assigned. The heaters used PI controllers based on the operative temperature. To define the highest heating power, internal heat gains were set to zero; to define the highest cooling load, 100% of internal gains were considered.

The air handling unit with heat recovery served both rooms. The mechanical ventilation system was balanced, the air was supplied according to the occupancy schedule, and the air was not recirculated or transported from one room to another. The ventilation system included an air filter for the intake air and a filter for the exhaust air, but no other methods of air cleaning were used. Air was supplied at 18°C.

To investigate the need for humidification or dehumidification, simulations were performed without humidification and dehumidification using a standard air handling unit. The setpoints of 60% of maximum RH and 25% of minimum RH were defined based on the requirements for Category II of EN 15251 and EN 16798. Humidification was considered if hours with low humidity operation (below 25%) exceeded hours of AHU operation in high humidity range (over 60%), dehumidification was used in the opposite case. In energy, simulations humidification was used for locations such as Copenhagen, Athens, Beijing and Tromsø, and dehumidification was used for locations such as Mumbai, Abu Dhabi, New Delhi and Miami.

Domestic hot water use was not included in the model. The heat losses from water circulation systems, and heating and cooling supply systems were not considered as well.

## 4. Results and Discussion

The standards ISO 17772, EN 16798, EN 15251, and ASHRAE 55 describe different methods for long term evaluation of the indoor environment, as mentioned by Khovalyg et al. (2020). While ISO 17772, EN 16798, and EN 15251 outline three methods, ASHRAE 55 only one, but all of them allow for long-term evaluation based on the number or percentage of occupied hours when the PMV or the operative temperature is within a specified range. Therefore, this method was chosen to evaluate the indoor environmental parameters across the standards, and all results are based on annual simulations. Thermal environment analysis based on o*perative temperature* was performed only for occupied hours, and it is given as a number of hours within each category of the reference standards. The results for the air quality presented as $CO_2$ concentration were based on the entire year simulations including occupied and non-occupied hours. To investigate how the switch from one category of a certain standard to another category can affect a particular IEQ parameter (operative temperature or $CO_2$ concentration), only one parameter was varied at a time.

Energy use results were evaluated based on annual simulations, and presented as the comparison of four categories of energy use:

- ”Cooling” accounted for the energy use of a chiller and cooling terminal units
- ”Heating” accounted for the energy use of a boiler and heaters
- ”HVAC auxiliary ” accounted for the energy use of fans and circulation pumps
- ”Lighting” accounted for the lights in all office spaces

### 4.1. Effect of climate regulation on energy use

The impact of the location on the energy use of classrooms is shown in Figure 3, where ventilation and indoor temperature were set to the reference values per EN 15251 Cat II. Generally, thermal conditioning (heating and cooling) was the main contribution of differentiating energy use across different climatic zones. Cooling uses a significant amount of energy in hotter regions such as Mumbai, Abu Dhabi, Miami and New Delhi, and its share decreases when the building location shifts north where energy use by heating becomes dominant in relatively cold locations such as Copenhagen, Beijing and Tromsø. Total energy use between two extreme cases, Mumbai and Copenhagen, varied by a factor of 7.6. Generally, the building model placed in Copenhagen had the lowest total energy use due to the mild climate of Denmark resulting in the optimum energy use for heating and cooling. Cooling needs of the buildings located in Copenhagen and Tromsø were the lowest, however, the buildings situated in Tromsø required more heating due to the northmost location.

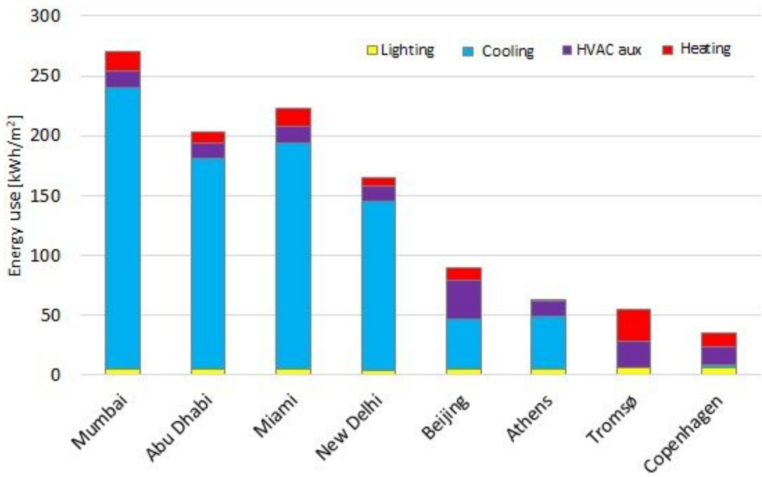


Figure 3. Energy use of the classrooms at reference conditions (EN 15251 Cat II.) situated in different locations

Variation of the energy use in different energy categories across the eight climatic regions considered is illustrated by the box plots in Figure 4. Cooling uses the greatest share of energy (appx. 59%), while "heating" and energy use of auxiliary loads such as fans and pumps ("HVAC aux.") was, on average, around 20% of total energy use across all climatic locations. For example, "HVAC aux." on average uses 21%, while "heating" uses 15%. The energy use for "lighting" is 6% which the smallest value compared to other categories of energy use.

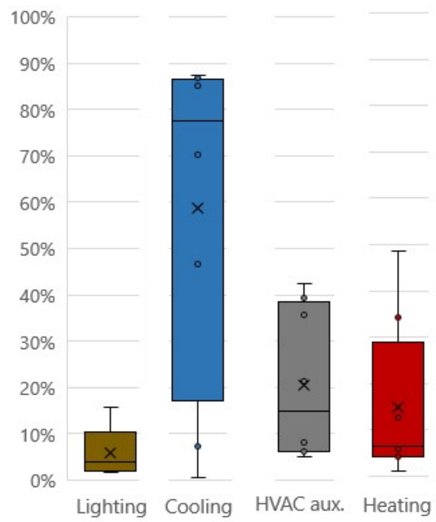


Figure 4. Distribution of energy use across 8 climatic locations

### 4.2. Comparison of energy use across standards

Comparisons of the energy use of the classrooms located in different cities designed according to the requirements of different standards are shown in Figure 5. The plots present energy use (kWh/m$^2$) for each category as well as the total value across eight climatic regions. Two locations, Mumbai and Copenhagen (Figure 6, 7), were selected for detailed illustration of energy use per energy meter since they correspond to the maximum and minimum total energy use.

Generally, the operation of the building designed according to EN 15251 uses the highest amount of energy if the corresponding categories across standards are compared (for instance, Cat. II of EN 15251 *vs.* Cat. II of EN 16798 *vs.* Class B of ISHRAE 10001). If two EN standards are compared, the operational parameters set according to the new EN standard, EN 16798, use slightly less energy if the corresponding categories are compared. For the school building, there were two differences between EN 15251 and EN 16798. The first difference was that the ventilation system was switched ON two hours before occupancy started according to EN 15251, while it was switched ON an hour prior occupancy using EN 16798. The second difference was in illuminance level - the illuminance was 300 lux in the classrooms per EN 15251, while it was 500 lux per EN 16798.

The change in energy use between the categories/classes within the same standard depends on the location of the building. For instance, for classes located in Copenhagen when requirements of the EN 15251 are applied, the total energy reduction is 40% from Cat. I to Cat. II, and 42% from Cat. II to Cat III. If requirements of the EN 16798 were applied, the reduction in energy use from Category I to Category II would have been 40% from Cat. I to II, 29% from Cat. II to III, and 14% from Cat. III to IV.

The difference in energy use between categories, as shown in Figure 7, of the Indian standard ISHRAE 10001 is relatively small. When requirements of ISHRAE 10001 are applied, energy use drops 28% from Class A to B, and 22% from Class B to C. While the requirements for the Class A and B are less energy expensive compared to Cat. I and II of EN standards, requirements for Class C are almost at the same level as Cat. III of EN 16798. The energy use of classroom operated according to ASHRAE standards was almost the same amount as for energy as Cat. III of EN 15251 and EN16798, and between Class B and C of ISHRAE 10001.

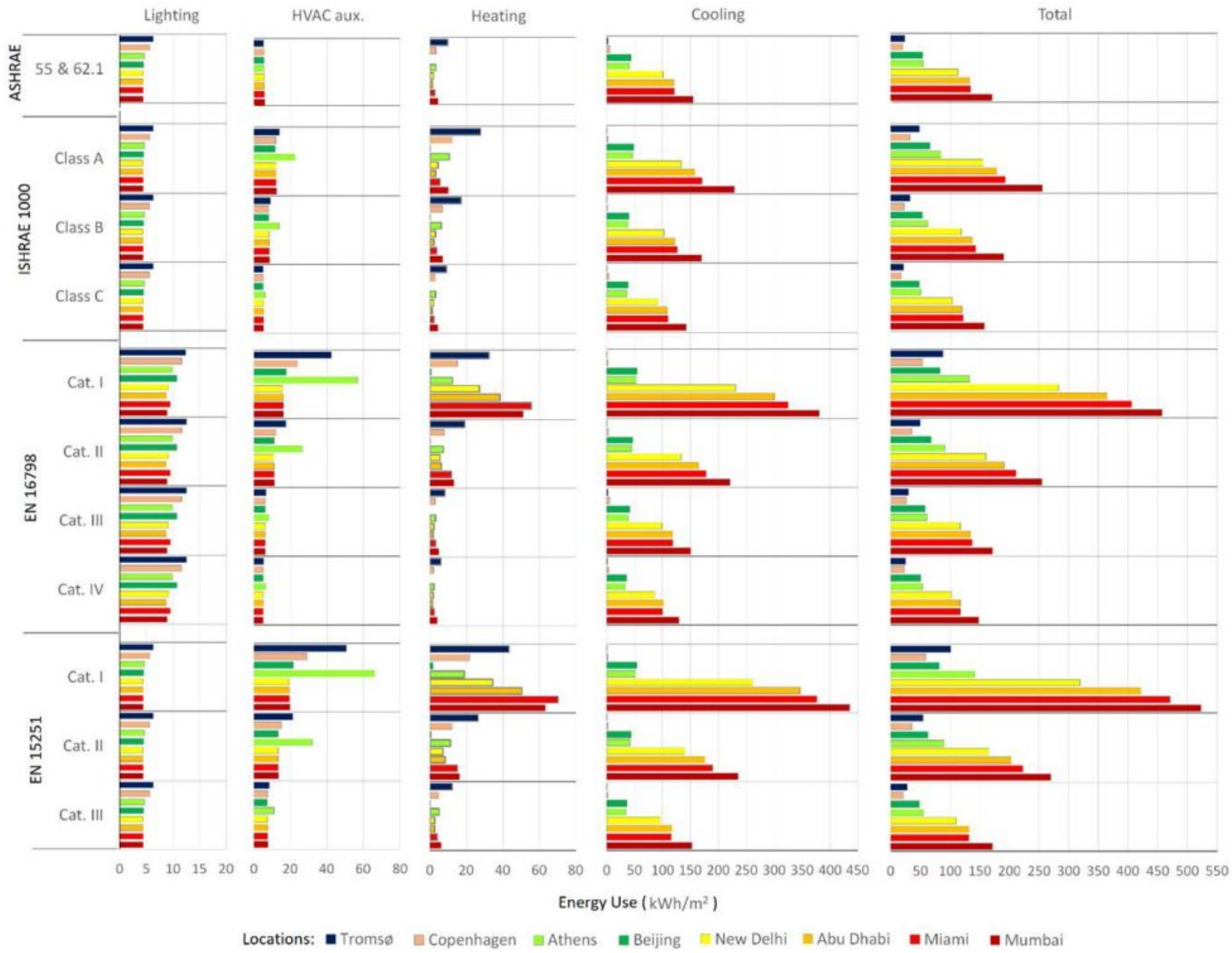

Figure 5. Comparison of the energy use of the school building designed according to various standards

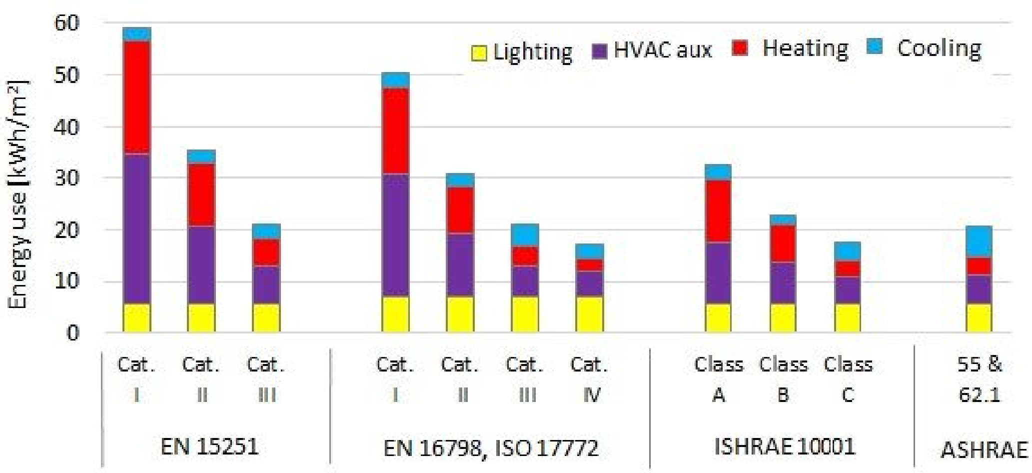

Figure 62. The energy use of modeled classrooms located in Copenhagen

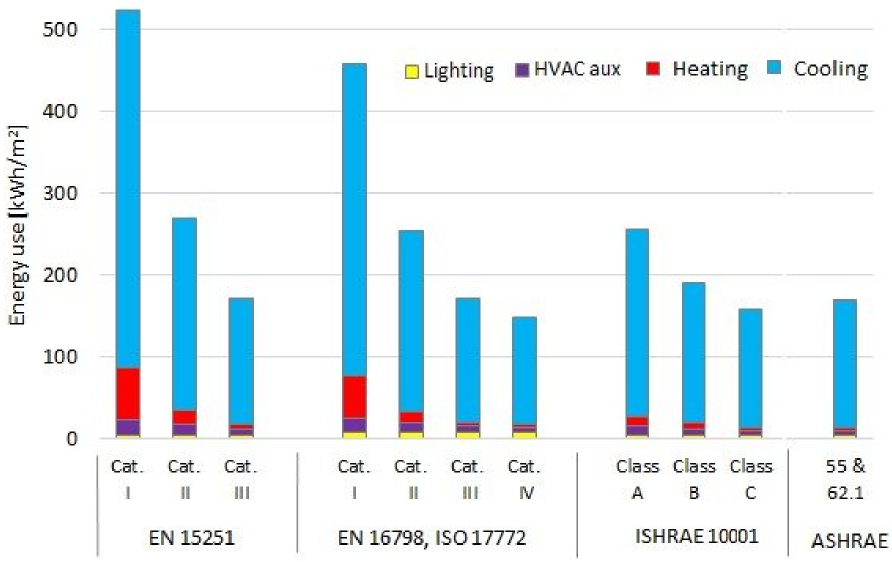


Figure 73. The energy use of modeled classrooms located in Mumbai

## 4.3. Comparison of IEQ parameters: operative temperature

Operative temperature comparison is illustrated in Figure 8 for setpoints corresponding to the different categories of standards EN 16798, ISO 17772, ISHRAE 10001, and ASHRAE 55. The plot shows operative temperature variation between different locations and between different standards both for south and north oriented rooms. Operative temperature ranges set by EN 15251 serve as the reference values. Generally, the south-oriented classrooms tend to be warmer and stay within the range required by a particular category of EN 15251 less of the time. If the building is designed according to Cat. I, it maintains the operative temperature within the narrow range of 21.0-25.5°C for a longer period. With the reduction of the Category, the temperature in the classroom varies in a wider range. For instance, if a building is designed according to Cat. I of EN 16798, 79% of the time temperature is within the range of 21.0-25.5°C (Cat. I, EN 15251) and 21% in the range of 20.0-26.0°C (Cat. II, EN 15251) on an annual basis. The same building designed according to the Cat. III of EN 16798 stays only 23% within the range 21.0-25.5°C (Cat. I, EN 15251), 11% within 20.0-26.0°C (Cat. II, EN 15251), 38% within 19.0-27.0°C (Cat. III, EN 15251), and 23% outside the range of 19.0-27.0°C (outside Cat. III, EN 15251). On average, the building designed according to the requirements of the EN 16798 has tighter control of the operative temperature compared to the buildings designed according to ISHRAE 1000 and ASHRAE requirements.

## 4.4. Comparison of IEQ parameters: $CO_2$ concentration

A comparison of the carbon dioxide concentration results is shown in Figure 9 for the school model designed according to the different categories of the standards EN 16798, ISHRAE 10001, and ASHRAE. As expected, buildings designed according to the highest category of a particular standard have the lowest value of the acceptable level of $CO_2$ concentration and the tightest control, while the buildings that meet the requirements of the lowest category tend to have the highest $CO_2$ concentration most of the time (over 800 ppm above the outdoor level according to EN 15251). As an example, the building model designed according to Category I of EN 16798 maintains indoor environment at the level of 350 ppm rise above ambient most (88%) of the time, while the building designed according to the Category IV of EN 16798 is above the 800 ppm above outdoor limit per Category III of EN 15251 74% of the time. The difference in $CO_2$ levels between the Category I and Category IV according to EN 16798 is drastic, compared to other standards, since EN requires only 550 ppm for Category I

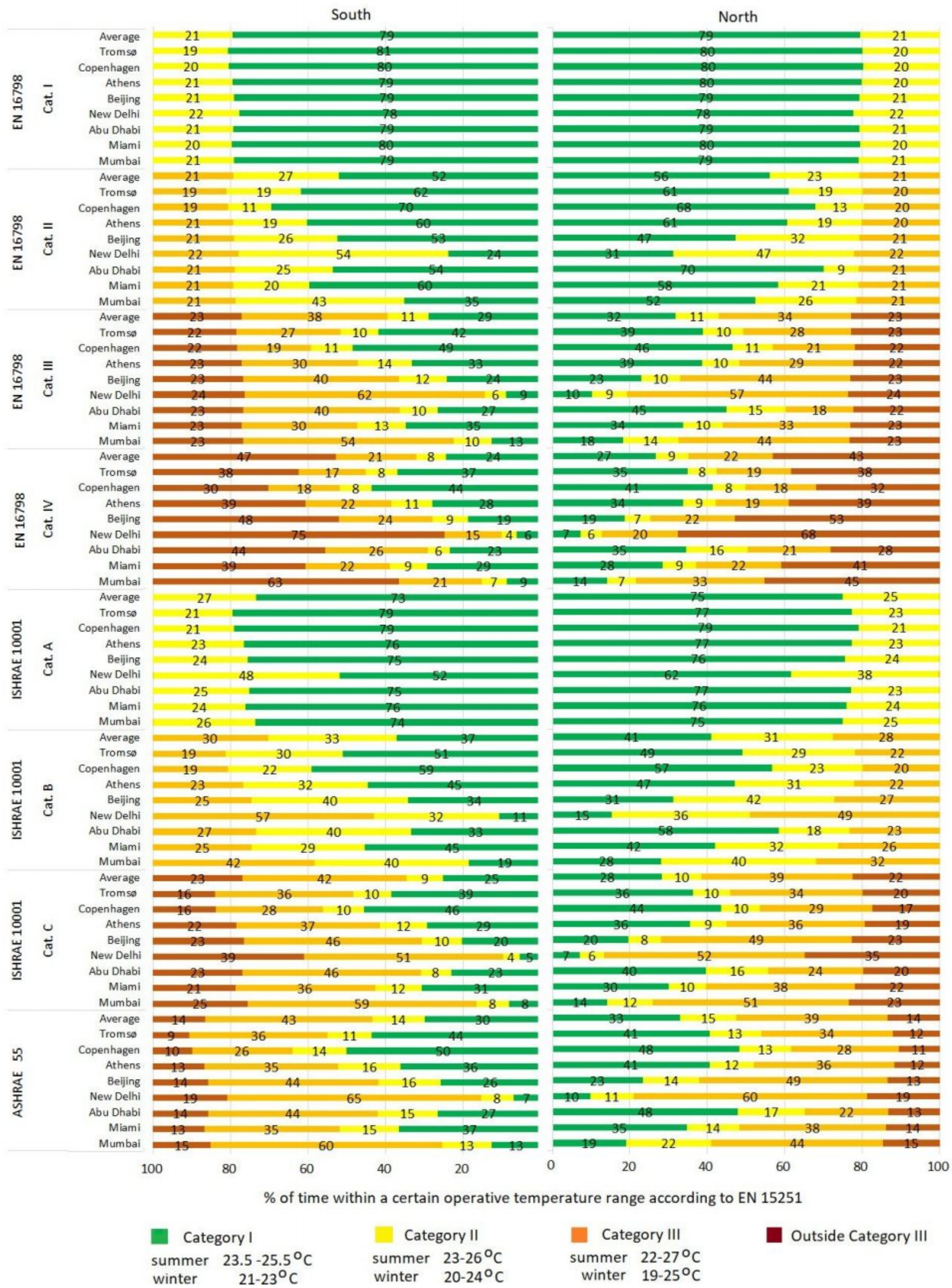

Figure 8. Percentage of the operative temperature within a certain range annually according to the settings of EN 15251 (summer and winter setpoints are indicated in the legend)

and allows over 1350 ppm for the Category IV. The difference between the Categories A and C of ISHRAE 10001 is less pronounced. Air quality delivered according to the ASHRAE is similar to the Category B of ISHRAE 10001. Between different locations of the classrooms, the building model located in Copenhagen tends to have lower $CO_2$ concentration across all categories of the standards, while the building located in Mumbai has the worst air quality.

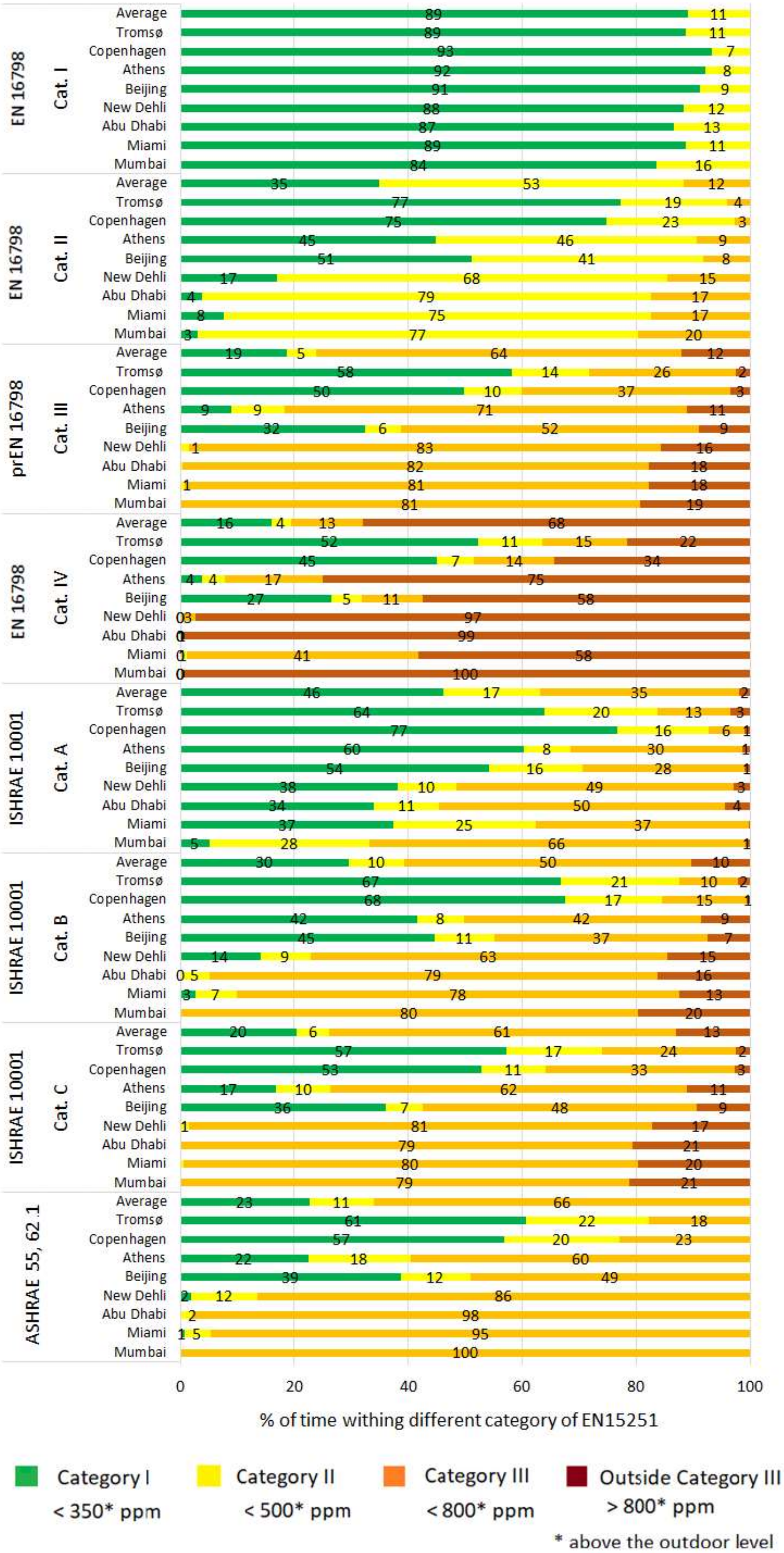

Figure 9. Percentage of the $CO_2$ level within a certain range annually according to the settings of EN 15251 for the classrooms (above outdoor level, the outdoor concentration of $CO_2$ is taken as 400 ppm)

## 5. Summary

The purpose of this work was to compare the energy use, thermal environment and IAQ for the school model with two classrooms using criteria from several standards in order to identify how the criteria from each standard affect energy use and IEQ. A comparison of the results was based on the total energy use for lighting, cooling, heating, and auxiliary equipment such as fans and pumps. The quality of the indoor environment was evaluated based on the operative temperature as an indicator of the thermal environment and $CO_2$ concentration as an indicator of air quality.

The results show that the climate has a significant impact on energy use affecting cooling/heating demand. A building located in warmer climates use significantly more energy to maintain an acceptable indoor environment year-round (for example, in Mumbai and Miami), followed by buildings in cold climates. Temperate climates have the lowest energy use, with the climate of Copenhagen demanding the lowest energy use. The lower energy use in Copenhagen might be influenced by the fact that the building was designed according to Danish building regulations that account for the issues important for the Danish climate.

Generally, energy use decreased with decreasing requirements for indoor environmental quality when criteria from selected IEQ standards were used. The decrease in energy use between adjacent Categories for the school building model was: (i) at least 23.1% when using criteria from EN 15251, (ii) 12.5% with criteria from EN 16798, (iii) 8.9% with criteria from ISHRAE 10001 in most of the cases. The energy use for IEQ set per EN 16798 was lower compared to EN 15251 since the ventilation system was switched ON one hour before the beginning of occupancy and not two hours before. However, the benefit varied depending on climate, with a reduction between 0.3% and 8.8%. The number of degree hours below 21°C and above 25.5°C and the number of hours with $CO_2$ concentration above 750 ppm increased with decreasing requirements to the indoor environmental quality in all categories of EN 15251 and EN 16798 and for seven out of eight locations for ISHRAE 10001.

Overall, the results show that the IEQ parameters significantly affect energy use and that a higher category of IEQ causes a higher energy use. However, for all eight climates, there were one or more categories that provided an acceptable thermal environment and IAQ at moderate energy expense compared to another category. In these cases, it was possible to achieve reduced energy use without reducing the quality of the thermal environment or IAQ. However, it varies from climate to climate, which category results in the lowest energy use, which category results in the best thermal environment, and which category assures the highest IAQ. Therefore, there is no category that always provides both the lowest energy use and the highest IEQ in all simulated cases.

The outcomes of this work inform regarding the relative relationship between different IEQ standards and different categories that could be used by practitioner and educational institutions to evaluate the penalty of not providing the adequate IEQ in educational buildings if only the energy reduction goal is pursuit. The comparison can be improved by accounting for the local building regulations in terms of the building envelope and accounting for the actual outdoor $CO_2$ levels order to have a better comparison of energy use of building in different parts of the world.

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