# Stack driven ventilative cooling for schools in mild climates: analysis of two case studies


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## ABSTRACT

This paper presents two case studies of stack driven ventilative cooling systems implemented in kindergarten schools located in the mild Subtropical-Mediterranean climate of Lisbon, Portugal. Both systems rely on stack driven natural ventilation supplemented by a larger, single-sided ventilation opening to be used in the warmer months. In both systems air enters the rooms at a low level, directly in front of the heating passive convector systems, and is exhausted in the back of the room, through a chimney. In addition to the smaller opening configuration, that is sized for the heating and mild seasons (1-3% of room floor area) both designs have larger openings to be used during the cooling season. This larger opening is fundamental to meet the minimum code requirement for total ventilation opening area (5% of floor area). The designs were developed and fine-tuned using dynamic thermal simulation (EnergyPlus). This approach allowed for straightforward statistical analysis of expected system performance, assessed in terms of thermal comfort and indoor air quality. Measurements in steady state mode show a good agreement between simulated and measured airflow rate. During the warmer months the smaller and protected heating season openings are opened for night cooling effect. The chimney exhausts were optimized to avoid opposing stack and wind effects. Both systems are user controlled. The importance of effective commissioning of passive systems is discussed and an example of a simple user manual is provided. The performance of these systems shows that a well-designed natural ventilation system can insure adequate levels of indoor air quality in kindergartens.



## KEYWORDS

Ventilative cooling systems; natural ventilation; thermal chimney; EnergyPlus; dynamic thermal simulation.


## 1 INTRODUCTION

In the last decades, heating, ventilation and air conditioning systems (HVAC) assumed an important role in buildings energy consumption as the increasing demand for thermal comfort, combined with the rising time that people spend indoors lead to a significant increase in HVAC related energy consumption in services buildings (up to 50% of the total energy consumed in buildings, Zhao, 2012). In this context, natural ventilative cooling systems can be essential tool to limit this growth and reach the Nearly Zero Energy Buildings (NZEB) target.

Natural ventilation systems can be driven by buoyancy, wind or a combination of the two mechanisms, generating pressure differences across different spaces inside a building or between interior and exterior, driving airflow from high to low pressures zones.

There are three natural ventilation system geometries: displacement ventilation (DV), single-sided ventilation (SS) and cross-ventilation (CV). In DV, air is introduced near floor level where buoyancy forces induced by temperature differences (between inflow and room air temperature) make the colder air supply spread over the floor until it reaches a heat source, where it will expand and rises as a thermal plume. Ideally, the air movement induced by the thermal plumes, from low to high level, will be capable to transport heat and pollutants above the occupied zone, promoting a vertical temperature and contaminants stratification (Mateus, 2015).

Single-sided and cross-ventilation are characterized by mainly use the wind pressure on building shape to induce air currents through the openings on the façade. SS uses one or more windows in the same façade and is also affected by local buoyancy effects that can promote bi-directional flows (Wang, 2012). In contrast, CV uses openings in opposite façades (Graça, 2015). Although Cross-ventilation can provide larger flow rates there are implementation difficulties in kindergartens due to draft, noise and room configuration issues.

The application of natural ventilation concepts in schools has been extensively studied (Santamouris, 2010; Wang, 2014; Jamaludin, 2014). These studies identified issues that could affect system performance, such as: system control (manual or automatic), the unpredictability of weather conditions, noise and ingress of outdoor pollution into the indoor environment. In spite of these issues, in many cases, natural ventilation systems are capable of maintaining comfortable indoor temperature as well as acceptable $CO_2$levels.

This paper presents two case studies of stack driven user-controlled ventilative cooling systems for kindergarten schools in Lisbon (Portugal) that use a combination of DV and SS techniques. The thermal building simulation software EnergyPlus (EnergyPlus, 2013) was used in the design and fine-tuning of both natural ventilation systems.

## 2 CASE STUDIES

This section presents the two case studies analysed in this paper: CML Kindergarten (Figure 1) and German School (Figure 2). Both buildings are situated in urban area of Lisbon (Portugal). The CML Kindergarten was built in 2013, with a total built area of 680 $m^2$ distributed into two floors with 3.1m floor to ceiling height each. The building was south-west oriented, with capacity for 42 children, and each ground floor classroom have direct access to the exterior courtyard, partially covered (courtyard view, Figure 1).

The second case study, the German School of Lisbon, has a main façade facing north (to minimize solar heat gains impact), with two floors, and capacity for 160 children (1200$m^2$, 3.3m floor to ceiling height). The building structure is concrete, with external insulation, creating a high thermal inertia building. The windows are low-emissivity double glazed with solar control and movable blinds (interior in German school and exterior in CML kindergarten case). In south oriented areas overhangs were installed to control high solar gains. Both schools were designed with large glazed areas for allow the use of natural lighting.

These two schools are located in the mild Subtropical-Mediterranean climate of Lisbon, Portugal (Figure 3), characterized by mild winters (minimum temperature ≈ 4ºC) and dry summers with high levels of solar radiation (maximum temperature ≈ 37ºC). In spring and summer there are many days with large thermal amplitude (up to 18ºC), that can potentially make a night cooling approach very effective. In a typical schools building in Lisbon it is expected that the main comfort problems occur when high direct radiation levels and the maximum outdoor temperatures are combined with high internal gains, easily leading to cooling loads of up to 100W/$m^2$.


Figure 1: Inside, exterior and courtyard views of the CML Kindergarten.


Figure 2: Lateral, front and inside views of the German school.

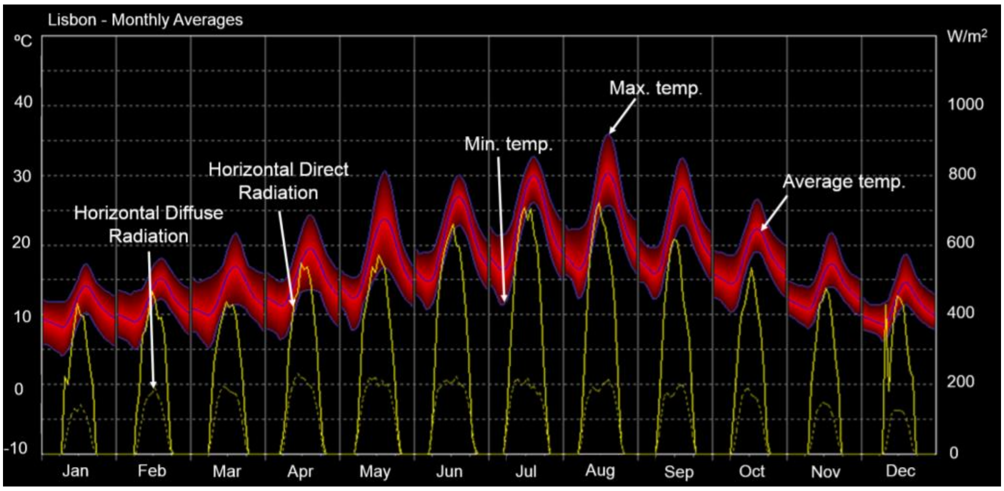


Figure 3: Typical year of Lisbon weather (outdoor temperature and radiation).

Both schools have no mechanical ventilation system installed, the fresh air is introduced into the spaces through low level grilles on the façade and will be exhausted in the back of the room, through a chimney. For the thermal conditioning of the spaces, the buildings Portuguese national code (RECS, 2013) only requires the installation of an active system for the heating period. For this purpose an hydraulic is installed in each classroom. For optimal performance of the ventilative cooling systems designed two operation modes were considered (winter and summer), as shown in Figure 4.

During heating period (winter mode), due to the buildings regulation impositions the airflow grilles should be opened to provide the required minimum airflow (fresh air) in order not to exceed $CO_2$ concentration limit (average below 1625ppm over an 8h period). In this mode, the air that enters though the grilles and was pre-heated directly in front of the passive heating convector that maintain the interior air temperature always above 19ºC.

In summer mode (during the cooling period), all the openings on the façade (low level grilles and openable windows) will be available to be opened, in order to enable larger flow rates to remove the higher heat gains. Taking advantage of the exposed concrete structure and building thermal inertia, passive night cooling used to pre-cool the building during non-occupied periods. In both modes blinds are user-controlled and can be used to minimize solar gains.

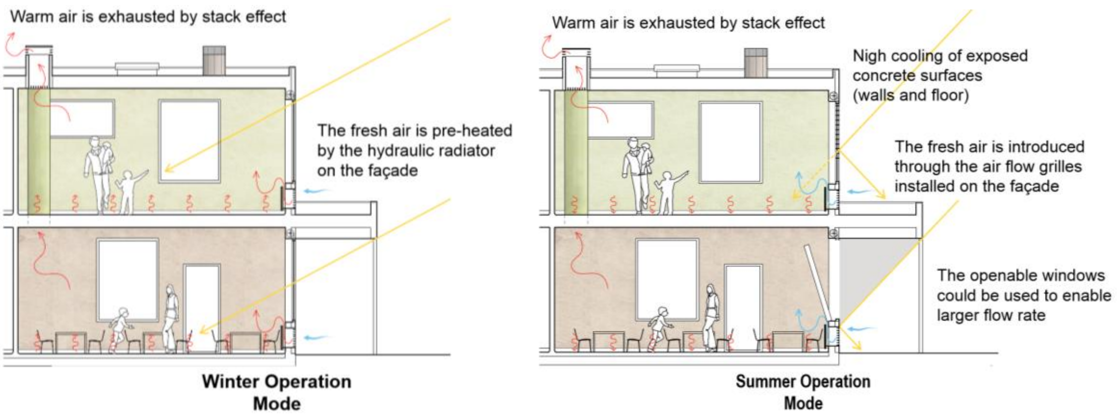


Figure 4: Kindergartens ventilative cooling systems operation modes (winter and summer).

# 3 METHODOLOGY - THERMAL SIMULATION

The dynamic thermal simulations were performed using the open source thermal building simulation software EnergyPlus. To simulate natural ventilation the airflow network approach (EnergyPlus, 2013) was used, modelling infiltration and openings in detail. This tool has been previously validated for natural ventilation of free-running buildings (Mateus, 2014; Zhai, 2011) and applied in SS (Wang, 2013; Schulze, 2013) and DV ventilation studies (Mateus, 2013).
Both kindergartens are shielded by surrounding buildings and for that reason wind effects were neglected and only buoyancy was considered in simulations (a conservative approach). In both cases, to analyse the performance of the natural ventilation systems only a representative classroom of each building was considered. These spaces including the principal features of natural ventilation systems: airflow grilles, thermal chimney and openable windows. Figure 5 shows the EnergyPlus model used to simulate CML Kindergarten and German School.

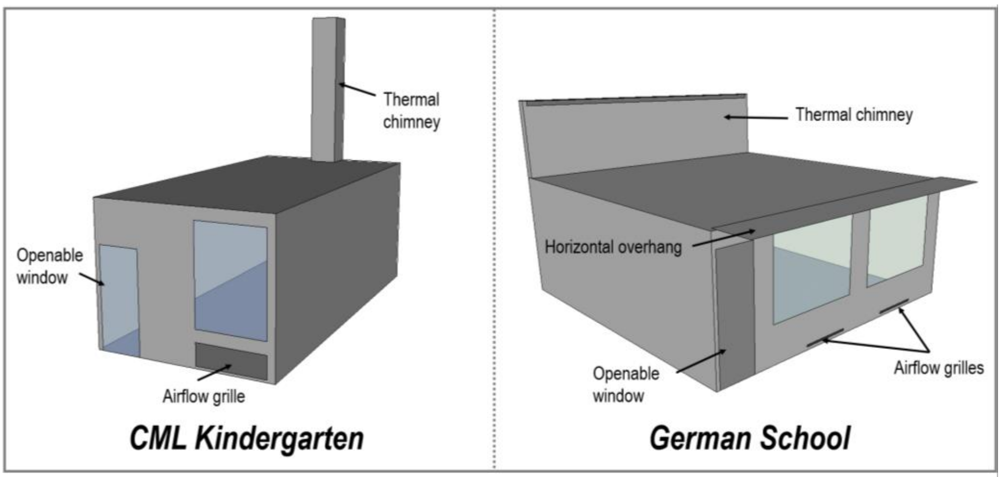


Figure 5: CML Kindergarten and German School EnergyPlus model.

In order to consider the thermal stratification effects both models are composed by two thermal zones (connected by a virtual horizontal window that is always open): room and thermal chimney.
The simulations were performed for a whole year, using the TMY weather file for Lisbon (EnergyPlus Weather), the rooms IAQ level promoted by the natural ventilation systems should be in agreement with buildings Portuguese code (RECS, 2013) and the users thermal comfort was analysed considering two international standards (CEN, 2007; ASHRAE, 2010):

- The rolling average of $CO_2$ concentration in 8 consecutive hours should not exceed 1625 ppm (RECS).
- Operative temperature range between 19-26ºC, (kindergartens limits, EN 15251).
- Adaptive comfort model (80% acceptability limits for naturally conditioned spaces, ASHRAE 55-2010).

In the simulation, the airflow grilles were open when the outdoor temperature is below the interior temperature. The hydraulic radiator is used during the heating months (from October to April) to ensure an interior air temperature above 19ºC. The openable windows will be used to increase the air change rates during the warmer months (from May to September) when additional heat removal will be needed. The Table 1 presents the internal heat loads considered for each case. Table 2 shows the size of opening areas considered for the winter and summer operation modes.
The smaller opening configuration is sized for the heating and mild seasons, corresponding to 1-3% of room floor area, while in the cooling season the total opening area should meet the minimum code requirement of 5% of floor area, that in the case of CML kindergarten reach the 8%.

Table 1: CML Kindergarten and German School heat loads scenarios used in simulation.

| **School** | **Occupancy** | ***Internal Gains*** | | |
|---|---|---|---|---|
| | | **Occupants (W/occupant)** | **Lighting ($W/m^2$)** | **Total ($W/m^2$)** |
| *CML Kindergarten* | 19 children + 1 adult | 70 + 100 | 8 | 53 |
| *German School* | | | 7 | 33 |

Table 2: Opening areas summary.

| Floor Area ($m^2$) | | ***German School*** | ***CML Kindergarten*** |
|---|---|---|---|
| | | 55 | 32 |
| Opening Area ($m^2$) | *Winter mode* | 0.8 | 1.0 |
| | *Summer Mode* | 2.7 | 2.6 |
| Max. Opening Area/Floor Area (%) | *Winter mode* | **1.5** | **3.1** |
| | *Summer Mode* | **5.0** | **8.1** |

# 4 RESULTS: NATURAL VENTILATION SYSTEMS PERFORMANCE

This section presents the simulation results for the two kindergartens (CML on section **Error! Reference source not found.** and German School on section 4.2). Figures 6-7 and 10-11 present the predicted performance for a typical day, in both operation modes (winter and summer). Finally, figures 8-9 and 12-13 show the predicted yearly operative temperature and indoor air quality (CO2 concentration), evaluated according to the EN 15251 and ASHRAE 55-2010 criteria.

## 4.1 CML Kindergarten

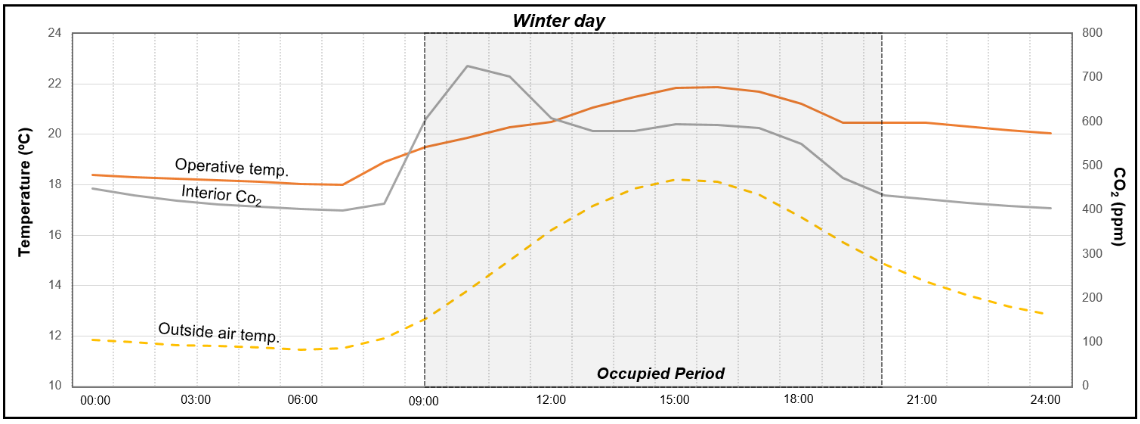


Figure 6: CML Kindergarten results: Operative temperature and $CO_2$ level (winter operation day).

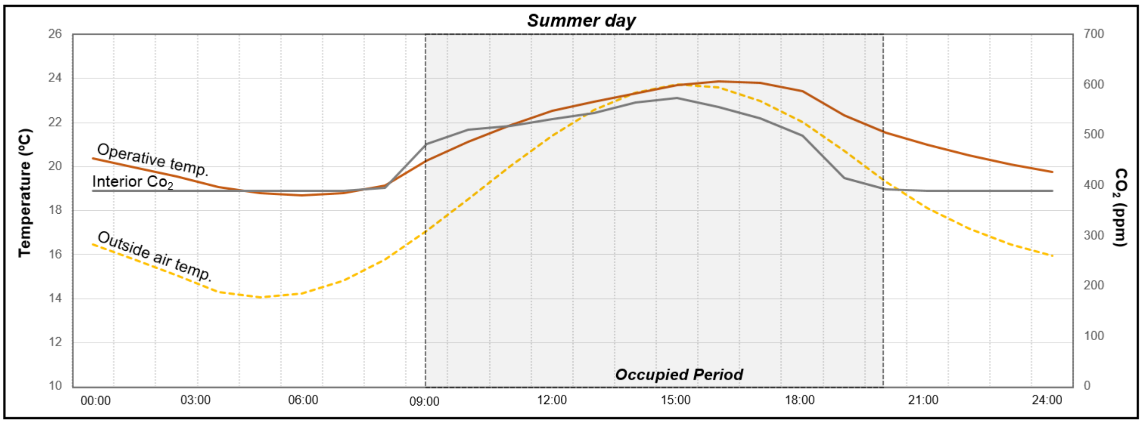


Figure 7: CML Kindergarten results: Operative temperature and $CO_2$ level (summer operation day).

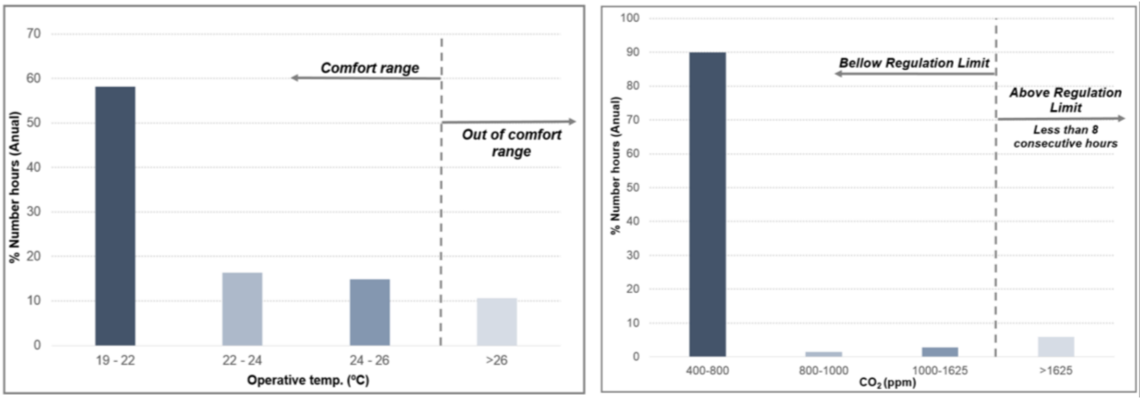


Figure 8: CML Kindergarten statistical analysis: operative temperature (EN 15251) and indoor air quality (RECS).

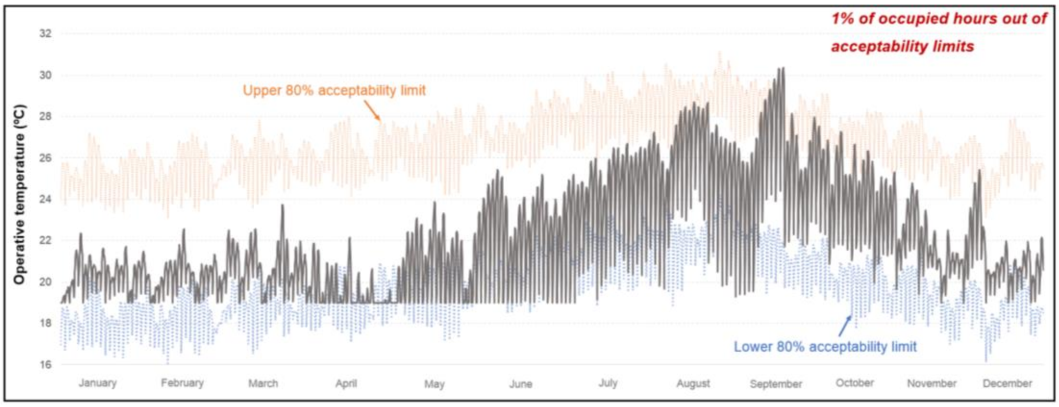


Figure 9: CML Kindergarten operative temperature adaptive comfort analysis (ASHRAE 55-2010).

## 4.2 German School

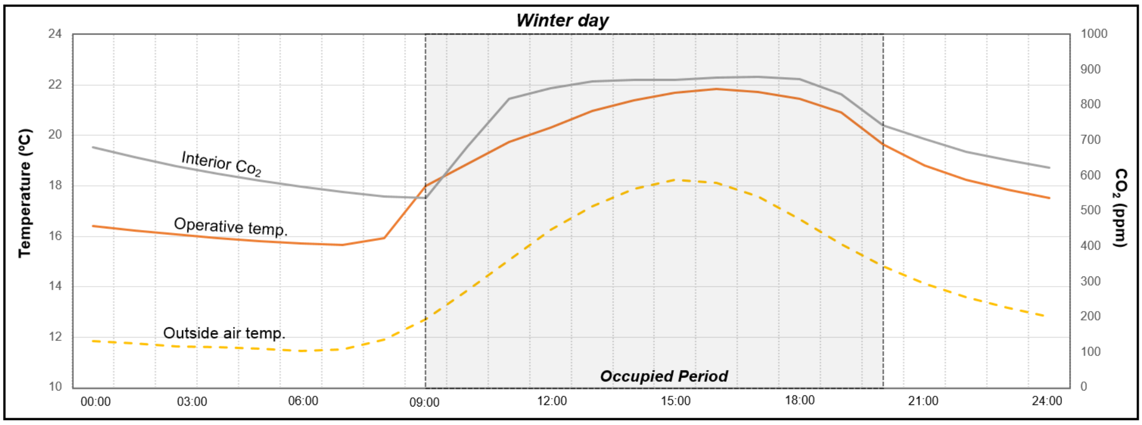


Figure 10: German School results: Operative temperature and $CO_2$ level (winter operation day).

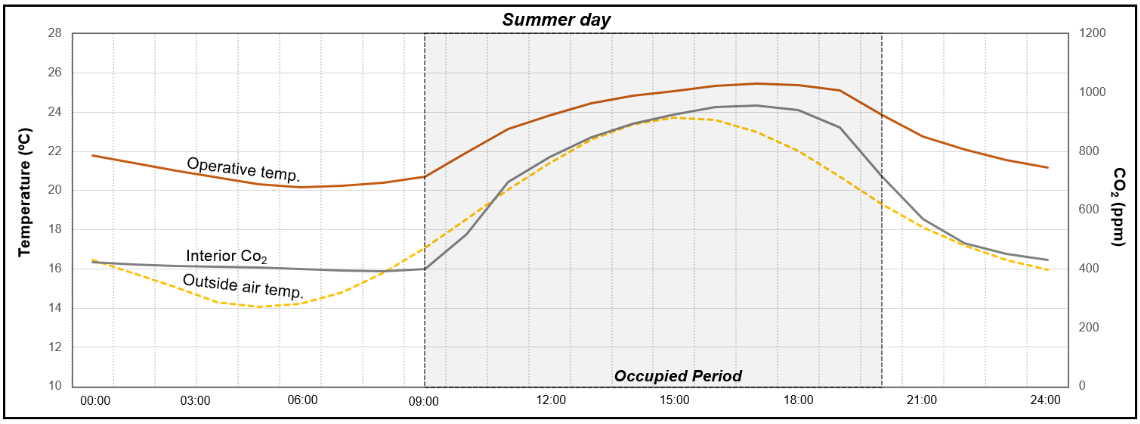


Figure 11: German School results: Operative temperature and $CO_2$ level (summer operation day).

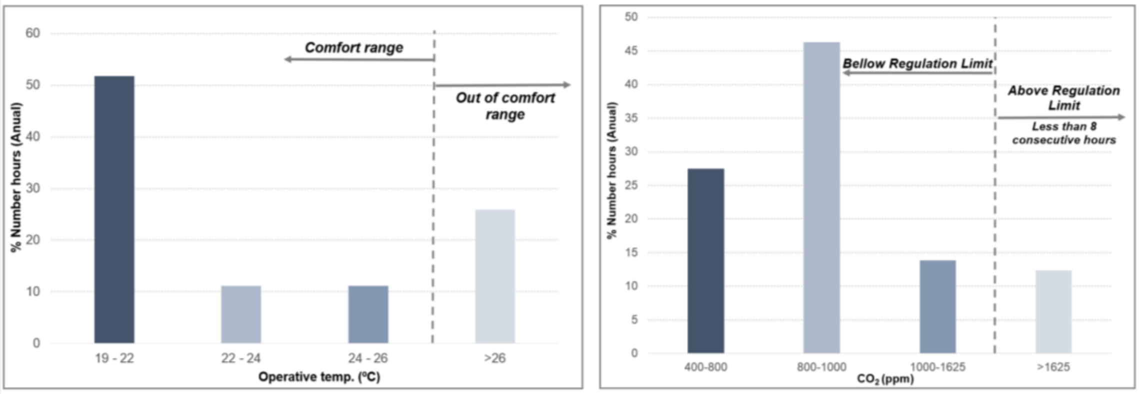


Figure 12: German School statistical analysis: operative temperature (EN 15251) and indoor air quality (RECS).

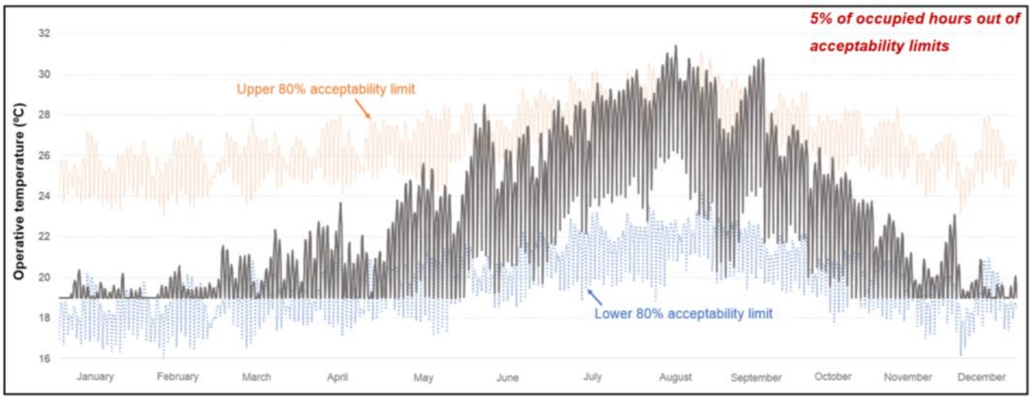


Figure 13: German School operative temperature adaptive comfort analysis (ASHRAE 55-2010).

The typical summer and winter operation days results (Figures 6-7 and 10-11) reveal that the system is capable to provide a natural ventilation airflow that is sufficient to ensure the thermal comfort and IAQ level in the majority of occupied periods. As expected, in both schools, when the occupants get into the space $CO_2$ concentration and operative temperature begin to increase until in the end of the working day. The night cooling approach effectively pre-cools the spaces until the beginning of the next occupied period. The proposed ventilative cooling designs meet the IAQ requisites defined by buildings Portuguese national code: the rolling average of $CO_2$ concentration in the 8 consecutive hours does not exceed 1625ppm.
The main problems occur in the summer, when it is necessary to promote the interior air renewal (to maintain acceptable $CO_2$ concentration) but the outside air is warmer. Ideally, in these moments all the openings should be closed to achieve comfortable interior air temperature but open to do not exceed 1625ppm ($CO_2$ concentration). In these cases, the users will determine what comfort parameter is more relevant to his comfort and to define if the openings should be maintained closed or be opened.
Analyzing the annual operative temperature results using the adaptive comfort model shows that the occupants comfort is obtained 99% of the occupied hours in CML and 95% in German school. However, when these results are compared with those obtained when using the limits proposed by EN 15251 (19-26ºC) the CML kindergarten obtain similar performance results (10% hours in discomfort), but the German school occupants are expected to be out of comfort during 28% of occupied periods. This poor performance is probably due to the lower opening area per floor area ratio that is used in this design. In light of these results, the designers recommended the installation of an active cooling system in German School to be used in conjunction of natural ventilation system. This recommendation was not followed by the building manager. As a result there have been systematic user discomfort complaints in the warmer weeks of the year. These results indicate that the adaptive thermal comfort model may be "optimistic" in the proposed limits. To obtain a high performance ventilative cooling system (like in the CML kindergarten case), we recommend the use of EN 15251 instead of to ASHRAE 55-2010 standard to analyse the occupant's thermal comfort, due to the more restricted temperature limits.

## 4.3 Limited validation of flow rate prediction

This section presents a comparison between a steady state airflow measurement and the correspondent EnergyPlus simulation results for the German School case. The measurements were performed using very high internal sensible heat gains (6kW). Table 3 presents the comparison between predicted and measured airflow rate and the correspondent percentage error. The results of the comparison between simulation and measurements (performed in steady state mode) show good agreement: 4% error.

Table 3: Steady state airflow measurements vs EnergyPlus simulation.

| **Steady-state** | **German school** |
|---|---|
| Outdoor-Indoor temp. dif. (K) | 8.8 |
| Inflow - measured airflow ($m^3/h$) | 194 |
| Simulated airflow ($m^3/h$) | 187 |
| **Error (%)** | **4** |

# 5 CONCLUSIONS

In the two case studies presented in this paper, thermal and airflow simulation was used to fine-tune the designs and diagnose possible thermal comfort and IAQ problems. The opening sizes used in both designs depend on system operation mode: 1-3% of room floor for winter mode and 5-8% for summer mode. Both projects meet the requirements imposed by Portuguese buildings code $CO_2$ concentration bellow 1625ppm (during 8 consecutive hours).

The capability to meet thermal comfort goals depends on the criteria used: both designs perform well when assessed using the adaptive thermal comfort standard. However only the CML kindergarten meets the thermal comfort standards proposed by ASHRAE 55-2010 and EN 15251(1% and 10% of occupied hours out of limits, respectively). Limited user feedback indicates that the stricter assessment is more accurate. The German school, deemed adequate by the adaptive thermal comfort analysis, has had excessive air temperature related user complaints since its inauguration (in 2008).

Sizing and controlling ventilative cooling systems is a complex task that is affected by many uncertainties that impact system performance. In this context, the use of a simulation tool such as EnergyPlus can be beneficial.

# 6 ACKNOWLEDGEMENTS

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