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Energy and comfort management of the educational spaces through IoT network for IAQ assessment in the eLUX lab

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Abstract. IoT networks for data gathering in the buildings allow to control and manage the operational phase of the systems for ventilation and IAQ, optimizing the energy flows and the indoor comfort conditions. The concept of Cognitive Building steers the implementation of such networks in the assets considering the sensors as scattered systems to inform and actuate the adaptation strategies which are crucial when variables have to be included in the process management. Variables as weather, occupancy flows during the day, energy production by renewable energies, energy storage strategies, affect the indoor conditions, the rate of use of the HVAC systems and the energy management of the used/storage resources. The eLUX lab at the Smart Campus of the University of Brescia is a pilot building in the field and it has been monitoring since 2017. The indoor conditions monitoring could unveil critical situations defined by temperature, humidity and indoor air quality (IAQ) in the educational spaces and envisage strategies and scenarios related to energy demand defined by the occupancy stream. The IoT network collects data about indoor air quality in the different spaces and it is used to verify and increase the accuracy on occupancy estimation. The HVAC management referred to the effective occupancy can enable an energy management process based on user-centred approach empowering an increment of the comfort hours facing critical situations and it is possible to promote actuation strategies preserving energy efficiency and IAQ (e.g. increase ventilation to decrease the CO₂ concentration, decrease temperature and control relative humidity in the indoor spaces by window opening or modulation of the fans and dehumidification systems activation). The educational spaces have been adopted as case studies to analyse the actual indoor conditions and come up with a detailed description of the profiles of use (i.e. occupancy, lighting, equipment, HVAC, CO₂) supporting effective management policies. The paper describes the analyses on the data collected to understand when and how the indoor conditions can be improved to preserve the learning performance of the users. The research addresses one of the main topics of the eLUX living lab.

1. Introduction

Buildings are the places where activities are carried on and users that can easily adapt their indoor condition in the working spaces are most productive and with high levels of perceived wellbeing and comfort. The paradigm of the cognitive building increases the concept of adaptation which is an active attitude promoted by the user and allows at the same time a passive data collection and an active dialogue



and communication between user and building through ICT technologies. A cognitive building provides advanced services and customizes indoor conditions according to user's preferences and changes in occupancy profiles or other variables, such as, for example, weather conditions and specific individual or collaborative activities occurring during the day [1]. The IoT infrastructure provides the crucial layer of information about indoor conditions and occupancy needs that can enable the actuation of strategies to adapt and correct the building behavior and indoor conditions towards enhanced levels of comfort in the smart city [2]. In school buildings the problem of indoor air quality and comfort condition is crucial, researches proved that insufficient ventilation rate [3], and thus an increase of CO₂ concentration [4], produces weaker results in the exam pass rate [5] which means a decreased cognitive performance in the accomplishment of learning task and knowledge restitution. Many studies reported that ventilation rates in schools are often substandard, and it is not rare to record CO₂ concentration above 3000 ppm in classrooms [6][7].

1.1. Comfort parameters

The standard comfort parameters include temperature and relative humidity in the indoor spaces and typical definition of the comfort values are given in the standard [8] and it is worthy to note that indoor air quality is strongly deteriorated when indoor air temperature and relative humidity increase in the thermal zone [9]. The quality of the classroom environment not only affects health and comfort [10][11], but it may also impair the learning performance of pupils. Following earlier studies which indicated such a correlation [12][13], there is growing evidence that weakening of learning performance and increased absenteeism are partly due to inadequate ventilation and unsuitable thermal conditions in classrooms [14]. A specific study on ventilation [15] defining how the provided rates upset cognitive performance in a primary school reported that the effects are best characterized by the power of attention factor which means the intensity of concentration at a particular moment with faster responses reflecting higher levels of focused attention.

1.2. Indoor air quality

In order to guarantee a correct indoor air quality (IAQ) for the users, the parameter of CO₂ concentration is assumed as relevant in the evaluation and the maximum acceptable level is considered 1000 ppm however 600 ppm is the level of acceptable conditions of indoor air quality in rooms and 1000 ppm is the upper limit of fresh air. The variation of CO₂ concentration level over time in the indoor building space is defined by the following equation (1):

$$c = \left(\frac{q}{nV}\right) \cdot \left[1 - \left(\frac{1}{e^{nt}}\right)\right] + (c_0 - c_i) \cdot \left(\frac{1}{e^{nt}}\right) + c_i \quad (1)$$

where: c is the CO₂ concentration in the thermal zone [m³/m³]; q is the CO₂ produced by the occupants [m³/h]; V is the net volume of the thermal zone [m³]; n is the specific number of air changes for building use [h⁻¹]; t is the time [h]; c_i is the CO₂ concentration in the inlet air assumed equal to 0 m³/m³; c_0 is the CO₂ concentration at the starting time $t = 0$ assumed equal to 350 ppm.

The occupants generate a quantity of CO₂ that can be determined according to the equation:

$$q = q_p \cdot n_o \quad (2)$$

Where q is the CO₂ produced by each occupant in the zone, related to the activity (in this case the value is assumed 0.05 m³/h/person) [m³/h]; n_o is the number of occupants in the thermal zone [-].

The link between CO₂ concentration and description of IAQ is defined on Table 1. The ventilation rates to uphold a suitable IAQ are calculated in different standards at the national and international level, generally adopting empirical data multiplied by the number of occupants and by the net floor surface occupied by building end-uses. The standard calculation follows the national norm, considering a minimum rate for IAQ of outdoor fresh air per person as in equations (3) and (4):

$$n = \frac{(v_{min} \cdot i_s \cdot A)}{V} \quad (3) \quad V_{a,k} = V \cdot n \quad (4)$$

where n is the specific number of air changes [h⁻¹]; v_{min} is the specific external air flow required in the occupancy period [m³/h per person]; i_s is the density of occupants [person/m²]; A is the surface area of the zone [m²]; $V_{a,k}$ is the air flow rate required [m³/h]; V is the net volume of the thermal zone [m³].

Table 1. IAQ based on CO₂ concentration.

CO ₂ concentration [ppm]	IAQ description
350-400	Fresh air, perfect conditions
<600	Acceptable conditions of indoor air quality in rooms
<1000	The upper limit of fresh air
<1500	Air perceived as stuffy and not fresh
<2000	People with respiratory illnesses may receive cough, weakened people may faint
<10000	Bad air quality causes increased breathing rates, problems with respiration, headaches, nausea

1.3. Cognitive performance

Scientific researches assess how the indoor parameters can affect the productivity of users into the building spaces and beyond economic interests, in educational spaces and universities facilities the concept productivity is replaced by learning performance and cognitive capacity that are reduced where comfort conditions are disregarded. Three main categories have been identified and the related design principles are considered when learning progress and indoor space quality are interrelated: Individualization: weight 30%; Naturalness: weight 42%; Level of stimulation: weight 28%. The Naturalness, which includes the physical parameters of the immaterial quality of the spaces are the most influential for the students into the learning spaces and parameters such as light, sound, temperature and indoor air quality are the main parameters to consider. The correlation between overall progress and each environmental parameter included in the Naturalness category is listed below: Light: weight 16%; Noise: weight 4%; Temperature: weight 10%; Air quality: weight 12%. In Table 2 the effect of the different parameters related to the specific variation of the values are reported [16] and it is worthy to note that the increase of the CO₂ concentration [17] is directly related to the decrement of the cognitive performance measured on different specific tasks: basic activity, applied activity, focused activity, task orientation, crisis response, information seeking, information usage, breadth usage, breadth of approach, strategy.

Table 2. Naturalness parameters with standard and recommended value associated to outcomes on the learning performance.

Parameters	Unit	Standard values	Recommended values	Outcomes	Standard
Indoor Air Temperature	°C	20±2	20-25	+2-4% for each -1°C	
Ventilation rate	l/s-p	3	8	+7% from 5 to 15*	ISO 7730
CO ₂ emissions	ppm	-	< 1000	-1-2.5%**	
VOC emissions	g/m ³	-	<200***	-	

* the 3 l/s-p is a minimum value and 8 l/s-p is a standard value; in the national regulation the values ranges as 2.5 to 5 volumes/h due to different school levels, evidence of the improvement are recorded in scientific literature shifting from 5 to 15 l/s-p;

** to less than 1000 ppm is associated a healthier environment and a -1-2.5% of absenteeism for sicknesses has been observed.

*** the threshold of 200 g/m³ is the lower value before a discomfort perceived condition

For 7 of 9 scales, mean raw scores consistently decrease with increasing CO₂ concentration and the score are lower than 11-23% with CO₂ concentration over 1000 ppm and lower than 44-94% with CO₂ concentration over 2500 ppm.

2. Methodology

The present study embraces a data driven approach and starting from the data gathered by sensors in different educational spaces analyzes three main parameters of comfort easily controllable in the indoor space to understand when, during the day, critical situation are reported and a prioritization of the indoor conditions related to the effective impact on learning performance is identified. The parameters are: 1) CO₂ concentration; 2) indoor air temperature; 3) relative humidity. The three parameters can be collected by two sensors one providing T and RH and the second measuring CO₂ concentration. For each parameter thresholds have been defined to evaluate the indoor conditions (Table 3). The CO₂ concentration can be also easily adopted to support and verify information given by count person devices that often have reliability problems [18]. The analysis focuses on these specific parameters, the combination of the three and hourly data allows to display the whole situation for the different spaces. The statistical analysis allows to understand the percentage of data that are out of comfort range and thus the possibility to promote intervention strategies and possibly energy savings with an on-time management.

Table 3. Thresholds for indoor comfort conditions and IAQ: comfort range is between L1 and L2.

Parameter	Symbol	L1	L2
Carbon dioxide concentration	CO ₂	600	1000
Indoor air temperature	T	20	22
Minimum Relative Humidity	RH min	35	30
Maximum Relative Humidity	RH max	40	45

3. Case study

The analysis has been performed on the pilot building eLUX lab (energy Laboratory as University eXpo) at the Smart Campus of the University of Brescia [19][20]. The building is located in the Faculty of Engineering and it includes three floors of educational spaces: in the ground floor the computer labs are located (i.e. MLAB1, MLAB2), at the ground floor two lecture rooms are used daily by the students (i.e. MTA, MTB) and at the first floor a lecture hall is used both for lectures and graduation days (i.e. M1). The building is a living lab and sensors are monitoring the daily conditions in the educational spaces and the monitoring campaign is ongoing since October 2017. The analysis performed are referred to all the spaces excluding the MLAB1 where problems in the acquisition device was detected.

4. Results

The first step of the data analysis aims at identifying in the different hours a critical situation: the frequency of at least one parameter out of the comfort and IAQ range is displayed in Figure 1. In the 50% of the cases for each classroom the condition are out of the comfort range (>L2) depicting a very harsh situation. M1 has the 80% of records in critical situation only between 13:00 and 14:00 however MLAB2 and MTB have the 70% of the records during all the day and 60% of the records for MTA.

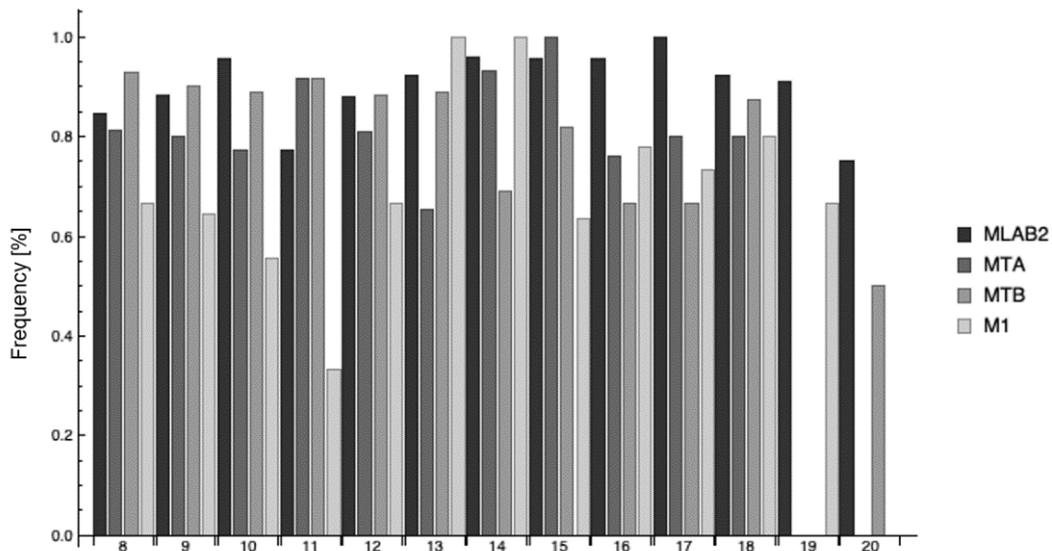


Figure 1. Frequency of at least one of the three parameter out of the comfort and IAQ value range during the day.

4.1. Hourly global comfort condition assessment

For each classroom the hourly distribution of the situation is reported in the following figures showing how many times in each hour of the day the three comfort parameters are, at the same time, above the chosen comfort thresholds. Values in the picture are given as frequency to easily compare distinct rooms with different amount of data. This difference is due to the fact that sensors collect data when there is a change in the measured parameters and not on a constant time span basis.

The values above L1 means a comfort condition while the value above the L2 limit define a strong non-compliance condition with comfort and IAQ. The comfort in MLAB2 (Figure 2) exceeds L1 in more than 8% of the cases between 14:00 and 15:00, 6.5% at 9:00 and $\leq 5\%$ in the other hours of the lecture day. For MTA (Figure 3) L1 threshold is overcome in more than 11% of the times at 9:00, 11:00 and 14:00, likewise, in MTB, is passed 10% of the time (Figure 4) at 10:00 and 11:00. In M1 (Figure 5) from 11:00 to 14:00 and after 18:00 there is the 2% of the cases in the comfort range while in the other hours the comfort is reached in less than 6% of the cases. The threshold L2 has been significantly exceeded in MLAB2.

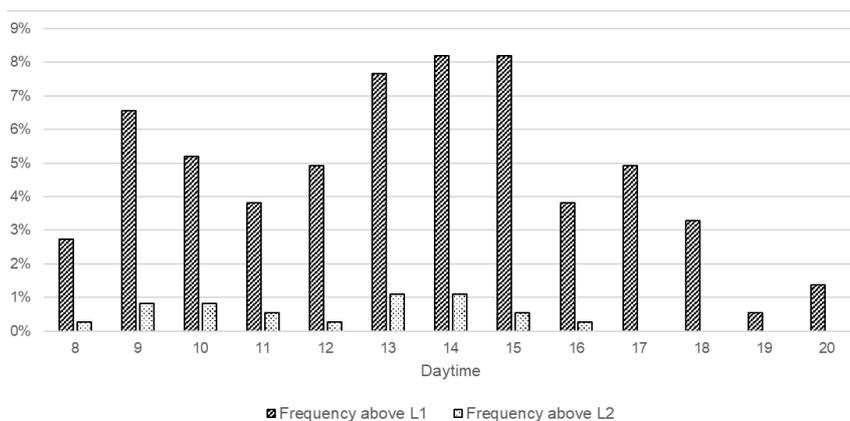


Figure 2. Frequency distribution of the data in MLAB2: three parameter >L1 and >L2.

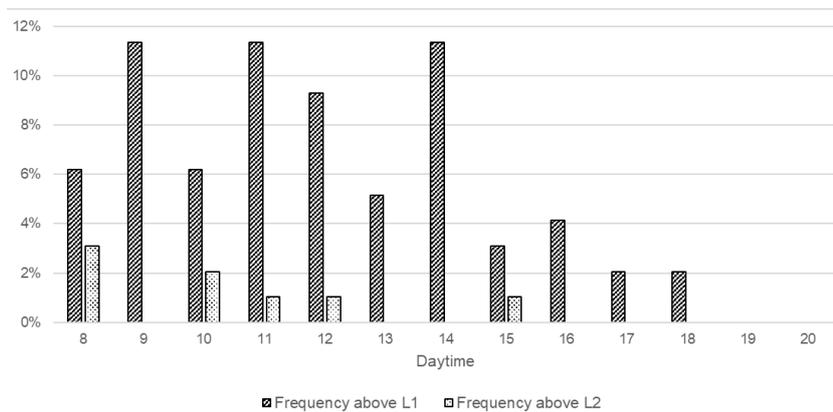


Figure 3. Frequency distribution of the data in MTA: three parameter >L1 and >L2.

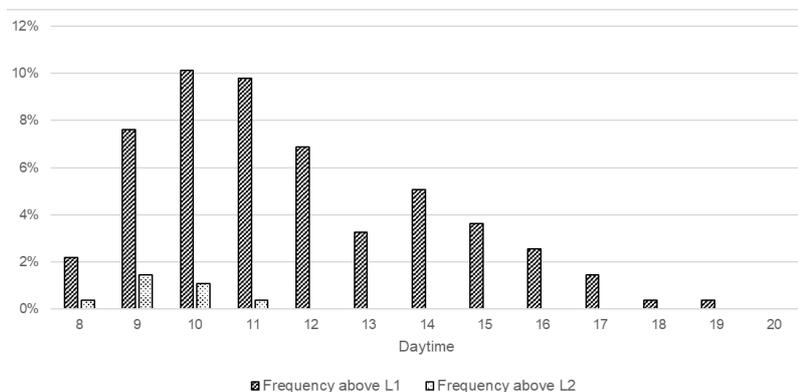


Figure 4. Frequency distribution of the data in MTB: three parameter >L1 and >L2.

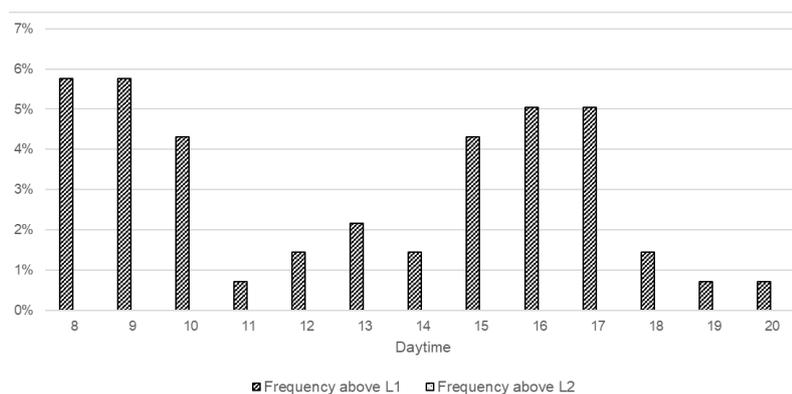


Figure 5. Frequency distribution of the data in M1: three parameter >L1 and >L2.

4.2. Global comfort condition assessment

Considering the three parameters out of the comfort range at the same time, data have been aggregated to understand the effective situation inside each classroom. The standard comfort value allowing to avoid energy waste (L1) is exceeded in about 50% of the recorded case reaching the 64% for MTA. The overrun of limit L1 means also for the IAQ parameter that the 600 ppm are disregarded in the same percentage. In the 8% of the cases in MTA, 6% in MLAB2 and 3% in MTB the conditions are not

acceptable. As average the 50% of the time the educational spaces are not in optimal conditions of comfort and IAQ (Table 4, Figure 6).

Table 4. Frequency distribution of the data related to the three indoor quality parameters.

Room	MLAB2	MTA	MTB	M1
Frequency above L1	55%	64%	50%	49%
Frequency above L2	6%	8%	3%	0%
Number of records	366	97	276	139

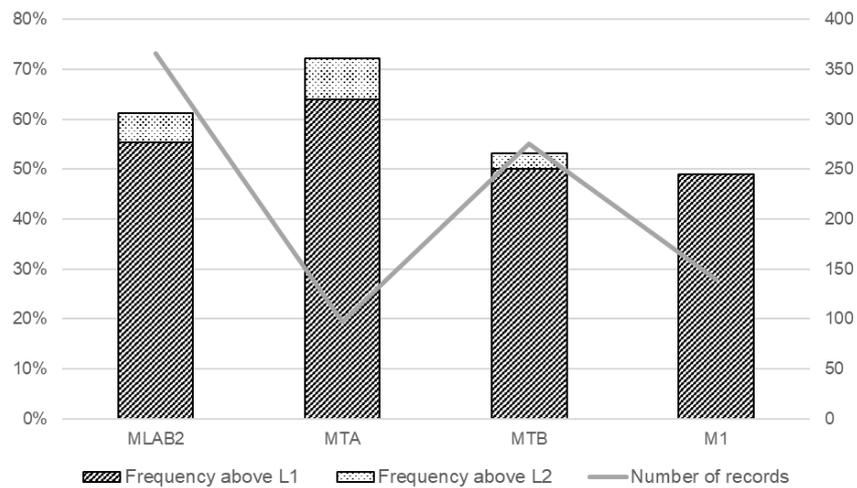


Figure 6. Frequency distribution of the data in the different classrooms of the eLUX building and number of data recorded.

4.3. Comfort zone given by the three quality parameters

The comfort conditions have been thus described by placing the measured temperature on the x-axis, the relative humidity on the y-axis and coloring the points green if the CO₂ concentration is below 600 ppm, yellow if it is between 600 ppm and 1000 ppm, red if it is above 1000 ppm. The result is a cognitive picture of the state of comfort of the classrooms rather worrying, the cases in which all three parameters are in optimal condition are very few how it is shown by Figure 7.

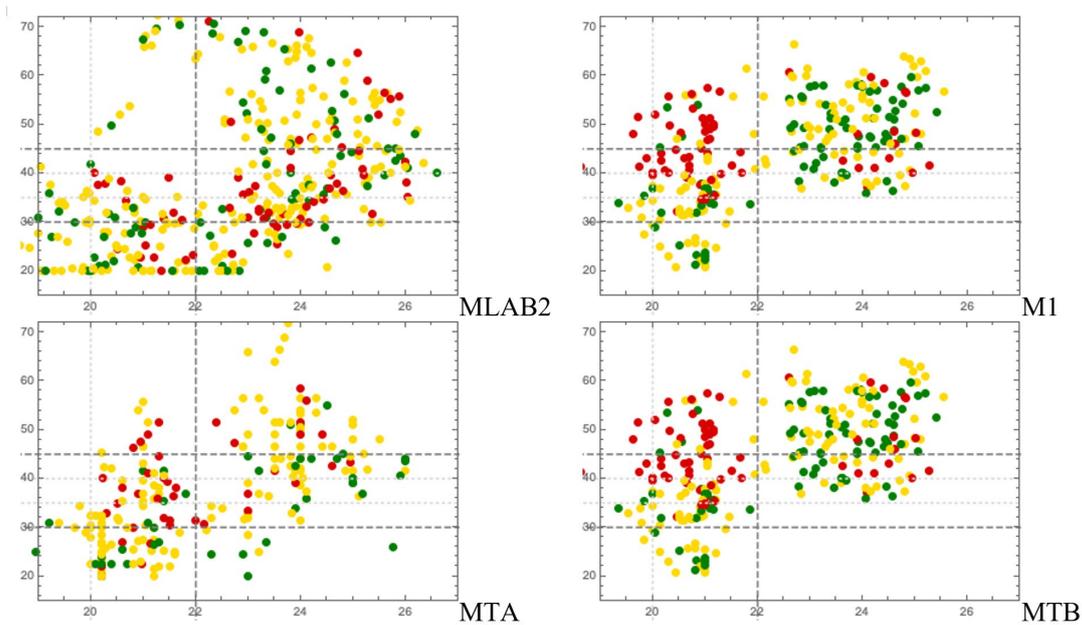


Figure 7. Frequency distribution of the data in the different classrooms of the eLUX building on hourly basis during the occupied days.

4.4. State of combined comfort and IAQ conditions

The three states (below L1, between L1 and L2 and above L2) for the three measured parameters (T, RH and CO₂) can be combined in 27 possible states. The states are listed in Table 5 starting from the best-case scenario (1) to the worst-case scenario (27). The best-case scenario considers: a) both the indoor air temperature and the relative humidity in the comfort range between L1 and L2; b) CO₂ concentration lower than 600 ppm which means a healthy indoor air quality. The average condition (13) is defined when an issue is perceived however the condition is not strongly critical: i.e. the temperature is below 20°C (a little bit cold), the relative humidity is lower than 30% (dry air perceived) and CO₂ concentration is between 600 and 1000 ppm (between fresh air and lower limit of fresh air). The critical conditions are defined when temperature is higher than 22°C (too warm and towards the reduction of optimal cognitive performance condition), relative humidity above 45% (which means a wet perception and CO₂ concentration higher than 1000 ppm).

Table 5. States list combining Indoor Air Temperature, Relative Humidity and CO₂ concentration and considering the lower progressive number as higher preferable condition.

N.	Temperature T [°C]	Relative Humidity RH [%]	Carbon dioxide CO ₂ [ppm]
1	T between L1 and L2	RH between L1 and L2	CO ₂ below limit L1
2	T between L1 and L2	RH below L1	CO ₂ below L1
3	T below Limit L1	RH between L1 and L2	CO ₂ below limit L1
4	T between L1 and L2	RH below L1	CO ₂ between L1 and L2
5	T below limit L1	RH below limit L1	CO ₂ below limit L1
6	T between L1 and L2	RH between L1 and L2	CO ₂ between L1 and L2
7	T below Limit L1	RH between L1 and L2	CO ₂ between L1 and L2
8	T between L1 and L2	RH above L2	CO ₂ below limit L1
9	T below limit L1	RH below limit L1	CO ₂ between L1 and L2
10	T below Limit L1	RH above L2	CO ₂ below limit L1
11	T above L2	RH between L1 and L2	CO ₂ below L1
12	T above L2	RH below L1	CO ₂ below L1
13	T above L2	RH above L2	CO ₂ below L1

14	T between L1 and L2	RH above L2	CO ₂ between L1 and L2
15	T below Limit L1	RH above L2	CO ₂ between L1 and L2
16	T above L2	RH between L1 and L2	CO ₂ between L1 and L2
17	T above L2	RH below L1	CO ₂ between L1 and L2
18	T above L2	RH above L2	CO ₂ between L1 and L2
19	T between L1 and L2	RH between L1 and L2	CO ₂ above L2
20	T between L1 and L2	RH below L1	CO ₂ above L2
21	T between L1 and L2	RH above L2	CO ₂ above L2
22	T below Limit L1	RH between L1 and L2	CO ₂ above L2
23	T below limit L1	RH below limit L1	CO ₂ above limit L2
24	T above L2	RH between L1 and L2	CO ₂ above L2
25	T below Limit L1	RH above L2	CO ₂ above L2
26	T above L2	RH below L1	CO ₂ above L2
27	T above L2	RH above L2	CO ₂ above L2

The frequency of each condition have been calculated for each room and it is shown in Figure 8 while the diagram in Figure 9 shows how many times the three main conditions (best, average and critical) occur in each classrooms. The 20-25% of the data show the best-case scenario for the rooms while critical situations are reported in the 15-20% of the records. In most cases the situation shows at least one parameter outside the comfort range and CO₂ concentration is critical almost in the 50% of time in the classrooms with the worst conditions (MTB).

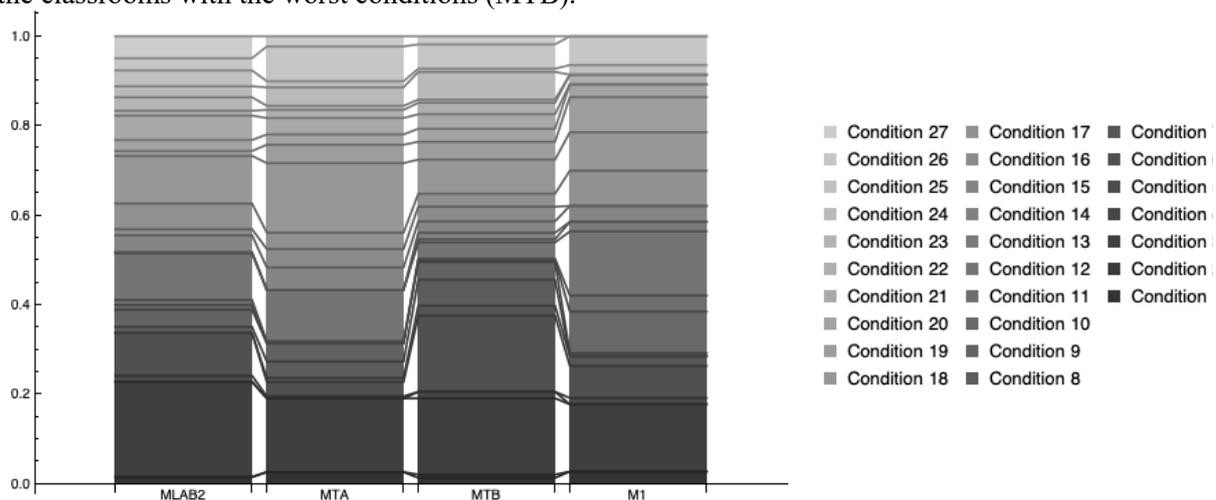


Figure 8. States of the different classrooms.

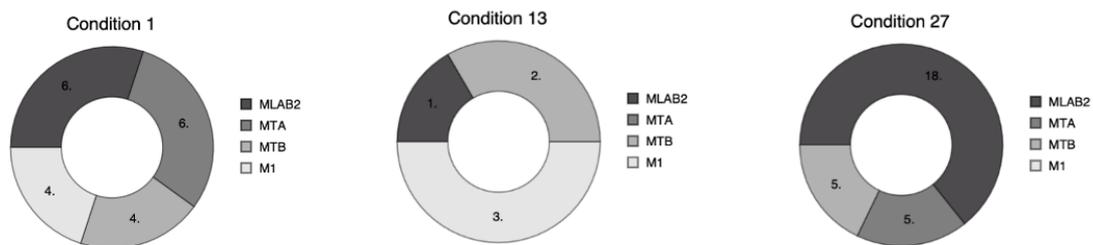


Figure 9. States of the different classrooms: 1: best-case; 13: average-case; 27: worst-case

5. Conclusion

The existing educational facilities have energy and comfort weaknesses that are daily experimented by the users. Adaptive behaviors are put in place however a dissatisfaction is commonly reported. Studies about schools denounce a widespread problem and among children, 87% was bothered by noise, 63% by smells, 42% by sunlight when shining, 35% didn't like the temperature in the classroom (too cold or too warm) and 34% experienced temperature changes. Main diseases reported comprise allergies (26%), rhinitis (17%), hay fever (16%) and eczema (16%) [21]. The possibility to tune the temperature in the indoor spaces according to occupancy level and when comfort thresholds are overrun due to external factors (i.e. solar radiation) could boost an energy saving to be balanced with higher rates of ventilation to remove the CO₂ concentration which affect IAQ. Whatever, the use of heat recovery on the ventilation system could be an optimized solution. In the case study, a temperature higher than the comfort value has been recorded as average in the 50% of the cases which means a strong energy saving if the issue might be solved in real time. The HVAC systems should be integrated with hygro-thermal control to maintain the correct relative humidity into the spaces avoiding an exacerbation of the discomfort perception. The increased ventilation rate, needed to mitigate the CO₂ concentration above the fresh air limit of 1000 ppm in the classrooms, should be activated in the 20% of the occupancy time and using an efficient mechanical ventilation unit it is possible to have up to 85% of efficiency which means a reduction of ventilation losses of about 63 to 82% with improved IAQ and learning performance of the students. The IoT network is crucial to detect the exceeding the thresholds and to actuate in real time the tuning of HVAC, ventilation and HR systems promoting a synergy in the systems of systems.

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