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Analysis of Thermal Comfort for a Romanian Rural School Using Experimental Measurements and Dynamic Simulations

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Abstract

In this article the main objective is to analyze the thermal comfort in a rural educational facility by means of an experimental campaign coupled with a simulation study. The experimental measurements were conducted in February and June 2014 and consisted of assessing air temperature, mean radiant temperature, humidity and air velocity. The case study building was comprised of a renovated new wing which was thermally insulated and an old one to which no insulation was added. The reference case is the building with 5 cm of insulation on the walls while the improved case consisted of a higher level of insulation. The environmental measurements facilitated the assessment of thermal comfort during a period of a few days and allowed the numerical model to be calibrated and tested, while the whole year dynamic simulation focused on illustrating the positive impact of higher insulation on the thermal comfort of the occupants. With an overall 10 cm insulation layer, the indoor air temperature during winter was higher while the summer values were closer to comfortable limits. Knowing that the lifetime of any school is spread across multiple decades, investing an extra amount in the exterior envelope insulation is more than recommended.

Rezumat

În acest articol obiectivul principal este de a analiza confortul termic într-o instituție de învățământ din mediul rural prin intermediul unor campanii experimentale împreună cu un studiu de simulare numerică. Măsurtrile experimentale au fost efectuate în lunile februarie și iunie 2014 și au constat în evaluarea temperaturii aerului, a temperaturii medii radiante, a umidității și a vitezei aerului. Clădirea folosită ca studiu de caz este compusă din două zone, una renovată și alta nu. Cazul de referință este clădirea cu 5 cm de izolație la nivelul pereților în timp ce scenariul îmbunătățit a constat într-un nivel superior de izolare. Dacă măsurările au permis analiza punctuală (câteva zile) a condițiilor de mediu, modelul numeric a permis simularea dinamică a întregului an școlar. Scopul simulărilor a fost să ilustreze impactul pozitiv pe termen lung al izolației asupra confortului termic al ocupanților. In aceeași clădire izolată cu 10 cm, temperatura aerului in timpul sezonului rece este mai mare iar in timpul verii mai mica fiind mult mai confortabilă. Tinând cont de faptul că durata de viată a unei școli este de câteva zeci de ani o investitie initială mai mare in izolarea termică este mai mult de recomandată.

Keywords: thermal comfort, educational buildings, dynamic simulations, experimental campaign, insulation level.

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1. Introduction

When looked at from an entire built stock perspective, in the category of most important establishments for our communities, educational facilities play a central role with children spending around 25% of their time in classrooms. In addition, since schools present a much higher occupancy than any other building [1] it is vital to have an indoor space that will not disturb the comfort, health or intellectual performance of the occupants.

Thermal comfort is an important part of the IEQ as well as significantly influencing the energy consumption of the building and the performance of those residing in it. Furthermore, as thermal comfort is both physiological and psychological, it may affect the overall morale of the occupants, impacting one's productivity and well-being [2].Its importance on the ambient environment cannot be underestimated since the vast majority of complaints about indoor climate relate to poor thermal comfort. When conditions are not met, complaints from both teachers and students may appear, leading to reduced attention spans and intellectual performance [3]. For this reason, research on thermal comfort pertaining to educational buildings is being carried out in various parts of the world: United States, EU (e.g. Greece, Italy, Netherlands, France, Germany, and the United Kingdom), the Middle East (United Arab Emirates), Asia (e.g. China, Malaysia, Indonesia), South America (Brazil).

The first scientific studies concerning the effects of thermal environment quality in classrooms on the students' performance began around the middle of the 1950s in the US. Initially most of these were carried out in the form of field studies [4]. Today, thermal comfort can be defined using two approaches, each one with its advantages and shortcomings: the first can be defined as "rational", the other as "adaptive". Fanger's model [5] based on steady state heat transfer theory in a fully controlled climate chamber, has a rational approach and provides the basis of the main thermal comfort standards for mechanically controlled environments [6-7].The PMV (predicted mean vote), based on this theory is the most widely used thermal comfort index. On the other hand through field studies an adaptive comfort model can be derived, which serves the purpose of analyzing the real acceptability of the thermal environment, which strongly depends on the context, on the behavior of the occupants and on their expectations. This would imply that the validity of PMV in every-day environments can only be tested through field research [8][9]. In addition field studies reveal that thermal preferences depend on the way people interact with their surroundings, modifying their own behavior and adapting their expectations, to match the thermal environment [10].

The importance of field studies, especially in investigating thermal adaptability of people, comes from the need to assess thermal comfort responses within the naturally occurring context since the quality of the classroom environment is known to affect children's health, well-being, learning ability and comfort [11]. The typical approach for field studies consists in administering a questionnaire to a group of occupants while the investigator records certain macroclimatic parameters such as temperature, relative humidity (RH), mean radiant temperature (MRT), air velocity (v_{air}), etc. [12] Thus people answering now refer to the very thermal environments to which they are subjected in their everyday life. The defense of the field study approach to thermal comfort depends largely on what has been named "experimental realism" of the field methodology. In other words, field studies highlight much better how people react to their environment compared to Fanger's controlled climate room approach. Ergo, such an investigation methodology is very important inside classrooms, which are an example of indoor environments where the adaptive opportunities are quite limited during the lessons period but they are free during the hourly lesson breaks. When seated at their desk, listening and understanding lessons children have limited freedom in modifying and adjusting their activity level, adding or removing layers of clothing, opening or closing the windows or moving the sun shading devices according to the thermal environment [13]. At the same time there is no assurance that the thermal comfort criteria applicable for adults are also optimal for children's comfort or performance.

Moreover few studies have focused on children's thermal perception in temperate climates. In tropical and subtropical regions research conducted in schools has explored the applicability of the ASHRAE Standard 55 (thermal comfort standard) to these climates [14] [15] [16]. At the European level, a study was conducted in the Netherlands which investigated the application of the predicted mean vote (PMV) charts and clothing adaptation on a sample of 79 children [17]. In the case of the UK, published data sets for schools studies date back to the 1970s [18][19]. In a more recent study on a UK educational building published in 2013, it was found that thermal comfort was not adequately achieved during occupied hours in winter. (Barbhuiya and Barbhuiya 2013) Field work regarding thermal comfort was equally performed in Cyprus and Portugal (Katafygiotou and Serghides 2014) (Guedes, Matias and Santos 2009) All in all, there is generally a need for more studies related to school children's thermal comfort perception [23]. A literature review performed by a dutch team showed that temperatures in classrooms are important factors in the learning process and improving thermal comfort should be given more priority. (Zeiler and Boxem 2009)

From a European perspective, in comparison to other countries, Romania offers interesting research opportunities concerning topics related to integrating indoor environmental quality (IEQ), energy efficiency and renewable energy options in schools. Since very little research has been carried out, Romania is close to a "terra incognita" in this field with many interesting findings yet to be uncovered. This article focuses on analyzing a rural school understanding the issues and finding solutions that can positively impact the thermal comfort of the children studying here.

The authors set out to find answers to a number of questions including: How is thermal comfort perceived in a Romanian rural school? How can the indoor conditions be best improved? How should dynamic simulations be used effectively?

2. Methodology and case study

Under the general objectives of the current study and after highlighting the research questions to be answered, the subsequent chapter will present the step-by-step approach used.

A detailed **field study** was carried out in a rural school situated in the commune of Mateesti, Valcea County – Romania. This particular investigation choice was influenced by a country specific observation: a considerable percentage of children under the age of 14 years study in rural schools. Taken together, in the primary (1^{st} – 4^{th} grades) and secondary (5^{th} – 8^{th} grade) schools located in the rural environment is educated approximately 49% of the student population of similar age. When it comes to high school and post-high school education (with the exception of universities) less that 40% of these establishments are situated in the countryside [25].

A comprehensive measurement campaign was conducted for the two main seasons: cold season (heating interval) and hot season (the interval when classroom cooling would be required). For the **cold season (winter)** spot recordings were conducted on February 10^{th} 2014 for a number of parameters at the same time that classes were being held. Temperature (T), relative humidity (RH), and CO_2 concentration have been investigated. Two types of instruments were used. The first is the **TESTO 480** while the second consists of data loggers from **CO_2Meters**. Air temperature (exterior and interior), mean radiant temperature (MRT), RH (exterior and interior), CO_2 concentration (exterior and interior) and air velocity (v_{air}) were measured using the TESTO 480 instrument. The data loggers recorded in a continuous manner: CO_2 concentration (exterior and interior), RH and temperatures for both the interior and exterior.

All instruments were set out to record on from 5:00 AM to 3:00 PM (after the education period had finished for the day). The intention was to thus cover both the 4 hour interval (08:00-12:00) when classes are scheduled as well as the transition period before and after. All recording of data was continuous with a time step of 1 minute and took place concomitantly in 10 classrooms spread throughout the three schools. Four classrooms were chosen for investigation (ground, first and second floors covered). Each classroom had its own particularity, either displaying a north orientation, having direct sunlight exposure during the experiments, or being positioned in different places in the building. The instruments were positioned in the middle of the classroom on one of the benches at a height of 0.6 m above the floor, as it is indicated in the standard ISO 7726 for seated persons [26]. CEN 2001

Concerning the **hot season (summer)** all of the above methodology applies with one major exception. All parameters were continually recorded (time step of 10 minutes) for a period of one week from Monday to Sunday (2^{nd} – 9^{th} of June 2014). In order to ensure that the 5 day school period was covered (Monday – Friday) as well as the weekend (Saturday and Sunday). All data obtained between 8:00 AM and 12:00 PM (interval when children are inside the classrooms) was averaged and the daily mean values were equally averaged. Moreover a school level value was computed by averaging the numbers obtained for the different classrooms.

Figure 1 shows the architecture of the investigated building as well as one of the classrooms with the installed measurement equipment.

Figure 1. A) Analyzed school; B) TESTO 480 Equipment used during experimental campaign

The investigated school was renovated in 2008, and has a total usable area of 784.9 m^2 spread across three floors. The school has a capacity of 164 pupils, there is no cooling system installed and the heating is done using wood/coal fired central system. The new wing of the building is insulated with 5 cm of polystyrene and the windows consist of double pane clear glazing with air filling (4-6-4). There are no interior solar shadings and the average classroom area is around 50 m^2. As mentioned before, the school is equipped with a centralized heating system using hydronic radiators installed under the windows without a set point or dead band temperature control. Referring to the issue of natural ventilation, the school uses operable windows that can be opened or closed by the occupants. Usually these were opened during breaks or teaching hours or after the school schedule had ended. During the heating season, usually one window was open per classroom, especially during the breaks and at the end of the classes. For the cooling season, in general there were two windows per classroom open, during the breaks, teaching hours and after classes. No air transfer openings between rooms were present.

3. Dynamic simulations using TRNSYS 17

Before any simulation could be run, a functional model of the building and its systems had to be created. The main elements making up the schematic in **Figure 2** are called blocks (or TRNSYS types) linked together by various conditional relationships. The school building is represented by

Type56 in TRNSYS where the different thermal zones (32), construction materials, heating, ventilation, infiltration and comfort scenarios are all defined to mirror reality as close as possible. Exterior blocks such as “Radiators” and “Ventilation equipement” are linked to the building to simulate the systems. Each classroom is individually assigned a number of hydronic radiator types (as found in the real building) and ventilation units controlled centrally by a number of equations. Additional inputs such as “Heat”, “Occupancy”, “Clo factor”, “Heating schedule” or “Light schedule” are connected to give a fully functional model. The outputs of the simulation can be displayed, printed or integrated according to the user’s needs.

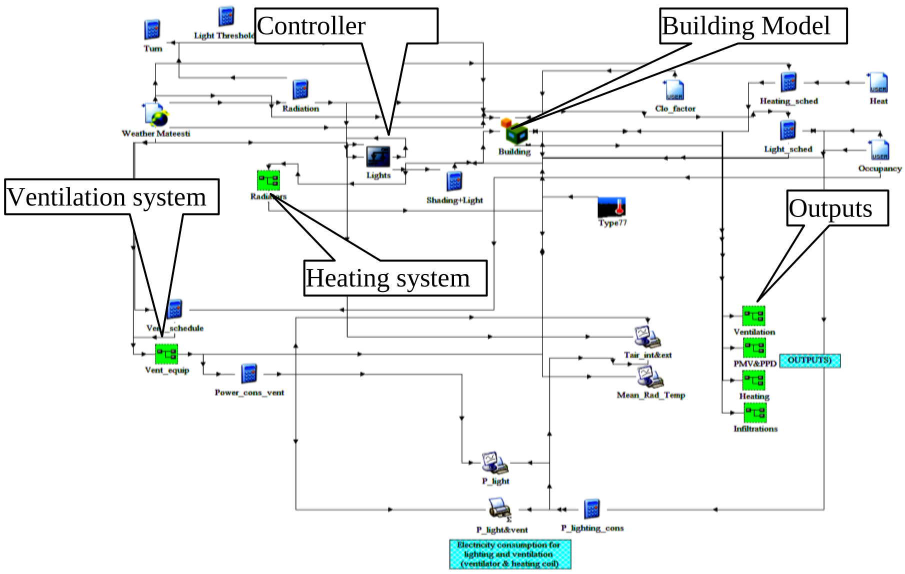

Figure 2. Schematics of the general TRNSYS model

The simulation part of the current study included running two scenarios: one in which the STANDARD school building was modeled and another one where the IMPROVED building was considered. The IMPROVED Building is in fact a building with a higher level of insulation (10 cm on the walls, 20 cm in the attic) having a significant impact on the thermal comfort conditions, as evidenced from the following results.

Table 1. Indoor and outdoor temperature levels *per* classroom and school (cold and hot season)

School type	Data logger code	Comments	Temperature (^{O}C)							
			Cold season				Hot season			
			Min	Max	Avg	SD	Min	Max	Avg	SD
	Exterior		4.2	5.4	4.7	0.4	15.1	17.9	16.3	1.1
Renovated	M1	Class 8 – new wing; ground floor (no direct sun)	16.8	18.7	18.1	2.3	22.5	23.9	23.3	0.6
	M2	Class 1 – old wing; ground floor (direct sun)	17.0	20.6	19.6	1.0	18.4	18.8	18.6	0.2
	M3	Class 6– new wing; first floor	16.1	20.0	18.9	1.2	23.6	25.0	24.3	0.6
	M4	Class 4 – new wing; second floor	16.3	19.9	19.0	1.0	23.4	25.1	24.3	0.6
	School		16.5	19.8	18.9	0.9	22.1	23.1	22.7	0.5

4. Results and analysis

Table 1 presents the indoor and outdoor temperature levels for each classroom and school during both seasons. As expected, during the **cold season**, the old school had the lowest daily temperature recorded (15.8 ^{o}C), followed by the new building (17.3 ^{o}C) and finally the renovated one (18.9 ^{o}C). The average temperatures in the new and the old school were below the Romanian design value of 20 ^{o}C. The only moderately better performing edifice was the renovated building which boasts a maximum temperature of 19.8 °C. The standard deviation (SD) was 0.9 for the winter case and 0.5 for the summer period.

In terms of the dynamic simulations, one of the outputs was the indoor air temperature taken for all thermal zones in the building (classrooms, offices and hallways). **Figure 3** highlights four of the classrooms in which measurements were performed during the week of February 10th 2014. In the default simulated case the temperatures are very close to what was recorded during the experimental campaign: M1 (17.3 °C vs. 18.1 °C), M2 (19.0 °C vs. 19.6 °C), M3 (19.6 °C vs. 18.9 °C), M4 (19.3 °C vs. 19 °C). The improved scenario shows interior temperatures on average 5%-10% higher than the default one which brings them very close to the 20 °C set point.

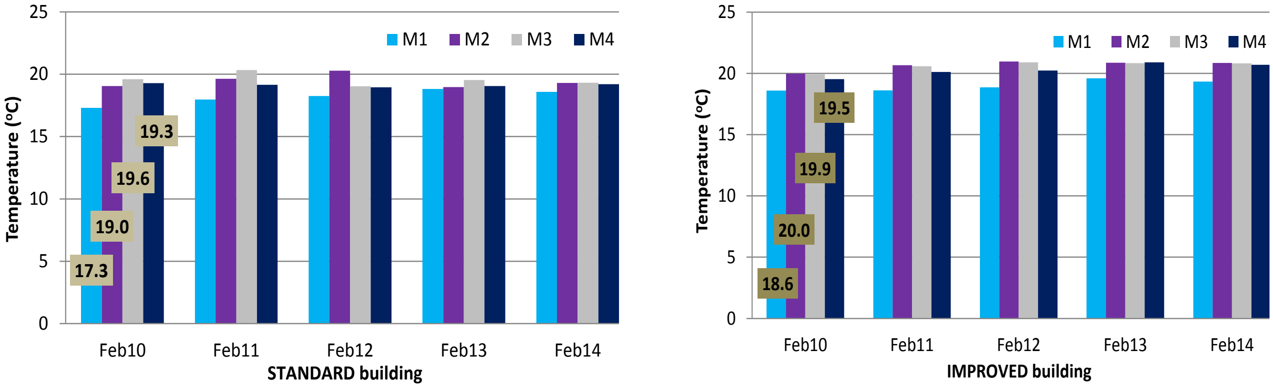

Figure 3. Indoor air temperature for the classrooms experimentally measured – FEBRUARY
(**M1**: Class1 – ground floor, old wing; **M2**: Class8 – ground floor, new wing; **M3**: Class11 – first floor, new wing; **M4**: Class14 – second floor, new wing)

Measurements were also carried out during the summer of 2014, this time for an entire week, and the outputs of the simulation study are presented in **Figure 4.** The temperature values resulting from the simulation for all classrooms are higher when compared to actual recordings.

The most relevant example is classroom M1 with 18.6 °C recorded vs. 20.8 °C simulated. As for the improved building scenario, given the increased thermal insulation and mechanical ventilation included, temperatures are approximately 10% lower than the standard case.

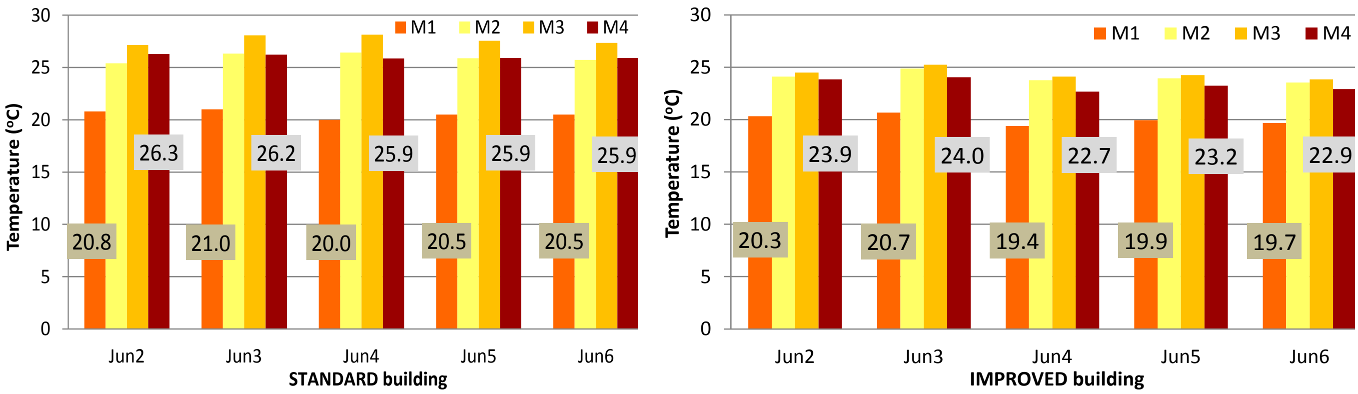

Figure 4. Indoor air temperature for the classrooms experimentally measured-JUNE
(**M1**: Class1 – ground floor, old wing; **M2**: Class8 – ground floor, new wing; **M3**: Class11 – first floor, new wing; **M4**: Class14 – second floor, new wing)

An equally important parameter when assessing thermal comfort is the mean radiant temperature (MRT) of the different thermal zones. For the week in February, the biggest progress between standard and improved scenarios can be observed for classroom M1 where the MRT jumped 33.6% from 11.6 °C to 15.5 °C. More modest improvements, in the range of 5% can be observed for the rest of the classrooms.

Positive developments in MRT values are also predicted by the improved building simulation results for the week in June. During the period June 2nd – June 6th reductions in the range of 13%-18% are to be expected. (**Figure 5**)

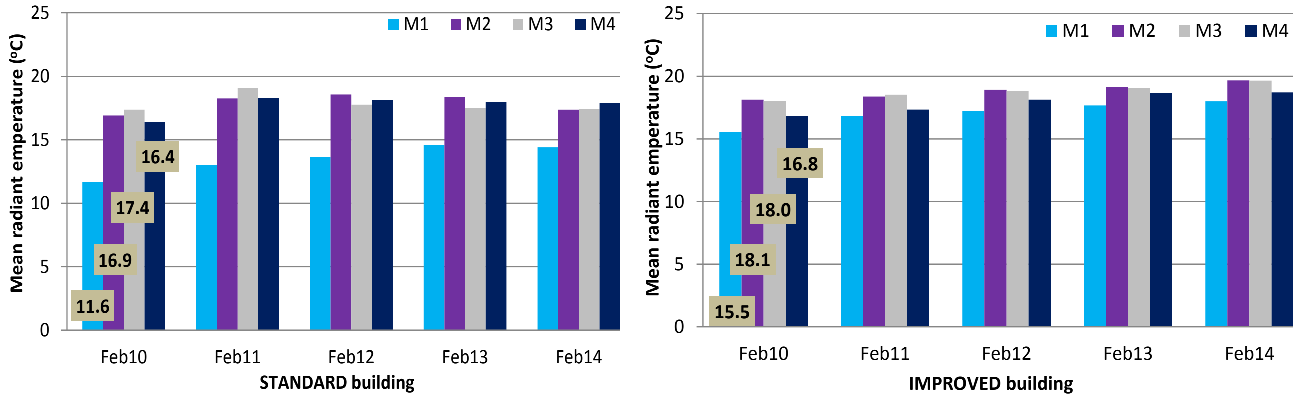

Figure 5. MRT for the classrooms experimentally measured-FEBRUARY
(**M1**: Class1 – ground floor, old wing; **M2**: Class8 – ground floor, new wing; **M3**: Class11 – first floor, new wing; **M4**: Class14 – second floor, new wing)

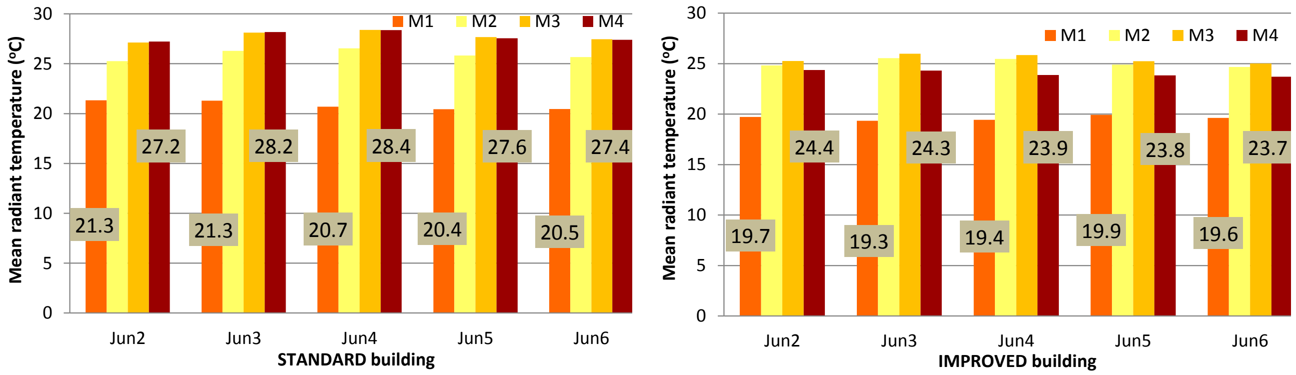

Figure 6. MRT for the classrooms experimentally measured-JUNE
(**M1**: Class1 – ground floor, old wing; **M2**: Class8 – ground floor, new wing; **M3**: Class11 – first floor, new wing; **M4**: Class14 – second floor, new wing)

For the IMPROVED building, the PMV reflects the positive evolution of the indoor air temperature and MRT both in the case of the cold season (February) and hot season (June). Since PMV is influenced by the clothing insulation (expressed in Clo) of the occupants, a dynamic evolution was included as a function depending on the previous day's average temperature and the current day's maximum forecasted temperature. (**Figure 6**) Using Fanger's method, the expected improvements in thermal comfort (PMV) suggested by the simulation results are clearly evident during the week in February.

From a slightly cool (-0.8, -1.2) perception in the standard case, the improved scenario marks a shift toward an overall neutral sensation (-0.1, -0.4) Furthermore, on February 10th, in the number of classrooms for which temperature measurements are available the average simulated PMV (-0.875) is relatively close to what was obtained during the field investigation (-0.65). These positive developments continue for the hot season (June). (**Figure 6**)

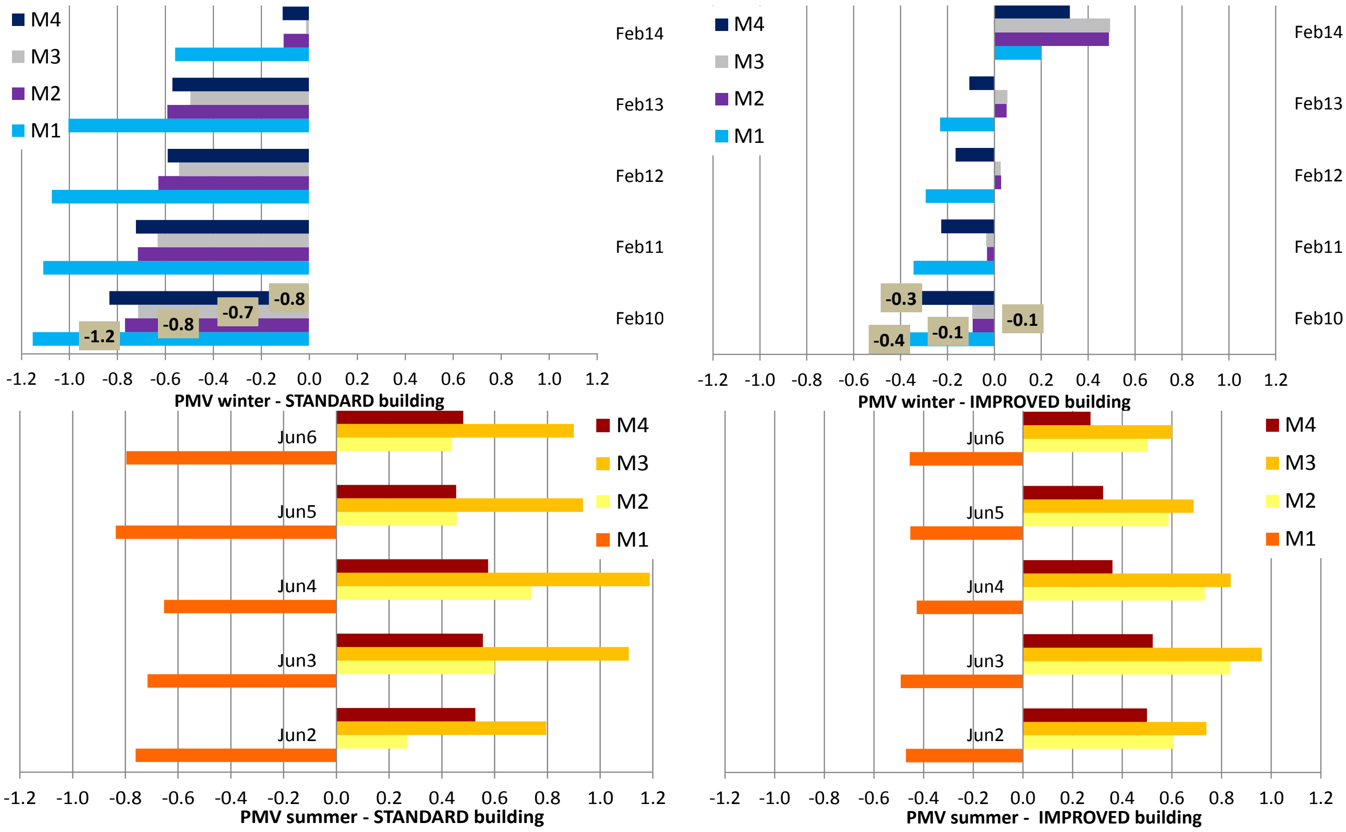

Figure 7. Predicted mean vote of the occupants for the cold season (top) and hot season (bottom): STANDARD vs. IMPROVED building

In terms of percentage of dissatisfied (PPD) the simulations for the IMPROVED building show that a drop to 5% is possible for certain classrooms (week of February). The results are significant given that the STANDARD building simulation indicated a dissatisfaction interval between 17% and 35% for the same period. The simulations for the hot season (week of June) indicate a possible reduction in PPD to an average level of 15%. (**Figure 7**)

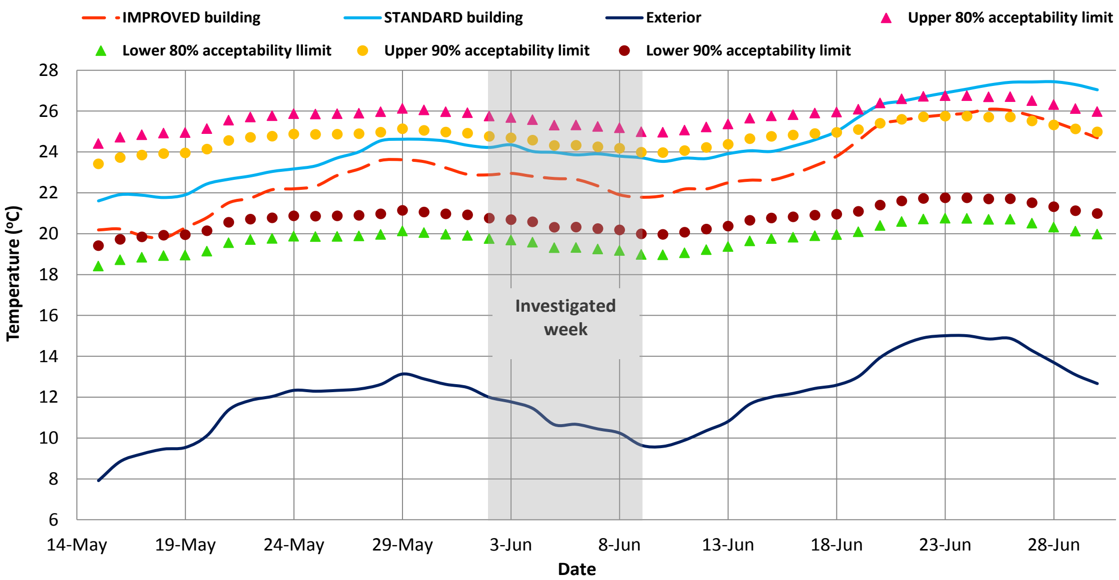

Figure 8. Adaptive thermal comfort graph (hot season)

Figure 8 presents the adaptive comfort model, which can be better applied to naturally ventilated buildings during the hot season. It also helps determine the acceptability of indoor conditions given the mean outdoor air temperature and the indoor operative temperature. The model also take into consideration people's clothing adaptation in naturally conditioned spaces by relating the acceptable range of indoor temperatures to the outdoor climate, thus no clothing values need to be estimated for the space. Additionally, no humidity or air-speed limits are required when this option is used.

The simulation results for the renovated school before and after the enhancements were implemented (STANDARD vs. IMPROVED building) are plotted on the corresponding adaptive thermal graph. Additionally the upper and lower 80% and 90% limits corresponding to Category II and Category I of Acceptability are equally included. Only the interval most prone to overheating is presented (15th May – 30th of June) to see how the building would behave. Overall during the selected period for the majority of the time both versions of the building stay within Category II of Acceptability. Only at the end of the interval (after 15th of June) would the STANDARD building exhibit overheating problems; however at that time children are already on holiday. Since multiannual averages show that exterior temperatures increase starting with the middle of June this leads to higher classrooms temperatures which would negatively impact the thermal comfort of the occupants. Luckily the schools are not occupied during the summer months, thus avoiding the overheating problem altogether. When children return at the middle of September exterior temperatures are no longer excessive. Circling back to the IMPROVED building, this can be labeled as Category I of Acceptability throughout the chosen interval, even after 15th of June. During the investigated week (highlighted in grey) both versions of the building are within Category I of Acceptability. At the same time individual classrooms may not fall within the acceptability limits of the adaptive thermal comfort depending on their orientation and position in the building.

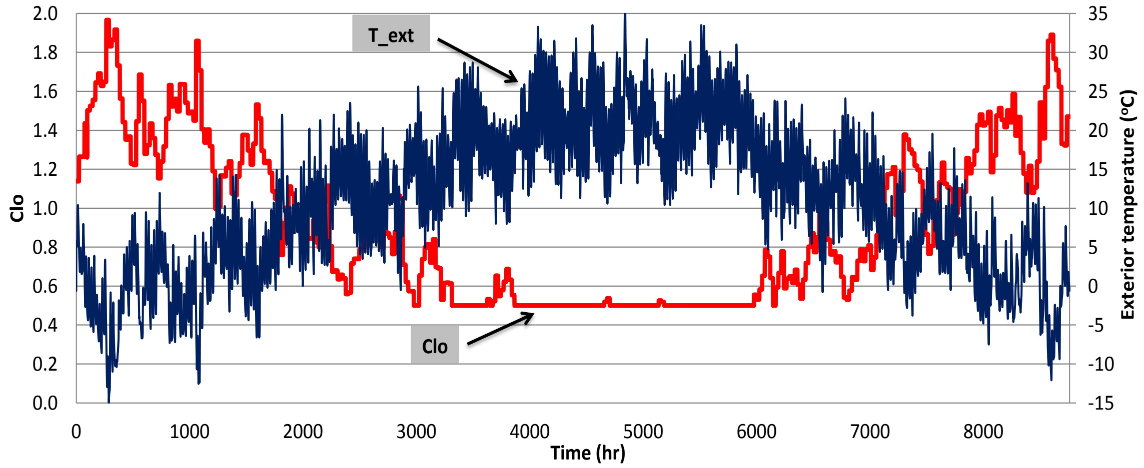

Figure 9. Yearly variation of the clothing factor

Note: clo=1.48-0.04272 × avg(T_{day-1})-0.009827 × max(T_{day}) [27]

The clothing factor has an evolution between a maximum of 2 (winter) and a minimum of 0.5 (summer). Since it is calculated based on exterior temperature values its variation follows an inversely proportional trend (the higher the temperature the lower the clothing factor).

5. Conclusions

For the cold season the assessment of thermal comfort showed that from an average indoor temperature point of view this is not met in the school (especially during the first hours of the morning). From a meteorological perspective the year 2014 proved to be a highly unusual one. Just as exterior winter temperatures were higher than multiannual averages for early February 2014, June was cooler than normal. Thus for the investigated week in the hot season, the exterior average was around 16 ^{o}C which influenced the indoor temperatures recorded in the school classrooms. The low interior averages recorded for the school have a twofold explanation. On the one hand, given that night time temperatures dropped to 13 ^{o}C resulted in a strong cooling of the interior, on the other hand children only study from 8:00 AM until 12:00 PM. This means that the schools don't

have time to overheat which would negatively influence the thermal comfort of the children.
When it comes to the PMV and PPD analysis there are a number of discussions in order. Based on the parameters inputted in the calculation it resulted that the building has a thermal comfort close to optimal during the hot season. Nonetheless, some classrooms performed marginally worse than the rest due to the lower interior temperatures. Moreover, the model used for calculating the indexes doesn't take into account the exact clothing insulation of the occupants but uses an estimated one which represents a limitation of the approach used. That is why the adaptive thermal comfort model (where clothing insulation is not taken into account) could apply better than Fanger's method. For the cold season the PMV and PPD results partially confirm some of the expectations had: the old edifice has the worst score, however the new building performed marginally poorer than the renovated one. This would be an indication that the quality of the construction work was not up to par.

Considering that the STANDARD building had an old, non-insulated wing and a new wing covered in 5 cm of insulation the effects could be best analyzed. The first observation was that thermal comfort in all the studied classrooms of the old wing ranked very poor. This was confirmed both by simulation results as well as the environmental campaign measurements and surveys. In comparison, the new wing with its low (but present) insulation performed better. The difference was however striking when the entire exterior envelope of the building was better insulated, marking an increase in thermal comfort (30% compared to the old wing and 10-15% compared to the new one) and energy efficiency. Thus by adding 5 extra cm to the new wing in conjunction with better glazing (R=2.5 m^2K/W) the thermal load was reduced by a factor of two. This initial analysis would warrant that when renovating existing buildings or constructing new ones, the minimum insulation to be considered should be 10 cm, covering the entire envelope (walls, floors, roof). Currently local Romanian construction guidelines recommend only 5 cm of insulation. The decision maker's argument is that educational establishments, due to their discontinuous heating schedule, do not justify the additional costs of better insulating them. However, based on a number of country specific assumptions, the investment differential between standard practice and enhanced version would be around 12€/m^2 of construction area. This number is similar to the 14 €/m^2 found in an Italian study [28]. For the current investigated building, the sum amounts to approximately 16100€ which includes the price of the additional insulation and better glazing.

The conclusion of this study is clear: investing in a higher level of insulation can to a large extent positively impact thermal comfort and increase energy efficiency. Given that a school is built to last several decades, an initial higher investment differential is warranted and strongly recommended.

Acknowledgements

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