THERMAL ENVIRONMENT EFFECTS ON COGNITIVE PERFORMANCE IN ELEMENTARY SCHOOLS IN WARM-HUMID CLIMATES AND ITS IMPLICATIONS FOR EDUCATIONAL ARCHITECTURE

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SUMMARY

The title of this thesis is **"Thermal Environment Effects on Cognitive Performance in Elementary Schools in Warm- Humid Climates and its Implications for Educational Architecture"**.

Chapter 1 presents an introduction to the impact that school buildings have on learning outcomes. This Chapter outlines the background and marks out this research, presenting the two main approaches. The first one studies the effects that the school building's condition and design have on academic achievement and what extent the different school spaces suit the learning process. This relationship has its theoretical basis in architectural psychology, a branch of environmental psychology that studies the influence of physical space on a human being's behavior and well-being. The second approach, which this research is specifically framed under, is associated with what is known as environmental ergonomics; a branch of ergonomics that studies the interaction between people and the environment. If human characteristics and capabilities are known, then it is possible to provide them with the environmental conditions that are conducive for physical, psychic and social well-being. Among the interior quality environment variables presented, the thermal environment was considered as the most important to achieve on being a primary factor in warm-humid climates. Namely climates which are characterized by a combination of high temperatures and high humidity.

In **Chapter 2**, data from 18 studies were used to build a relationship between learning outcomes and thermal environment in classrooms. Psychological tests measuring cognitive abilities and skills, school tasks including mathematical and language-based tasks, ratings schemes and tests used to assess progress in learning, including end-of-year grades and the exam scores, were considered to represent learning outcomes. The thermal environment was characterized by classroom temperatures. The results predicted that the speed temperate climate pupils perform psychological tests and school tasks was on average 10% higher when the temperature was reduced from 26°C to 22°C. However, no studies developed in the tropical climate were found.

In **Chapter 3**, a two-week long intervention study was performed in two elementary school classrooms in Costa Rica. Two different air temperatures were imposed in adjacent classrooms. A split air conditioner (AC) was installed to reduce temperatures in the classrooms. Pupils in Classroom 1 were exposed to reduced temperatures the first week and normally occurring temperatures the second week. Classroom 2 experienced the same conditions, but in reverse order. A total of 37 children performed tasks that are similar to their school work and completed questionnaires reporting their thermal sensation and perceptions. The results showed that children performed language and logical-thinking tasks significantly quicker at the lower temperature, while the less able pupils performed better on all tasks at the lower temperature. According to the experiment's results and what

recent research in the topic has shown, temperatures above neutral for heat balance should be avoided in tropical school classrooms. Therefore, the maximum temperature limit (To-max) in tropical classrooms should be equal to the neutral temperature.

In **Chapter 4**, one classroom of a school building located in the warm-humid climate of Costa Rica was chosen as a Case Study. The purpose was to evaluate whether traditional lightweight construction classrooms which only had window openings were able to provide pupils with an optimal thermal environment for learning in the tropics. ASHRAE's Exceedance Hours method (ANSI/ASHRAE 2013) was used to run the evaluation, estimating the number of school year hours where the classrooms' operative temperature was over the maximum operative temperature limit (To-max). All calculations were made using the adaptive thermal comfort model of the ASHRAE standard 55-2013 as a rational basis. The classroom's operative temperature (To) was estimated under two approaches: a simplified numeric one and a dynamic computational simulation method. The results show that indoor temperatures were over the upper temperature limit more than 80% of school hours. During these periods, temperatures are on average, 3°C above To-max; however, peak differences over 8-9°C are common during warmer days. As a result, the children spend 80% of their time in a thermal environment that is not suitable for teaching.

In **Chapter 5** identified different passive or low energy consuming cooling strategies and individually or jointly evaluated these to know whether they are capable of providing an optimal thermal teaching environment in the tropics. The same classroom employed in Chapter 4 was used as a Case Study. The archival literature was surveyed to find publications that reported the most effective strategies for non-residential small buildings in tropical climates. Four of these were chosen for further research: (1) The cooling effect of ventilation, (2) roof thermal properties and shading, (3) ground cooling, and (4) microclimate controls. The highest cooling potential, in degrees, was estimated for the chosen strategies and different simulations models were created, applying these strategies individually or combining them for the Case Study building. The results show that in at least 7 of the models, the He percentage is reduced to less than 10% of the annual school hours. In three of them, the criteria to avoid overheating of the CIBSE TM52 for natural ventilated buildings is achieved. Therefore, an optimal thermal learning environment in the warm-humid climates can be achieved by just using passive or low energy consuming cooling strategies, avoiding using air conditioners. However, the solutions required to achieve these thermal conditions are not so simple.

Chapter 6 is the concluding chapter of the thesis. A final discussion is presented where some key questions that have emerged throughout the research are addressed. Recommendations for future research are listed and the contributions of the study are shared.

1. INTRODUCTION: SCHOOL BUILDINGS AND LEARNING OUTCOMES

Education is a base element of sustainable development (ONU 2015), as it is one of the most powerful tools to reduce poverty and inequality. It is also a fundamental piece to achieve sustained social and economic growth (World Bank, 2015). Through the Millennium Development Goals (MDG) set out in 2000, important changes have been produced regarding access to education and the increase in schooling rates; however, education still needs to be more inclusive, more just and be of a better quality (UN 2015).

How well children learn, depends on a great number of factors. Some of them fall outside the school itself, like family problems, inadequate educational methods, a poor socio-cultural environment, the parent's level of education and the student's attitude towards school work. However, others directly concern the school, like the center's psycho-social climate, the teacher's technical ability, the teacher's punctuality, the educational institution's administrative and organizational conditions and the teaching resources these have.

Among these resources, the built environment is one of the most important, and even when most studies indicate that its impact on learning is less than socio-economic factors or the teachers may have (Young, Green, Roehrich-Patrick, Joseph, Gibson 2003), in recent years, school infrastructure has stopped being just a factor associated to school coverage (Duarte, Gargiulo, Moreno 2011). It has become a tool that is capable of driving quality, facilitating access for the underprivileged and fostering the physical and environmental conditions of classrooms which make the learning process easier. Along this same line, one of the objectives of Quality Education proposed by the UN in the Sustainable Development Goals (SDG) is promoting the construction and adaptation of school facilities so that they meet the needs of children and the less abled, considering gender while providing safe, non-violent, inclusive learning environments that are effective for one and all (UN, 2015).

A literary review of the main databases available, shows that the impact of the built space on the academic achievements of students and their behavior has been investigated from different professional fields: education, psychology, sociology, health sciences, engineering and architecture. In all of these, the number of studies that demonstrate positive associations between the physical conditions of schools and the children's learning is constantly rising. Therefore, there is enough evidence to suggest that a poorly built environment affects the children's health, performance and attendance (American Federation of Teachers 2006; Young, Green, Roehrich-Patrick, Joseph, Gibson 2003).

Although response variables and methodologies used in the studies are very diverse, a general classification is presented in Table 1.1 which divides them into two large groups. The first focuses on the impact the state, age and design of the school building can have, while the second concentrates on the quality of the classroom's indoor environment. Both approaches, the main findings and drawbacks will be summarized in the following sections.

TABLE 1.1 General classification of the studies done between school buildings and learning outcomes

	School building condition and design and academic achievement		School indoor environment and learning outcomes	
Grounds	Environmental phychology		Environmental ergonomics	
	Learning theories	Architectural phychology		
Dependent variable	Academic achievement		Academic achievement	School work performance or measure of cognitive abilities and skills
Measure of the dependent variable	Scores in tests to assess progress in learning		Scores in tests to assess progress in learning or end of year grades	Speed and accuracy in school work tasks and neuro-physchologycal tests
The researcher has control of the tests	NO		NO	YES
Control of the socio-economical factors	Student records with free or reduced-price lunch		Student records with free or reduced-price lunch	Experiment design
Independent variable	School building condition	School building condition and design	Indoor environment	
Research method	Questionnaire studies		Field studies	Laboratory experiments or field intervention studies
Exposure length	Long- term: Associated with school periods		Long- term: Associated with school periods	Short- term: Between 1 day and 8 weeks
School setting	School building	School building	School classroom	School classroom or laboratory
Setting intervention	NO	NO	NO	YES
Conclusions	Inferences		Inferences	Causal relationships
Use	Studyng relationships among variables		Studyng relationships among variables	Identifying causal relationships between variables

1.1. SCHOOL BUILDING CONDITION AND DESIGN AND ACADEMIC ACHIEVEMENT

The effects of the state and age of the schools on the academic achievements attained by the students have been broadly addressed in doctoral theses from the Virginia Polytechnic and State University (Cash 1993; Hines 1996; Al-Enezi 2002; Bullock 2007; Earthman 2002; Earthman, Cash, Van Berkum 1995; Earthman, Lemasters 1996; O'Neill 2000), Texas A&M University (Mcgowen 2007; Monk 2006; O'Neill 2000), the University of Texas (Blincoe 2008) and the University of Mississippi (Broome 2003).

The studies compared the state of school facilities with the grades obtained by the students in standardized testing like the Test of Academic Proficiency, Standards of Learning, the Test Basic Skills (TBS) and the Texas Assessment of Knowledge and Skills (TAKS). Each study covered samples of up to 100 school centers. The socio-economic factors of the students were controlled by recording students with free or subsidized lunches (Cash 1993; Bullock 2007; Hines 1996; Mcgowen 2007), or by dividing the study into areas with a more or less homogeneous average incomes.

To evaluate the facilities, tools like the Commonwealth Assessment of Physical Environment (CAPE) or Total Learning Environment Assessment (TLEA) were used. The analysis is qualitative and observation based. In CAPE, the valuation of the buildings is based on 27 criteria divided into 2 categories: structural aspects and cosmetic aspects (Cash 1993). These criteria were chosen based on previous studies that identified the components or characteristics of the building that had a measurable impact on the student's academic achievements. Once the diagnosis was finalized, the buildings are divided into 3 levels depending on their score: substandard, standard and above standard. Meanwhile, the TLEA is an assessment tool which measures the perception of quality and sufficiency of the educational facilities via a survey made to directors and teachers (O'Neill 2000). It comprises 82 multiple-choice questions which can be answered: completely agree, agree, neither agree nor disagree, disagree and completely disagree.

Most of the investigations found that students who study in buildings in a poor condition had grades that were between 5 and 10% lower than those attending ones in a good condition, regardless of their economic situation.

Researchers of the School Design and Planning Laboratory (SDPL) of the University of Georgia (Hughes 2005; Tanner 2000) also studied the relationship between the built environment and academic performance; however, they focused on establishing to what extent the different school spaces and places are friendly for the learning processes.

For this, they designed a tool called Design Assessment Scale for Elementary Schools (DASE) with 39 items. Each item measures the degree in which there is a design pattern in a school. Each design pattern was then evaluated according to its level of presence, safety, functionality and quality. Unlike the tools elaborated by Cash and O'Neill, DASE is a tool that a trained researcher fills out. Hughes (2005), in his research, added other factors like architectonic design, color, design matching the children's size, the location of the school center, the availability of outdoor areas and spaces for technology, art and music, as well as environmental variables like acoustics and thermal comfort.

In order to complement both fields of study, Ayers (1999) and Bishop (2009) used school infrastructure assessment tools with both CAPE and DASE criteria. Ayres made a quantitative analysis where he statistically demonstrated a significant connection between the built environment and academic results. Bishop meanwhile focused on the qualitative aspect, explaining the reasons that cause this relationship. He based his research on the assumption that the design elements present in a group of new schools, have a positive impact on the attitudes, behavior and opinions of students and teachers, basing these on Albert Bandura’s theories of cognitive social and social learning, as well as Abraham Maslow’s hierarchy of needs (Bishop 2009).

As can be seen in the theoretical model proposed by Cash (1993), the state of the building depends on the director’s leadership and financial ability (Figure 1.1). The good condition of the property, does not just generate a positive attitude among the students which makes them better students, but it also generates one among their parents and teachers. This relationship has its theoretical grounds in architectural psychology, a branch of environmental psychology which studies the influence of the physical space on human experiences, behavior and well-being (Steg, Van den Berg, De Groot 2013). It is also related to other learning theories of psychologists like Carl R. Rogers and student-centered learning, B.F. Skinner, the environment as a behavioral modifier or Kurt Lewin, with field theory.

Architects like James S. Ackerman suggested the idea that architecture is the physical form of social institutions and, in this way, it must respond to changes in behavioral conventions. It can also stimulate new forms of behavior. Thus, the educational building does not just fulfill functional aspects, it is also a reflection of how important children and their education is for society. Young et al. (2003) suggest that the physical entities symbolize certain qualities, values, aspirations and experiences for people and a school can symbolize opportunity, hope and stability, as well as failure or oppressive authority. In this

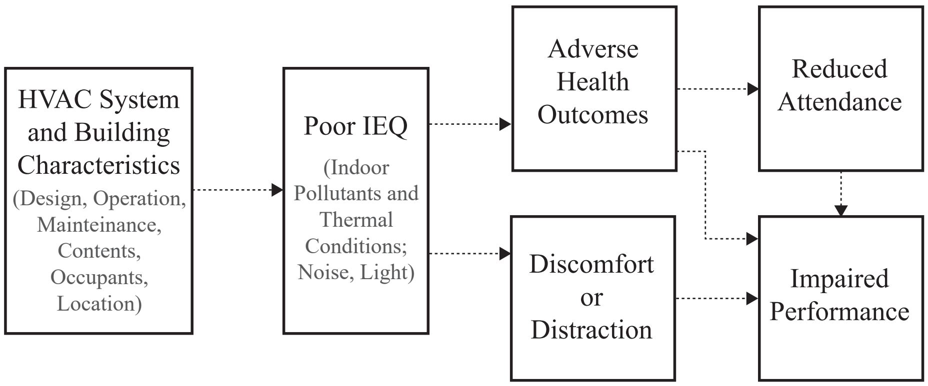


FIGURE 1.1 Theoretical model of Cash: relationship between the physical environment and its impact on academic performance. Retrieved from Bishop 2009.

same sense, Lanham III (1999) claims that architecture and education are linked in both a symbolic and functional relationship.

The students of this first group use the questionnaires method (Steg, Van den Berg, De Groot 2013). This method has the advantage that the school building's assessment is qualitative, observation-based, which allows focusing on the school as a whole. It is a cost-effective method where it is possible to reach large populations. Some studies have samples of 100 or more schools. In addition, they use the grades scored by students in standardized tests, as such they estimate the long-term impacts of the educational infrastructure on the academic results.

However, there are also some disadvantages. Perhaps the most important one is that this allows establishing relationships between two or more variables but not the causal inferences. On some occasions, a third variable (i.e. confound) is what causes the relationship. For example, according to the CAPE tool, the building's age and the leaks in the roof, form part of the variables that explain low performance, however, one could be the consequence of the other. In addition, the direction of the relationship between some variables is not clear. Therefore, the results do not allow explaining which specific characteristics of the building affect them and which most affect them, to stress those. The studies show little information about statistical methods used and whether the results are significant or not. The questionnaires are applied by the school's directors or maintenance chief, as such there could be bias in the answers. The children are not involved in most cases, even though they represent the highest percentage of users.

Finally, because of the aforementioned causes or other associated factors, the impact of the results of these investigations on the development of planning and regulation tools that directly apply to school design has been discrete. This is one of the main reasons to discard its use in this research.

1.2. SCHOOL INDOOR ENVIRONMENT AND LEARNING OUTCOMES

According to Young et al. (2003), the physical environment rarely has a direct and immediate impact on human health and well-being. It is the interaction between the individual and physical characteristics of the environment which must be examined to understand how environments, including the schools, affect behavior.

The second approach could be associated with what is known as environmental ergonomics, a branch of ergonomics which studies the interaction between people and the environment. Through knowledge about human traits, it is possible to provide the necessary environmental conditions behind physical, psychological and social well-being, where an increase in the people's safety, effectiveness and productivity would be expected (Mondelo, Gregori, Barrau 1999).

This approach goes back to the second decade of the 20th Century where manufacturing companies began to promote studies about indoor environment factors that affected the performance of their employees (Young, Green, Roehrich-Patrick, Joseph, Gibson 2003). On one hand, the purpose was to guarantee a comfortable, healthy environment, where the worker reaches their maximum productivity, which on the other hand, sets limits on conditions under which certain activities must be done, to guarantee the workers' health. This vision was later taken from factories to other work sites and classrooms.

Research has been done, under this perspective, in areas like lighting (Heschong 2003a, 2003b), acoustics (Wyon 1970; Haines, Stansfeld, Brentnall, Head, Berry, Jiggins, Hygge 2001; Stansfeld, Berglund, Clark, Lopez-Barrio, Fischer, Öhrström, Haines, Head, Hygge, Van Kamp, Berry 2005; Hygge 2003; Hygge, Evans, Bullinger 2002), indoor air quality (Bakó-biró, Kochhar, Awbi, Williams 2007; Mendell, Eliseeva, Davies, Spears, Lobscheid, Fisk, Apte 2013; Haverinen-Shaughnessy, Moschandreas, Shaughnessy 2011; Shaughnessy, Haverinen-Shaughnessy, Nevalainen, Moschandreas 2006; Petersen, S.; Jensen, K. L.; Pedersen, A. L S; Rasmussen 2015; Wargocki, Wyon 2007a) and thermal conditions (Wargocki, Wyon 2007b; Auliciems 1972; Wyon 1970; Wargocki 2008; Wyon, Andersen, Lundqvist 1979), with the results showing that a building's poor indoor environment quality (IEQ) has negative repercussions on the users' health, comfort and attention, thus affecting their work performance.

In Figure 1.2, Mendell and Heath (2005) propose some hypothetical causal links between the building, performance and attendance. The authors show that certain characteristics of the building along with the heating, ventilation and air conditioning (HVAC) system, may affect the indoor environment quality and this, in turn, the user's health and performance.

Under this approach, subjective, objective and behavioral methods have been used when assessing the users' responses to these environmental variables (Parsons 2000). However, only one study can combine more than one method.

The objective methods include the use of simple grading scales, like ASHRAE's thermal sensation scale, as well as detailed answers and questionnaires. These are relatively easy to carry out and very useful when the factors that contribute to the response variable are not known. However, they have disadvantages in that they are difficult to design because of the

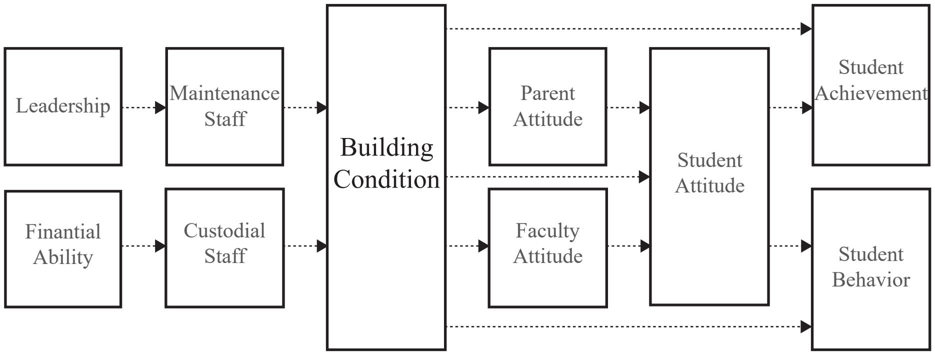


FIGURE 1.2 Hypothetical causal links which connect environmental quality inside schools with performance and attendance. Retrieved from Mendell and Heath 2005

potential bias in the methodology, people are not always capable of detecting when they are under strong physiological stress and they require using a representative population sample of users exposed to the environment of interest (Parsons 2000).

The objective measures methods are those where the occupant's response is directly measured. Human biomarkers that are directly associated with the indoor environmental variables are used. They provide objective evidence of the environmental effects on the occupants' physiology. For example, when assessing the thermal environment effects on human body, the most common measures are variations of skin temperature, internal body temperature, heart rate, and sweat rate/loss (Willem 2006). They are a good method to analyze the effects of IEQ on the users' health as they do not depend on their perception; however, subjective results like thermal comfort cannot be easily predicted and instruments can interfere with what they are trying to measure (Parsons 2000).

Finally, behavioral models are those which focus on analyzing the subject's behavior. They include changes in posture, changing clothing or adjusting the environment. They have the advantage that this is the least invasive method as it is observation-based. However, they require an experienced observer and a prior model that explains the reasons behind the behavior (Parsons 2000). They allow establishing relationships, but it is difficult to reach causal inferences.

To study the relationship between IEQ and productivity, researchers used many different environments like laboratories, normal school classrooms or intervened classrooms. The studies carried out in laboratories have the advantage that it is possible to more accurately control and measure environmental variables and quickly modify them. However, these are artificial environments that are unfamiliar for the subjects, whose dimensions do no permit large samples. Also, in laboratories, it is possible that the students, knowing that they are participating in an experiment, make their best efforts to get the best results (Wargocki, Wyon 2007b). Conversely, field studies can reach large populations and subjects are exposed to natural conditions in a familiar environment. However, it is not possible to manipulate any of the environmental variables. On the other hand, field intervention studies present a good balance between the options mentioned. They are carried out in familiar, natural settings, where it is possible to partially control some environmental conditions and these can be done with larger samples than the laboratories allow.

According to Steg et al. (2013) laboratories provide high internal validity that allows researchers to identify strong causal relationships between the variables. However, the external validity due to artificial conditions is limited; therefore, results cannot be generalized to other populations. The opposite happens when working with field studies, with the intervention field studies having a good balance between external and internal validity and the population size.

To reflect pupil's learning outcomes, rating schemes and tests to assess learning progress, schoolwork tasks, and neuropsychological tests have been used. These represent in themselves, an attempt to measure children's cognitive abilities and skills, while in the latter, the accuracy and speed or reaction time the tasks were performed in, was one of the common measurements of their performance. Speed is related to quantity, the number of tasks completed in a certain period of time. Accuracy meanwhile refers to quality, and is the freedom of error in discrete tasks (Lan, Wargocki, Lian 2011).

Some studies however, reported results where subjects perform the task very quickly with a high number of errors or very slowly with very few errors (the effects on performance measurements occur in two opposite directions) (Lan, Wargocki, Lian 2011). They show that there is a quantity-quality trade-off. To avoid this trade-off, some authors (Lan, Wargocki, Lian 2011; Bakó-Biró, Clements-Croome, Kochhar, Awbi, Williams 2012) integrated speed and accuracy as a unique performance index (PI).

One of the advantages of the studies grouped under this approach, is that they have been able to establish causal inferences between IEQ and productivity. Inferences which have been applied using norms, standards and technical notes, among others, for the design and operation of buildings. However, the main criticism is that most investigations present sample populations with a small number of subjects and solely focus on isolated variables (Clark 2002).

1.2.1 Thermal environment and performance

Among the factors that characterize indoor environment, thermal conditions is one of the most important regarding health and performance affectation (Lan, Wargocki, Wyon, Lian 2011). Creating a comfortable thermal environment is often considered the most important variable to achieve a quality indoor environment (Frontczak, Wargocki 2011). In addition, it is an essential factor in warm-humid climates, that are characterized by a combination of high temperature and high humidity (Givoni 1994), where thermoregulation processes of the human body can be reduced by an atmosphere saturated with water vapor.

There are occasions where the site's microclimatic conditions, the metabolic activity or the limited possibility of adaptation, among others, do not allow a thermal balance between the body and the environment. Heat overloads force people to make physiological adjustments to keep their internal temperature within normal limits. These adaptations, depending on their intensity, create discomfort and fatigue or even reduce physical and mental capacity, which could affect performance and, as a result, productivity (Mondelo 1999).

Thus, lengthy exposure to hot or cold spaces can cause behavioral changes for humans, like the loss of motivation and reduced concentration and attention, with the resulting increase in accidents, which ultimately have an effect by reducing work and performance quality (Mondelo 1999).

In warm environments, heat overloads normally cause veins to dilate, increasing blood flow through the skin. The body, due to a larger thermal load, begins to sweat and unconsciously, facing the absence of a conscious effect, lowers internal heat production and reduces or even manages to avoid sweating. This behavioral adjustment provokes reduced motivation which in the end means work is done more slowly (Kosonen, Tan 2004a).

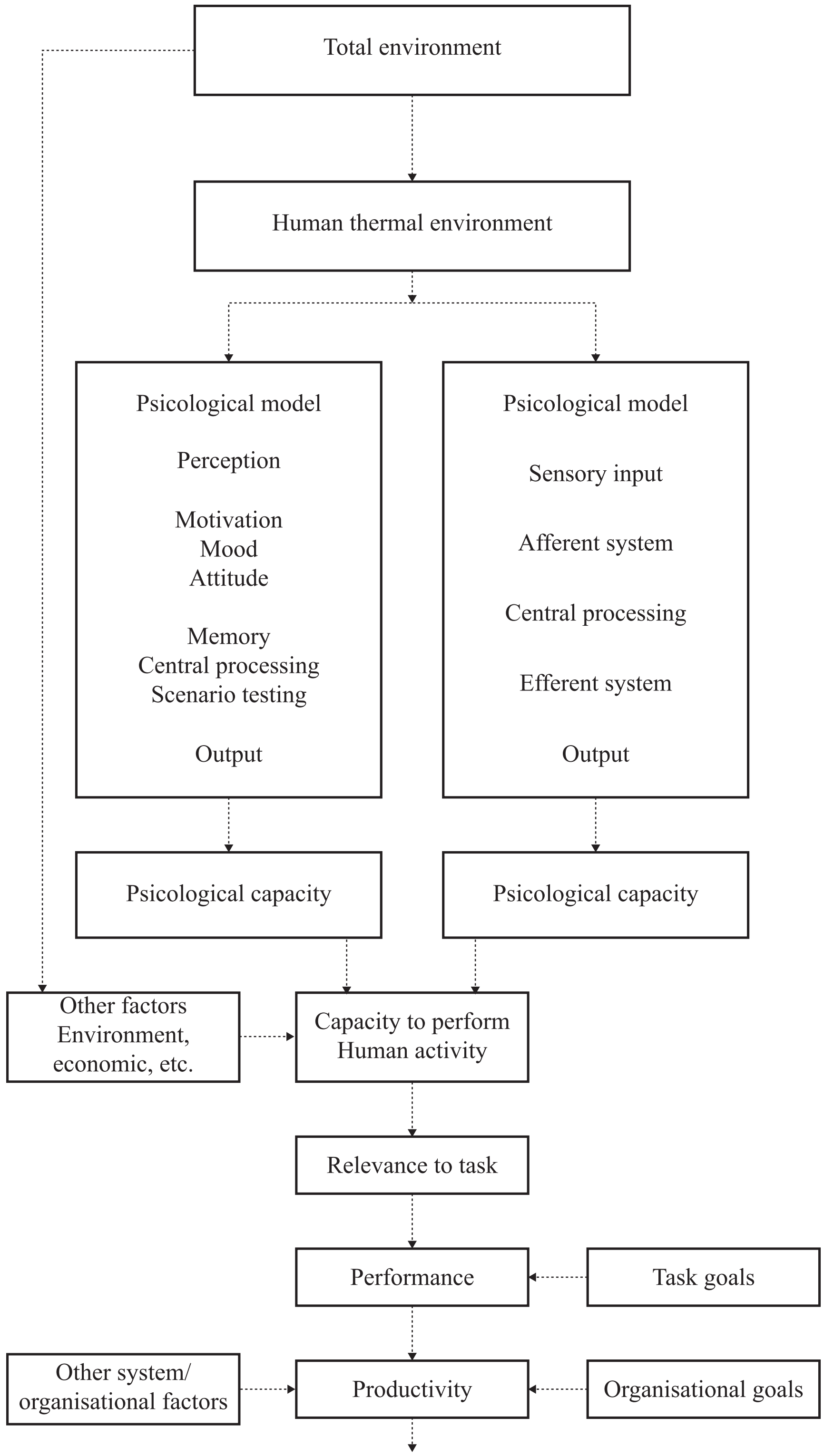


FIGURE 1.3 Model for considering the effects of the thermal environment on human activity performance and productivity. Retrieved from Parsons 2002.

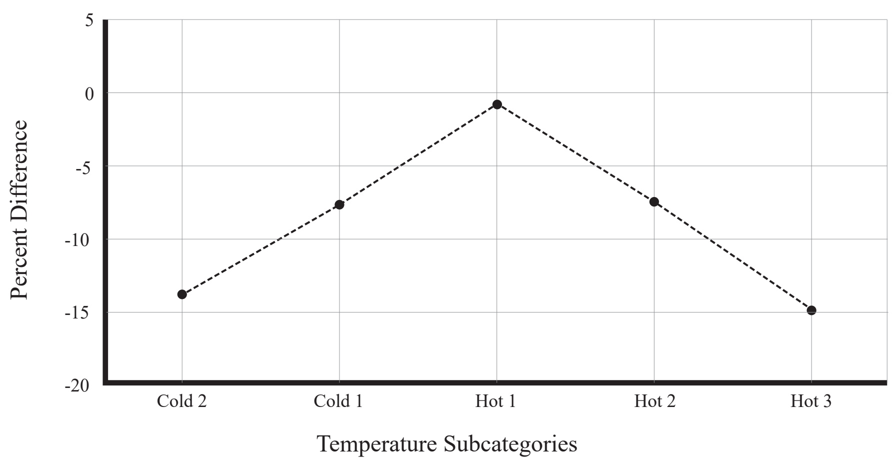
The wide range of tasks that are done in jobs as well as the complex series of abilities involved in these, make it difficult to accurately measure the effect of the indoor thermal environment on workers' performance (Lan, Lian 2009). However, Wargocki and Wyon (2017) show that there are at least 6 mechanisms where thermal conditions (hot and cold environments) of a space can affect work performance: (1) Attention and distribution, (2) motivation to exert effort, (3) arousal, (4) manual dexterity, (5) neurobehavioral symptoms and (6) acute health symptoms.

However, while the temperature effects on comfort are widely acknowledged, modeled and documented, the effects on performance and cognitive abilities have received less attention and are less well known (Seppänen, Fisk, Faulkner 2006; Hancock, Vasmatzidis 2003).

Figure 1.3 presents the conceptual model proposed by Parsons (2002) to consider the effect of the thermal environment on human performance and productivity.

In 2002 Pilcher et al. (2002) made a meta-analysis of the data from 22 studies, comparing the relationship between temperature and the people's' performance while performing different tasks (Figure 1.4). Their conclusion was that maximum performance decreases occur when the temperature exceeds 32.2°C WBGT or is below 10.8°C, with the reduction in both cases being around 14%. The study also shows that temperatures between 21°C and 27°C have a low effect on performance.

In 2006 Seppänen et al. (2006a) carried out a meta-analysis based on 26 studies that had been run independently, both with students and workers in offices and laboratories. The results show that performance increases with the temperature up to 21-22°C, but falls as of 23-24°C. Maximum productivity is achieved at a temperature of 22°C and at 30°C, the reduction in performance is 8.9% (Figure 1.5).



Temperature subcategories: Cold 2: 10°C | Cold 1: 10 a 10.3°C | Hot 1: 21.1 a 26.6°C | Hot 2: 26.7 a 32.2°C | Hot 3: > 32.2°C

FIGURE 1.4 Diferencia porcentual del rendimiento en relación a 5 subcategorías de temperatura. Retrieved from Pilcher, Nadler, Busch, 2002

However, there is no consensus between researchers about whether optimal thermal comfort conditions, determined by comfort models, coincide with those associated with maximum productivity (de Dear, Akimoto, Arens, Brager, Cândido, Cheong, Li, Nishihara, Sekhar, Tanabe, Toftum, Zhang, Zhu 2013; Cui, Cao, Park, Ouyang, Zhu 2013). Griffiths and McIntyre (1975), de Dear et al. (2013) and Hancock and Vasmatzidis (2003) suggest that it is within comfort ranges where an optimal work performance is reached. However, authors like Wyon Clements-Croome (2006), Lan, Wargocki and Lian (2014) and Parsons (2002) consider that thermal conditions which provide optimal comfort, are not the same as those where maximum efficiency is reached.

For de Dear et al. (2013) the results of Pilcher et al. (2002) indicate that maximum performance is reached in a 6°K range, between 21°C and 27°C. This coincides with the normal comfort zone for sedentary occupation (de Dear, Akimoto, Arens, Brager, Cândido, Cheong, Li, Nishihara, Sekhar, Tanabe, Toftum, Zhang, Zhu 2013). In the same sense, Hancock and Vasmatzidis (2003) suggest that thanks to the human being's ability to physiologically and psychologically adapt, there is a zone where people can tolerate thermal stress and not have negative effects on cognitive performance.

Seppänen et al. (2006) indicated that the information available from their revision of the literature (Seppänen, Fisk, Lei 2006b) does not provide consistent evidence that temperature variations within the comfort zone significantly affect workers' performance. According to the authors, performance decreases are more clearly established for temperatures outside the comfort zone and more clearly documented for high temperatures.

Recently a study made by Pepler and Warner in 1968 put these differences up for discussion once again. During the experiment, made in a climatic chamber, 72 normally dressed young people (36 men and 36 women), performed different mental tasks at temperatures of 20°C and 27°C. The researchers, as a result, obtained that the temperature where fewer errors

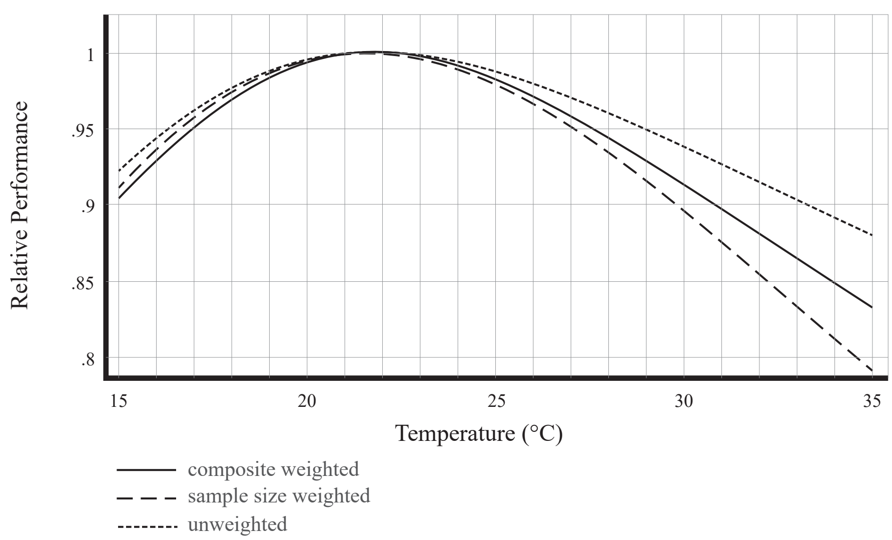


FIGURE 1.5 Relación entre rendimiento y temperatura. Retrieved from Seppänen, Fisk, Lei 2006

were made was at 27°C, which also coincided with the temperature where the students said they felt comfortable. However, it was at 20°C where a higher work speed was achieved, as when the temperature was increased, the speed at which students solved the mathematical operations fell.

Mendell and Heath (2005) considered the findings to be inconsistent, as the temperature increase affected the time to complete tasks and the number of errors by unit of time, but not the work speed or the errors made by item. The effects on performance measurements occur in two opposite directions. De Dear et al. (2013) share the idea that there are contradictory associations in the results of Pepler and Warner's investigation. However, for Wyon and Wargocki (2014a), the results are clear on indicating that the best performance is achieved at 20°C when the maximum work speed is reached, which differs with the temperature where the students said they felt comfortable. According to the same authors, the explanation that they have made fewer mistakes at the comfort temperature is simply because they were more relaxed and did fewer tasks per minute.

The 20°C temperature where the highest working speed was achieved in Pepler and Warner's experiment approaches the 22°C which Seppänen et al. (2006a) set as the maximum productivity temperature in their meta-analysis.

In this same way, Wyon and Wargocki (2014b) note that even though a building's indoor temperature can be changed to conserve energy, following the adaptive thermal comfort model, the performance will not necessarily be kept at these temperature levels. The user may be capable of behaviorally adapting and based on their expectations, psychologically handle the high temperatures. Furthermore, there are physiological reactions that could not be controlled as it will not be possible to reach thermal neutrality, thus provoking an imbalance.

Studies that have recently examined the effects of thermal sensation on work performance (Lan, Wargocki, Lian 2011; Jiang, Wang, Liu, Xu, Liu 2018; Kosonen, Tan 2004b; Jensen, Toftum, Friis-Hansen 2009; Willem 2006) have corroborated this assumption. Results show that maximum performance was achieved when occupants felt the thermal environment between neutral (0) and slightly cool (-1) according to the ASHRAE's seven-point scale, and that increasing the temperature above the neutral temperature could lead not only to a decrease of performance but result in negative health symptoms (Lan, Wargocki, Wyon, Lian 2011).

This is particularly important in warm-humid climates, because it establishes the upper threshold for an optimal thermal learning environment at a neutral temperature. While ASHRAE's adaptive comfort model, which is employed nowadays in the evaluation and the design of naturally ventilated, occupant-controlled school classrooms, predicts that 80% of occupants will respond that they feel comfortable at temperatures 3.5°C above the neutral (upper 80% acceptability limit). However, most of the research that has examined the effects of thermal sensation on work performance has been done with adults and there is only one in tropical climates.

1.2.2 Thermal environment effects on children's cognitive performance

In school centers, the number of studies that have been made on this matter is significantly lower than those made in offices. Mendell and Heath (2005) show in a revision of the literature that from the 12 studies, only 2 were made with children under 17. The rest were made with adults in offices and laboratories.

One of the reasons that could explain this situation is that in a standard commercial building, the economic weight that the workers' salaries have is much higher than the operations and maintenance costs, something which does not occur in schools (de Dear, Akimoto, Arens, Brager, Cândido, Cheong, Li, Nishihara, Sekhar, Tanabe, Toftum, Zhang, Zhu 2013; Kosonen, Tan 2004a). Holz et al. (1997), found that in a typical American office building, the cost of salaries is 100 times more than that of energy. Therefore, while in offices the thermal environment and performance relationship is related to financial aspects with possible direct savings for the companies, in schools the link is rather more economic, as such it tends to be indirect, making it more complex to quantify and perceive its benefits in the short-term.

However, in classrooms, the affectation of thermal environment becomes critical. The kids spend a third of their time in the school and low school performance provokes both short and long-term consequences, which affect the students directly and society as a whole (Wargocki, Wyon 2007b). Thus, a better understanding of cognitive performance under thermal stress can help not just to define exposure limits in the classroom, but also to improve the quality of life (Hancock, Vasmatzidis 2003).

In **Chapter 2**, a revision of the literature is presented in depth, identifying 18 studies made with children over the last 50 years. All of them amply demonstrate that thermal discomfort conditions can have both long and short-term consequences for the learning process that affect not only children, but teachers, parents and the future job market.

However, all of them were performed in countries with mild climates like Denmark, Sweden, the USA, England and China and as such, their results could be extrapolated to similar climatic and economic contexts, but not the prevailing conditions in a warm-humid climate or those of developing countries (Wargocki, Wyon 2007b).

There is, therefore, a lack of evidence of the effects of warm-humid environments on cognitive performance and an absence of knowledge about the implications that these effects could have on the way school buildings are designed and constructed in these climates.

1.3. HYPOTHESIS AND RESEARCH OBJECTIVES

1.3.1 Hypothesis

Children's schoolwork performance in warm-humid climates will improve if normally occurring classroom temperatures are reduced.

IF YES

Thermally optimal classrooms environments in warm-humid climates can be achieved solely using passive or low energy consumption strategies.

1.3.2 Research objectives

The main objective of this study is to analyze the effect of the thermal environment of classrooms on children's school performance, in order to develop design guidelines that promote optimal thermal environments for learning that are also energy efficient.

The specific objectives are as follows:

1. To develop a relationship between the classroom's thermal environment and learning outcomes, based on the existing body of knowledge.
2. To analyze the effects of classroom temperatures on tropically acclimatized children's thermal perception and school performance, defining the temperature limits that will provide an optimal thermal environment for learning.
3. To evaluate whether passive classrooms in the tropics are able to provide children with an optimal thermal environment for learning.
4. To identify and evaluate passive or low energy consumption cooling strategies that are individually or jointly capable of providing an optimal thermal teaching environment in the tropics.

1.3.3 Methodology

The methodology proposed for this study follows the research objectives. Therefore, a specific methodology, which can be found in the corresponding Chapters (2 to 5), was developed for each one of the specific objectives. In this section, a summary is presented. Objective 1:

To achieve the first objective, the archival literature was reviewed to find articles reporting studies on learning performance outcomes and classroom conditions. Only studies performed in elementary schools were included. Psychological tests measuring cognitive abilities and skills, school tasks including mathematical and language-based tasks, rating schemes and tests used to assess progress in learning, including end-of-year grades and exam scores, were considered to represent learning outcomes.

For psychological tests and school tasks, the fractional changes in their performance were regressed against the average temperatures the changes were recorded; all reported data were used regardless of whether the change was statistically significant. For other learning outcomes, the relationships created by the original studies were used.

The analytical approach used to develop relationships describing the effects of temperature on performance during psychological tests and schoolwork was the same as used by

Seppänen et al. (2006c, 2006a). For each individual task and test, the fractional change in performance per degree was calculated per 1°C change in the temperature range examined.

The calculated changes in performance were regressed against the average temperature. The estimation was made based on the range of temperatures they were calculated for. Different models of fit were used to produce functions, associating the percentage change in performance per 1°C change in temperature versus temperature; eventually linear fits were used. The relationships were produced, using these fits, between temperature and the performance metric assuming that the highest performance will occur at 20°C; therefore, at these levels the performance was set at 100%.

1.3.3.1 Objective 2:

A two-week 2x2 crossover intervention design was carried out during the dry season (February-March). Two different air temperatures were imposed in adjacent classrooms. A split air conditioner (AC) was installed to reduce temperatures in the classrooms. Pupils in Classroom 1 were exposed to reduced temperatures the first week and normally occurring temperatures the second week. Classroom 2 experienced the same conditions but in the reverse order. 37 eleven-year-old (5th grade) children, dressed similarly (0.5 clo), participated in the experiment.

Pupils performed cognitive tasks 10 times over 2 weeks (one task per school day). Four type of tasks were used: multiplication, reading and comprehension, grammatical reasoning and addition and subtraction; reading and comprehension was done twice a week. The tasks lasted 15 minutes or less. Upon completing the tasks, the students filled out a survey containing questions on thermal acceptability, thermal sensation, and thermal preference. The tasks and questionnaires were administered by normal teachers. Indoor environmental parameters were measured at 10-minute intervals outside classrooms and in three different locations inside each classroom. A Wilcoxon Matched-pairs Signed-ranks test was used to compare the children's performance.

1.3.3.2 Objective 3:

One classroom of a school building located in a warm-humid climate was selected as a case study. To evaluate whether the classroom was able to provide children with an optimal thermal environment for learning, the number of school year hours where the classrooms' operative temperature was over the maximum operative temperature limit (To-max) was estimated using the ASHRAE's Exceedance Hours method (ANSI/ASHRAE 2013).

All calculations were done using the adaptive thermal comfort model of the ASHRAE standard 55-2013 as a rational basis. The operative temperature (To) of the classroom was estimated under two approaches: a simplified numeric and a dynamic computational simulation method. In the former, the estimation of the To was made upon the dry bulb temperature (TBS) of the meteorological year type (AMT), assuming that the operative and outdoor air temperatures are similar ($T_o = T_{out}$). This simplification is based on the argument that in tropical buildings, due to their lightweight construction, the envelope has a low thermal capacity and does not dampen and/or delay the amplitude of the thermal wave. In the second approach, the behavior of the classroom was simulated during a whole year employing the Design Builder software, version v5.3.0.14.

Prior to this analysis, two classrooms of the case study school building were monitored for three months to calibrate the model used in the simulation method and to adjust the outdoor temperature to the real indoor conditions in the simplified approach.

1.3.3.3 Objective 4:

The archival literature was reviewed to find articles and books reporting what are the most effective design strategies and architectural solutions for non-residential small buildings in tropical climates. The identified strategies were listed and classified according to their passive cooling potential.

A case study school building was selected and qualitatively evaluated, while missing or under developed passive strategies with a high cooling potential were chosen for further analysis.

The highest cooling potential, in degrees, was estimated or identified for the selected strategies. Finally, the combination of strategies with the highest cooling potential in degrees was applied to the case study school building and the number of school year hours where the classrooms' operative temperature was over the maximum acceptable operative temperature limit ($T_{o\text{-}max}$) was recalculated using ASHRAE's Exceedance Hours method.

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2. A RELATIONSHIP BETWEEN CLASSROOM THERMAL ENVIRONMENT AND LEARNING OUTCOMES

2.1. INTRODUCTION

Research has documented that classroom environmental quality in elementary schools, where children spend significant part of their waking hours, is often inadequate (Wargocki, Wyon 2007a), and that this has significant consequences for learning process (Wargocki, Wyon 2013, 2017). There has been shown that pupils are less able to perform their school work when classroom's temperature is increased and/or they are thermally discomfortable.

One possible reason of the effects observed is that pupils cannot concentrate and/or are distracted from the work that they are supposed to do. As a result, the effective learning process is disturbed, which has consequences on (1) learning performance outcomes, (2) teachers work that is done in a suboptimal environment, and on (3) stress of parents who in some cases have to stay at home when their children get sick; all of the above having significant socio-economic implications (Wargocki, Wyon 2013).

Nowadays, it is difficult to estimate the actual size of the effect on learning due to suboptimal conditions in the classrooms. The reason is that the experiments that examined effects of classroom thermal environment on learning are difficult to normalize because of the use of various methods to measure the performance of pupils. Therefore, the effects on performance are not directly comparable across the different studies. Such information, if summarized, would be particularly useful in cost-benefit analyses concerning the selection and application of methods and solutions for mitigation of negative effects and improvement of classroom conditions. Or for the owners and administrators of school buildings, as well as decision makers setting codes, standards and regulations. Additionally, this information would be also useful for educators and professionals dealing with teaching when different methods and approaches for optimizing and improving teaching process are discussed and considered, in particular ergonomic solutions where the thermal environment in classroom can be considered as one important ergonomic factor.

For office work there are relationships between temperature and performance that show that the potential size of the effect of changes in temperature on cognitive performance exist but they reflect mainly office-type work and not learning performance (Roelofsen 2002; Lan, Wargocki, Wyon, Lian 2011; Berglund, Gonzales, Gagge 1990; Seppänen, Fisk, Lei 2006a). These quantitative relationships integrate data from studies investigating the thermal environment on primarily office-type work for adults and cannot be extrapolated to predict the effects of temperature on learning because of contextual differences and diversity in populations and performance outcomes. Some of them are described below.

Seppänen et al. (2006a) used the data from studies that measured temperature and associated them with task performance for office work and there were also few data from measurements examining the effects of temperature on schoolwork. They used the results from 24 studies of which eight were performed in offices (Federspiel, Fisk, Price, Liu, Faulkner, Dibartolomeo, Sullivan, Lahiff 2004; Korhonen, Salmi, Tuomainen, Palonen, Nykyri, Niemelä, Reijula 2003; Niemelä, Hannula, Rautio, Reijula, Railio 2002; Niemelä, Railio, Hannula, Rautio, Reijula 2001; Tham, Willem 2004; Tham 2004; Chao, Schwartz, Milton, Muillenberg, Burge 2003; Heschong Mahone Group 2003); and used work performance or complex tasks as the performance outcome. One in the factory (Link, Pepler 1970) and one in the office (Chao, Schwartz, Milton, Muillenberg, Burge 2003) which used complex and simple tasks as performance outcomes. Eleven in laboratories (Heschong Mahone Group 2003; Meese, Kok, Lewis, Wyon 1984; Wyon, Wyon, Norin 1996; Mortagy, Ramsey 1973; Löfberg, Löfstedt, Nilsson, Wyon 1975; Langkilde 1978; Fang, Wyon, Clausen, Fanger 2004; Hedge 2004; Berglund, Gonzales, Gagge 1990; Langkilde, Alexandersen, Wyon, Fanger 1973) that used simple tasks related to office work and adult subjects; and four studies that used learning outcomes to measure performance or were performed in classrooms in elementary schools or colleges (Wyon, Holmberg 1969; Johansson 1975; Pepler, Warner 1968; Allen, Fischer 1978). Using data reported in original papers, they calculated a fractional change in performance per degree (λ) to estimate the magnitude of the effect in relation to temperature change (Equation 2.1). They assumed that due to the narrow range of temperatures studied in original papers the relationships were linear. Then, they regressed the fractional changes against the average temperatures measured in the studies included in their analysis. They used the regression done to derive the relationship between performance and temperature. The relationship shows that performance would decrease below 21-22°C and above 23- 24°C with which optimal performance would be around 22°C (Seppänen, Fisk, Lei 2006a).

The effect on performance was about 1% decrease for 1°C change in the temperature (over the range of temperatures which were on average between 15 and 35°C). Weighting the results by the number of observations and using the arbitrary weighting factor describing the relevance of performance outcome for real work had a negligible impact on the observed effects and the shape of the relationship except when temperatures were higher than 28- 30°C.

Lan et al. (2011) made a different approach and developed a relationship between thermal sensation and performance on psychological tests and tasks simulating office work. They used the data from three experiments performed in the laboratory with recruited adult subjects for which the data on thermal sensation was available (Lan, Wargocki, Lian 2011; Lan, Lian 2009; Lan, Lian, Pan, Ye 2009). The relationship showed comparable effects on performance as the relationship developed by the analysis of Seppänen et al. (2006a) but much lower than other relationships between thermal environment and performance developed by Berglund et al. (1990), Roelofsen (2002) and Jensen et al. (2009). Lan et al. (2011) showed also that optimum performance is obtained when people feel slightly cool rather than when thermally neutral. Their relationship can be extrapolated to different combinations of thermal parameters and climates while the relationship of Seppänen et al. (Seppänen, Fisk, Lei 2006a) is valid only for temperatures for which data was obtained and for the temperate and cold climates where the studies were performed.

Concerning to the schools and the effects on performance of school work there were few attempts to establish relationships between learning performance and temperature

(Auliciems 1972; Wargocki, Wyon 2013; Haverinen-Shaughnessy, Shaughnessy 2015; Jiang, Wang, Liu, Xu, Liu 2018) but unlike the analyses of Seppänen et al. (2006a) and Lan et al. (2011), they used only the results that had been obtained in their own measuring campaigns. These relationships indicated that improvement in learning outcomes was about 5-15%. There have been no attempt to establish the relationship thermal conditions in classroom and learning performance by integrating the data from many studies. In other words no dedicated quantitative relationships between temperature and learning performance outcomes have yet been developed that systematically analyze and integrate the results obtained in many studies.

The present work was undertaken to fill this gap. The specific objective was to develop a quantitative relationship that associates temperature in classrooms with learning performance outcomes in elementary schools using all available information in the published archival literature. Temperature rather than the thermal response (discomfort) was used because this parameter was measured and then applied to describe thermal environment, and not all the studies reported the pupils' thermal sensation.

2.2. METHODS

The archival literature was searched to find the articles reporting studies on learning performance outcomes and classroom thermal conditions (temperatures). Articles published from the late 1960s until the end of 2018 were included, i.e. covering and summarizing half a century of research on this topic. To be selected, the articles had to report both measurements of thermal environment in classrooms and measurements of cognitive performance of pupils. Only studies performed with elementary school pupils (primary, middle and/or secondary school pupils) were accepted i.e. with children no older than 18 years. Therefore, data from colleges and university students like Pepler and Warner (1968), Murakami et al. (2006), Ito et al. (2006) and Sarbu and Pacurar (2015), were excluded.

Diverse measures of cognitive performance were accepted including psychological tests measuring cognitive skills and abilities to perform school work, the tasks typical of schoolwork, results of aptitude and national tests examining progress in learning, and the results of midterm and final exams, as well as end-of-the year grades. Table 2.1 in the supplementary material provides detailed description of all learning performance outcomes used in the identified studies. Reports providing information on subjectively rated performance were not included, and the authors are actually not aware of the existence of these type of data. Proxies for reduced performance such as prevalence and intensity of acute health symptoms, especially fatigue, difficulty to concentrate, sleepiness or headaches were not considered either. Neither were perceived disobedience, manifested behavioral changes or reported discomfort with classroom environment accepted as indicators of potentially reduced performance.

Papers reporting cross-sectional and intervention studies were included. The former do not usually perform the measurements of classroom conditions concurrently with the application of performance tests. They typically associate short, medium and long-term measurements with historical data on performance or collect data on performance after the

TABLE 2.1 Summary of the data from studies examining the effect of classroom temperature on performance of psychological tests and school tasks by school child

Study	Location	Type	Population (schools)	Population (pupils)	Age of pupils	Temperature range examine reported temperature levels (°
Holmberg and Wyon 1967	Sweden	Field intervention: classroom was heated	3 classrooms in an elementary school	50	9	20, 27, 30
Holmberg and Wyon 1967	Sweden	Field intervention: classroom was heated	4 classrooms in an elementary school	80	11	20, 30
Wyon 1969	England	Controlled laboratory study in a climate chamber	N/A	48	11	20, 23.5, 27
Wyon and Holmberg 1970	Sweden	Field intervention: classroom was heated	3 classrooms in an elementary school	50	9	20, 23.5, 27
Ryd and Wyon 1970	Sweden	Controlled study in a language laboratory	2 classrooms in an elementary school	34	13	20, 27
Ryd and Wyon 1970	Sweden	Field study	4 classrooms in an alementary school	89	13	23, 25, 27
Auliciems 1972	England	Longitudinal 2-year field study	23 classrooms in 19 elementary schools	600	11-16	12 - 25
Schoer & Shaffran 1973	USA (Iowa)	Field intervention	2 classrooms in an elementary school	44	9	22.4, 24.9
Schoer & Shaffran 1973	USA (Iowa)	Field intervention	2 classrooms in an elementary school	22	10	22.6, 26.1
Schoer & Shaffran 1973	USA (Iowa)	Field intervention	2 classrooms in an elementary school	40	11-12	22.3, 25.4

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d C)	Measurement of performance	Change in speed or reaction time per 1°C decrease in temperature	Signif. (P)	Cohen's d	Change in accuracy per 1°C decrease in temperature	Signif. (P)	Cohen's d
	Reading speed	3.96%	0.05				
	Comprehension	0.98%	0.05				
	Reading speed	1.94%	0.05				
	Comprehension	6.15%	0.05				
	Reading speed	[1]					
	Comprehension	[1]					
	Reading speed	[2]					
	Comprehension	[2]					
	Learning test	[3]					
	Multiplication	[4]					
	Comprehension	[8]					
	Vocabulary	[8]					
	Reading Speed	[8]					
	Spelling	[8]					
	Denominators	[8]					
	Repeated Numbers	[8]					
	Continuous addition	[5]					
	Cancellation	[6]					
	Triplet numbers	[7]					
	Simplex GNV intelligence test	[7]					
	Mazes	2.38%	0.05				
	Design completion	0.41%	0.05				
	Checking names	7.64%	0.05				
	Checking numbers	7.69%	0.05				
	Canceling letters	0.79%	0.05				
	Canceling numbers	1.46%	NS				
	Analogies	4.23%	NS				
	Addition	3.78%	0.05				
	Solving problems	5.83%	0.05				
	Films	2.56%	NS				
	Handwriting	1.34%	NS				
	Machine accuracy	0.17%	0.05				
	Mathematic worksheets	0.50%	NS				
	Programmed learning	1.33%	NS				
	Spelling	-0.20%	NS				
	Vocabulary	4.93%	NS				
	Program Time	1.99%	NS				
	Program Test Time	5.63%	0.05				
	Program Test Errors	8.54%	0.05				
	Arithmetic	1.34%	NS				

Johansson 1975	Sweden	Controlled laboratory study in a climate chamber	N/A	36	10	23, 30, 36
Wyon. Andersen and Lundqvist 1979	Denmark	Controlled laboratory study in a climate chamber	N/A	72	17	20 - 29
Wargocki and Wyon 2007a	Denmark	Field intervention	2 classrooms in an elementary school	44	10-12	20, 23.6
Wargocki and Wyon 2007a	Denmark	Field intervention	2 classrooms in an elementary school	44	10-12	21.6, 24.9
Bakó-Biró et al. 2012	England	Field intervention	2 classrooms in an elementary school	36	9-10	23.1, 25.3

(1) Performance was maintained but a measure of sinus arrythmia indicated that significantly more effort was exerted at higher temperatures. (2) Highly significant and temperatures changes from 20°C to 27°C. (4) Results show that raised temperatures had unfavorable effects on performance. Effect is greater on the least able. (5) the r between reduced performance and temperature: 6.17T - 0.0491T2 - 99.33. (7) no relationship was observed. (8) no significant effects were observed and data not report

TABLE 2.2 Summary of the data from studies examining the effect of classroom temperature on standard tests and rating schemes used to examine progress in learni

Study	Location	Type	Population (schools)	Population (pupils)	Age of pupils	Temperature range ex reported temperature le
Haverinen-Shaughnessy and Shaughnessy 2015	U.S.A (Southwest)	Cross-sectional study	140 classrooms in 70 elementary schools	3019	10	20-25
Park 2016	U.S.A. (New York)	Cross-sectional study	947 high schools	1 million	17-18	15.5-35
Goodman, J., Hurwitz M., Park, J. and Smith, J. 2018	U.S.A.	Cross-sectional study	N.A.	10 million	14-17	N.A.

Learning 1	0.84%	NS				
Learning 2	0.53%	0.05				
Retention 1:1	-0.14%	0.01				
Retention 1:2	0.80%	0.00				
Retention 2	0.25%	0.05				
Addition	0.81%	0.10		-1.54%	0.01	
Multiplication	1.01%	0.05		0.94%	0.05	
Partington 1	0.20%	0.05				
Partington 2	-0.49%	0.05				
Auditory startle response	-0.22%	0.05				
APT: Raw Score	0.89%	0.01				
APT: Bonus Score	1.19%	0.01				
Sentence comprehension	-1.06%	0.05				
Multiplication	1.78%	0.05				
Word memory	-0.41%	0.05				
Clue utilization	3.42%	0.05				
Spelling	[8]					
Vocabulary	[8]					
Reading	[8]					
Creativity	[8]					
Manual dexterity and perseverance	[8]					
Subtraction	8.90%	0.01	0.50	-0.27%	0.14	-0.04
Multiplication	-0.51%	0.41	-0.01	-0.07%	0.56	-0.01
Number comparison	1.56%	0.10	0.17	-0.14%	0.24	-0.10
Addition	1.77%	0.04	0.33	-0.55%	0.90	-0.16
Logical reasoning	0.43%	0.62	0.04	0.51%	0.27	0.09
Acoustic proofreading	N/A	N/A	N/A	1.24%	0.05	0.21
Reading and comprehension	6.85%	0.00	0.54	0.82%	0.41	0.16
Proofreading	N/A	N/A	N/A	0.19%	NA	0.03
Subtraction	5.26%	0.06	0.31	1.20%	0.08	0.39
Addtion	2.15%	0.00	0.17	0.48%	0.86	0.15
Logical reasoning	1.38%	0.60	0.15	-0.11%	0.56	-0.02
Acoustic proofreading	N/A	N/A	N/A	0.22%	0.76	0.04
Reading	2.57%	0.59	0.20	0.65%	0.71	0.10
Simple reaction time	3.64%	0.03				
Choice reaction time	3.64%	0.04				
Colour-word vigilance	2.73%	0.001				

linear changes were observed in posture. clothing and appearance with increasing temperature. (3) Children's oral performance significantly deteriorates when
relationship was developed between reduced performance and temperature: 7.23T - 0.0594T2 - 122.3. (6) the relationship included only boys, and was developed
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amined/ evels (°C)	Measurement of performance	Effect
	Standard test in mathematics, reading and sciences	Math scores increased significantly between 12-13 points for each 1°C decrease in temperature. No significant effect on scores in reading and sciences
	New York State Regents exams from 1999- 2011	Performance decreased significantly when taking an exam on a day with 32°C compared with performance on a day with 22°C; the effect was d=0.19 standard deviation. Cumulative heat exposure can reduce the rate of learning
	PSAT exam from 2001- 2014	Each 1°F increase in school year temperature reduces the amount learned that year by one percent. Air conditioning can mitigate this effect. Extreme heat had larger effects for low income and minority students

measurements had been completed. They assume that the measured conditions represent typical conditions experienced by pupils when in schools and that they are connected to learning outcomes. In case of intervention studies, performance was measured generally in parallel with the measurements of classroom conditions. In this studies, changes in performance were obtained as a result of interventions to thermal conditions in classrooms usually by reducing temperature.

The analytical approach used to develop the relationship describing the effects of temperature on performance of psychological tests and school work was the same as used by Seppänen et al. (2006a, 2006b). For each individual measure of performance, the fractional change in performance was calculated per 1°C change in the range of temperature examined (λ) (Equation 2.1).

Equation 2.1:

$$\lambda = \frac{P\,(TL) - P\,(TH)}{P\,(TH)} \times \frac{1}{(TH - TL)}$$

Where P (T_L) is the performance at the lower temperature, and P (T_H) is the performance at the high temperature, T_L corresponds to low temperature, and T_H to high temperature.

To estimate λ at the midrange of temperatures in each study (λ_{mid}), Equation 2.2 was used. λ_{mid} gives the effect of temperature on performance at the midpoint of the reported range of temperatures (Seppänen, Fisk, Lei 2006c, 2006b)

Equation 2.2:

$$\lambda\, mid = \frac{\lambda}{1 + 0.5\ \times \lambda\ \times (TH - TL)}$$

λ and λ_{mid} were calculated separately for the speed at which the tests were performed or the reaction time, if reaction time was reported, and accuracy describing the percentage of errors committed.

If the study examined more than two levels of temperature at which performance was tested, a linear regression was fitted using the reported measurements and the slope of the regression line was used to represent the change in performance. It was assumed the underlying relationship is linear within the rather narrow range of conditions for which the change was calculated, similar to the assumption made when calculating λ and λ_{mid}. Only the studies performed in climate chambers reported more than two temperatures (Wyon 1970; Johansson 1975; Wyon, Andersen, Lundqvist 1979). Table 2.1 show the calculated changes in performance that were used to derive the relationship.

The calculated changes in performance of teaching outcomes were regressed against the average temperature, which was estimated based on the range of temperatures for which they were calculated ((T_L + T_H)/2 or average of the temperatures studied). To determine the degree of the polynomial that best fits the data and the 95% confidence interval, the technique known as fractional polynomials was used (Royston, Sauerbrei 2008).

Bootstrap procedure was run (Canty, Davison, Hinkley, Ventura 2006) after the functional from the polynomial describing the relationship between temperature and learning performance outcomes was determined. To find the median and the confidence limits, a random sample with data replacement was selected and adjusted to the functional form found, estimating the values of the parameters in question that best fit the sampled data.

Starting at 20°C with half-degree (K) increments, Relative Performance values were estimated 1000 times. The median was estimated to be at the center of the data and the percentiles 0.05 and 0.95 were considered as limits of the confidence interval. Finally, the curves corresponding to these values were adjusted.

In case the data on means and standard deviations were reported by the studies included in the present analyses, Cohen's effect size d was calculated using Equation 3 (Cohen 1990) (Table 2.1).

Equation 2.3:

$$d = \frac{\overline{X_1} - \overline{X_2}}{s}$$

Cohen's d describes the size of an effect of intervention relative to standard deviation. It provides a standardized difference, therefore it allows comparison of effects obtained in different studies with diverse populations having different size of populations even when measuring scales are not the same. It is often used in meta-analyses thus was considered as a suitable approach in the present work but could not be applied for all data available because only few studies provided standard deviation of the measured performance outcome. This is also the reason why the approach proposed by Seppänen et al. (2006b, 2006a) had to be followed as it could be applied to all data available from various studies even though they used different measuring scales. Effect size of d = 0.2 (small effect) indicates that in a group of 100 people undergoing intervention or treatment only six persons will experience the change. In case of medium effect (d = 0.5) and large effect (d = 0.8) this number will increase respectively to 17 and 28 people. Thus Cohen's d provides thus additional and supplementary information on the magnitude of effect on performance not in form of the effect size expressed as percentage loss in performance but in form of number of pupils that would be affected by the change in classroom temperature.

2.3. RESULTS

2.3.1 Summary of individual studies

Eighteen studies were identified in the literature. They were published as early as in the 1967 and as late as in 2018. All the studies were performed in non-tropical climatic zones, thus in areas with generally moderate rather than exceptionally high or extreme outdoor temperatures and relative humidities. Most of the studies were performed in the classrooms normally used by the children participating in the experiments except for the study of Wyon (1969), Johansson (1975) and Wyon et al. (1979) performed in the climate chambers, Ryd and Wyon (1970) which was performed partially in a language laboratory, and Schoer and Shaffran (1973) who transported the children in buses to other classrooms where their performance was measured. Thermal environment in classrooms was characterized by the measurements of temperatures; daily and weekly average temperatures were reported and these temperatures were used in the subsequent analyses. Thermal sensation or thermal discomfort experienced by pupils was not reported consistently by the identified studies, consequently no analyses could be made using these ratings. The majority of studies reported the effects of classroom thermal conditions on the performance of psychological tests and school tasks. Only one study (Park 2016) reported the results of exit exams from secondary schools (number of pupils passing the exam) and one (Haverinen-Shaughnessy, Shaughnessy 2015) reported results of academic achievements on tests examining progress in reading, writing and numeracy. No studies were found that reported the effects of thermal conditions in classrooms on absence rates.

The list of the 18 papers are presented in Table 2.1 which also provides information characterizing the studies including details on thermal environment and performance measurements. The studies are summarized below:

Holmberg and Wyon (1967) found that the reading speed and comprehension of 9-year-old Swedish children was reduced by 31% to 40% when the temperature in a classroom was elevated from 20°C to 30°C. They also showed that when the temperature increased, significant postural changes occurred (Wyon, Holmberg 1969) as noted by independent observers blind to the classroom temperatures and behind one-way mirrors. Cognitive performance decreased by 19% to 61% in a similar study of raised classroom temperatures that used 11-year-old Swedish children (Holmberg, Wyon 1967). In a further study in the UK with 11-year-old children, Wyon (1970) was unable to show any change in the performance of routine tasks when the temperature was raised from 20°C to 23.5°C, and then to 27°C, but an analysis of sinus arrhythmia indicated that significantly more effort had been exerted by pupils at the higher temperatures. At 27°C, Tsai-Partington tests showed reduced arousal and the pupils tended to provide more answers in a creative thinking exercise, but they were less critical of their own answers in that there were significantly more repetitions.

Ryd and Wyon (1970) reported negative effects on 13-year-old pupils performing multiplication tasks when temperatures were raised from 20°C and 23°C to 25°C and 27°C. The results showed additionally that less able pupils performed worst. Similar results were found in a language laboratory, when answers were given verbally (Ryd, Wyon 1970).

Auliciems (1972) carried out a longitudinal field study in England in the late 1960s with 600 children between 11 and 16 years old. The experiment was carried out in 23 classrooms of 19 secondary education centres. Cognitive performance was evaluated between October and May 1966-67 and October and March 1967-68, using four different tests. Using the results from math tests, Auliciems proposed two relationships between temperature and the performance of schoolwork. This predicted a 15.5% decrease in continuous addition (boys and girls) and 10% in cancellation (boys only), when the temperature is raised from 16oC to 25°C. The optimal temperature for learning was in this experiment about 16-17oC.

Schoer and Shaffran published the results from three studies carried out between 1962 and 1966 in the USA (Schoer, Shaffran 1973). Nine- to twelve-year-old pupils were matched in pairs according to their performance, intelligence, age and gender, and later assigned at random to two physically identical classrooms that were maintained at two different temperatures. One classroom was air conditioned and the temperature was set at 22.5°C, and the other one was not air conditioned and the temperature was set at 26°C. Nineteen different school tasks and psychological tests were administered by normal teachers to students who were tested for 25 minutes twice a day during the entire experiment. After normalizing results from the different tests applied authors found that children performed better at lower temperatures in both types of tests.

Johansson (1975) exposed 36 lightly-dressed Swedish pupils to temperatures of 23°C, 30°C and 36°C in a climate chamber. They performed psychological tests and school tasks. The results showed that the number of units completed in addition and multiplication decreased by 10% and 13% at the higher temperatures.

In a study by Wyon et al. (1979), 72 high school students were exposed for 3 hours to realistically increasing temperatures in a laboratory in Denmark. They performed different performance tests. Pupils were assigned to three different groups according to the range of temperatures experienced in the climatic chamber: 20 increasing to 23°C, 20 to 26°C and 23 to 29°C. Results across all temperatures and hours showed that the performance of multiplication and cue utilization tests decreased with increasing temperature under all three conditions.

Wargocki and Wyon (Wargocki, Wyon 2007a) performed intervention studies in Danish schools with 44 Danish 10-12-year-old children. In one study, average classroom temperatures were reduced from 23.6°C to 20°C. Reducing the temperature significantly improved the performance of subtraction, addition, reading comprehension and acoustic proof-reading tasks. In an independent repetition the following year, with different children in the same two classrooms, the performance of two numerical and two language tests was significantly better at 20°C compared with 25°C. In both experiments, the temperature was reduced by operating split air-conditioning (AC) units which were idled in the placebo condition, and it was the speed at which the tasks were performed that was affected: there were no effects on errors.

Bakó Biró et al. (2012) reported experiments on ventilation rate carried out in 8 schools in the United Kingdom. In one school a total of 36 pupils performed nine neuropsychological tests at two different temperatures. The results show that at the lower temperature of 23.1°C pupils' reaction time and vigilance were significantly improved compared with a temperature of 25.3°C.

Haverinen-Shaughnessy and Shaughnessy (2015) performed measurements in 70 elementary schools located in the south-western United States. They monitored 140 classrooms (2 per school) and regressed classroom conditions against the scores on a standardized math, reading and sciences test. They found that the average score in mathematics at 2286 points went up by 12-13 points for each degree that the temperature was reduced in the range 25°C to 20°C. A similar improvement at lower temperatures was observed in the reading and science tests, but they could not be shown to be significant.

Park (2016) used the 1999-2011 results of the Regents exams from the New York State

Department of Education that had been taken by almost one million students and regressed them against the outdoor temperatures measured at nearby weather stations over the same period. He showed that taking the exam at an outdoor temperature of 32°C lead to performance being reduced by 0.19 standard deviations, as compared with taking the test at 22°C. This difference is equivalent to a quarter of the gap between black and white students. No data on classroom temperatures were available but it can be assumed that they followed outdoor temperatures.

2.3.2 Effects on performance of psychological tests and school tasks

The graph in Figure 2.1 shows that performance decreases with temperature; however this decrement is not linear having larger effects at temperatures on the lower side of the studied range (21.8 to 29.5°C). The shaded area in the figure represents 95% confidence interval of the curve and suggests that at temperatures higher than 28°C no further reduction in performance can be expected.

Figure 2.2 shows the relationship between temperature and performance on psychological tests and school tasks, showing the effect on speed or reaction time at which the tests were performed. Because it was assumed that the highest performance will occur at the temperature of 20°C and there were no studies with an average temperature lower than 21.8°C, the curve was extrapolated to 20°C and is presented in a dashed line. The figure suggests that changing the temperature between 20 and 30°C can result in a performance decrement of about 20%, and that the largest effect will occur between 20 and 26°C.

The effects on accuracy were not estimated because from the 18 tests or tasks found 16 of them came from the studies of Wargocki and Wyon (2007a, 2007b), whose results have been already published (Wargocki, Wyon 2013), showing that there are no effects of

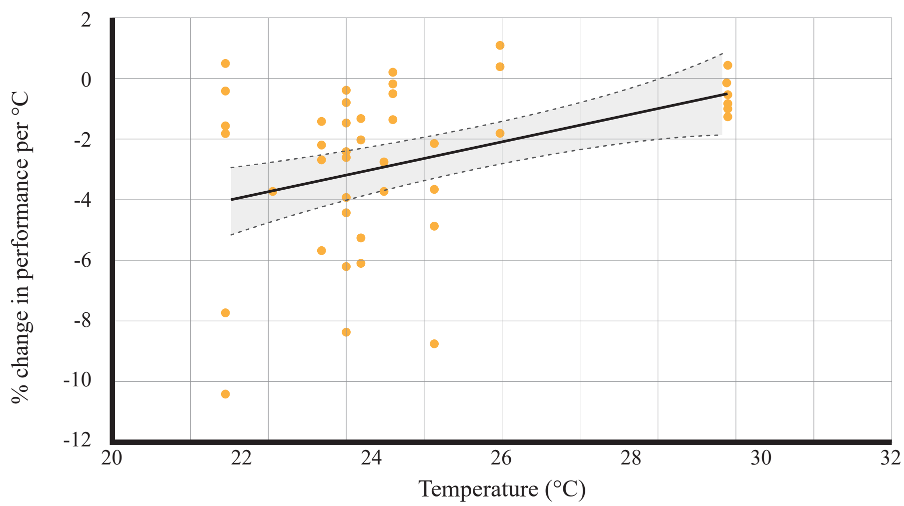

FIGURE 2.1 Percentage change in performance vs. temperature. Negative values indicate deteriorated performance with increase in temperature. Lines show the regression (solid line) with 95% confidence bands (dashed line). Dots show the estimated λ mid for individual tasks (Table 2.1).

temperature on accuracy. However, data for each individual task or test and the estimated fractional change in performance per degree can be found Table 2.1

The Cohen's d could be calculated using data reported by Wargocki and Wyon (2007a) only. Median d for data describing the speed at which the tasks were performed was 0.19 and for accuracy it was 0.04.

2.3.3 Effects on performance of standard rating schemes and final exams

Table 2.2 lists only three studies that examined the effect of temperatures on performance of standard tests examining progress in learning the exit exams. These data are too limited to establish the relationship between classroom temperature and the performance on standard tests. The available data presented in the study of Haverinen-Shaughnessy and Shaughnessy (2015) suggest about 0.5% change in scores on standard test measuring proficiency in math (compared to the average performance) if classroom's temperature change between 20°C and 25°C. Park's (2016) data suggest that 6% more students would not pass the exam if temperatures are increased from 22°C to 32°C.

2.4. DISCUSSION

The relationship presented in the present paper shows that performance of school work (or learning performance outcomes) will be reduced by 20% when classroom's temperature changes from 20 to 30°C. Park (2016) showed that such a change may result in 6% of children not passing the exit exams. Seppanen et al. showed that the effect will be less than 10% in the case when office- type work was considered. These discrepancies could be due to the methods of evaluating performance and the analytical methods. They do however

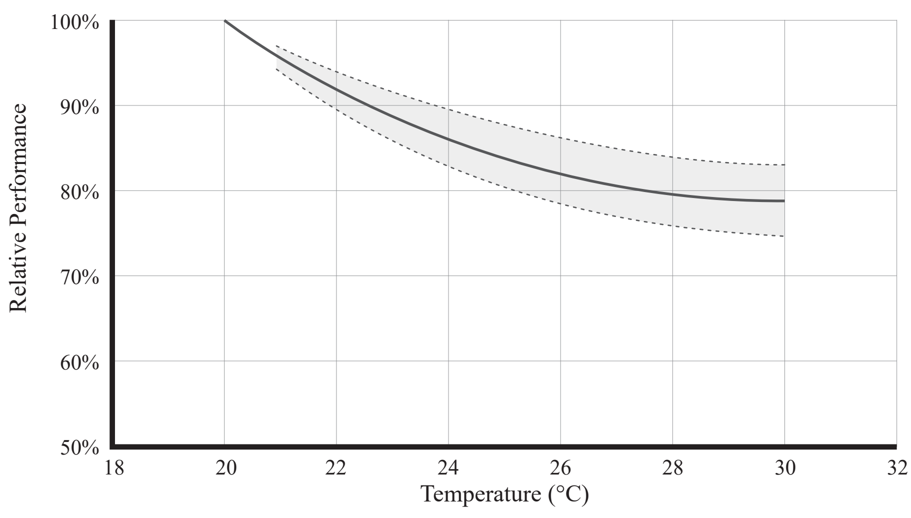

FIGURE 2.2 Performance of schoolwork as a function of classroom temperature. Performance is expressed in terms of the speed at which tasks were performed. Lines show the median (solid line) with 0.05 (top) and 0.95 (bottom) percentiles (dashed line), which were considered as confidence intervals. In the Y axis 100% means optimal performance

show that the impact of temperature on performance cannot be considered negligible due that schoolwork (pupils) are affected much stronger. Is it difficult to say why but the reason can be less opportunities to adapt and higher vulnerabilities.

Figure 2.3 compares the relationship between temperature and learning performance outcomes developed in the present work to similar relationships developed previously by Auliciems (1972) and Wargocki and Wyon (2013) using data on performance of schoolchildren, by Seppänen et al. (2006a) using mostly data on performance of adults, and by Lan et al. (2011) using data on performance of adults only.

Auliciems (1972) created two relationships between the temperature and performance of schoolwork. The performance of children on continuous addition and cancellations tests were used to create the relationship. As shown on Figure 2.3, on continuous addition the highest performance would occur at the temperature of about 16.1°C, and on cancellation, using the results from only boys, maximum performance would be achieved at the temperature of 17.2°C. The fractional percentage change in performance per 1°F change in temperature proposed for both tests was constant (-0.12 and -0.1 per Celsius degree, respectively). Wargocki and Wyon (2013) developed the relationship between the temperature and performance of schoolwork and showed that it exhibits the linear shape that extends until 20°C at which temperature the performance was highest.

Seppänen et al. (2006a) proposed a relationship between temperature and office task performance with an inverted u- shape were optimal performance is achieved around 22°C. A similar curve and optimal performance temperature were estimated by Lan et al. (2011). The difference between the relationship developed in the present work compared

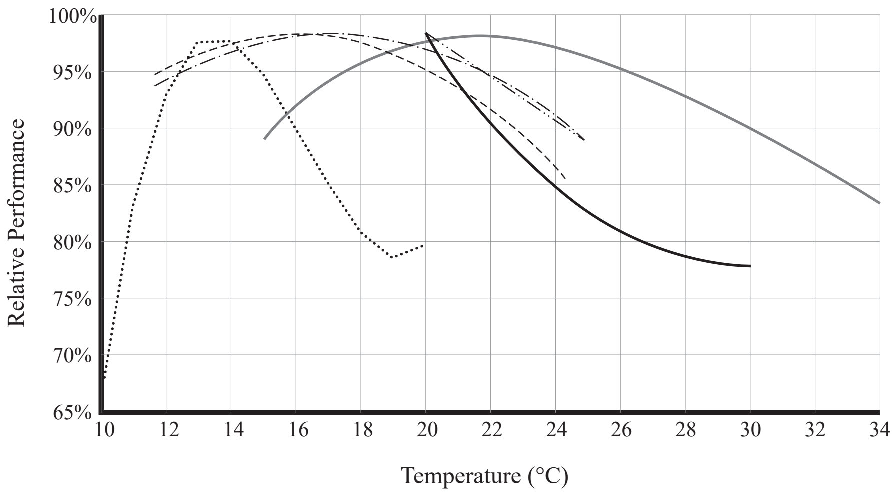

FIGURE 2.3 Comparison of the relationship developed in this chapter (———) with the ones proposed by: (- - - - - - - - - -) Auliciems (1972) (School work: Continuous addition test only. Boys and girls), (·—·—·—·—) Auliciems (1972) (School work: Cancellation test only. Boys only), (··—··—··—··) Wargocki and Wyon (2006) (School work. Different tests. Boys and girls), (......................) Jiang et al. (2018) (School work. Different tests. Boys and girls), and (———) Seppanen et al. (2006) (Mainly office work. Adults). In the Y axis 100% means optimal performance

with those developed previously by Seppänen et al. (2006a) and Lan et al. (2011) is that the effects of temperature on school work seems to be stronger in magnitude than in office work and shifted to the lower temperatures.

As shown in Table 2.1 present relationship was developed using data from studies examining the effect of thermal environment on performance outcomes in the range of temperatures between 21.8°C and 29.5°C. Therefore, can only be used to predict what may happen at this temperature range. However, is most likely that below a certain temperature performance may start to reduce which will lead to the inverted U-shape that have been proposed in previous studies.

Whether the inflection will happen at 21.8°C or below is not clear at the moment. Considering the analysis of Lan et al. (2011) it is expected to occur at the temperature at which pupils feel slightly cool. Because there is very little actual information on thermal sensation of children at school-age, and it is not known whether it will follow the sensation reported by adults (Fanger 1972), it is not possible to estimate thermal sensation using the actual evidence. However, using the PMV-Model, Clo- Value, and a slightly higher activity level (MET), considering that metabolic rate of children is about 15-20% higher than adults (Henry 2005; Henry, Dyer, Ghusain-Choueiri 1999), the temperature causing school pupils to feel slightly cool is among 19.5°C. This estimation is in agreement with the findings that suggest that there is a difference between the thermal perception of children and adults, arguing that children prefer temperatures within their classroom to be up to 2- 3°C cooler than Adults (Kim, de Dear 2017; Montazami, Gaterell, Nicol, Lumley, Thoua 2017; Teli, Jentsch, James, Bahaj 2012; Trebilcock, Soto-Muñoz, Yañez, Figueroa-San Martin 2017). The selection of this temperature should be verified in future experiments and if necessary, modifications should be made to the developed relationship. Therefore in the present work it was assumed that optimal temperature for performance would be around 20°C. Whether 20°C is optimal for school work is to be determined in the future, and if necessary modifications should be done to the relationship.

At temperatures higher than 29.5°C it may be expected that performance could further reduce or that it will reach a certain level and will not reduce further. This requires further studies. The curve presented in Figure 2.2 suggest that at temperatures higher than 28°C no further reduction in performance can be expected. A plausible explanation could be that there is few data around 30°C or that at 30°C children experienced such a high level of dissatisfaction, that incrementing the temperature will not affect their performance any more. Nevertheless, this appreciations are only hypothetical and should be validated/ studied in future work.

No relationships were created describing the effect of temperature on performance of standard tests or absence rates as the data were too limited or nonexistent. Table 2.2 shows that three published studies reported the effect of classroom temperature on standard tests assessing progress in learning and one on the results of final exams; there was no study published that examined impact of classroom temperatures on absence rates.

Learning outcomes from psychological and school tasks were treated independently from end-of-year grades and the exam scores. Each of them measures different aspects of performance that are important for the efficient and proper learning process but there is no information which would allow one to weight how important they are and how well they depict the educational level. Seppänen et al. (2006a) applied arbitrary weighting coefficients depending on the type of performance test: For overall work performance the coefficient of 1 was used, for single tasks simulating work the coefficient of 0.5 and for psychological tests the coefficient of 0.25 were used. There was however no justification in the scientific literature for the selected coefficients and they were based only on the expert judgment of the authors. It was, therefore, decided not to use this approach in the present analysis. Even though the results presenting effects on different performance outcomes were not combined it is interesting to notice that the effects are similar.

Changes in performance were calculated for all data reported by the studies independently of whether the change in performance was statistically significant or not. No evaluation of the quality of reported results was made. This approach was adopted to ensure that data from all studies were treated equally and to avoid the situation in which data from some types of performance tests that are more sensitive to changes in classroom conditions are over-represented in the developed relationship. No normalization or weighting of the effects were made, for example, based on the number of pupils taking the test. Consequently the estimated effect on learning should be considered as a conservative minimum crude estimate.

Park (2016) showed that both acute and chronic exposure to elevated temperatures negatively affects the performance of learning outcomes. No such comparison could be made using present data although it is likely that the relationships presented in Figure 2.2 reflect the acute (instantaneous) conditions by measuring temperatures during the test performance. Though it cannot be excluded that the prior exposures also affected the performance. Relationships showing the effect of temperature on the performance of standard tests are most likely representative of chronic conditions especially as they are derived from cross-sectional studies (i.e. Auliciems (1972), Haverinen-Shaughnessy and Shaughnessy (2015)). Future experiments should closely look into this aspect but it seems that the effects of chronic and acute exposures are more or less similar in size.

No studies where socio-economic estimates of the benefits that would lead to the improvement of the thermal conditions of the classrooms were found. The only study reporting socio-economic benefits of improving the indoor environment estimated the benefits of improving classroom air quality by reducing CO2 concentration in Danish schools (Wargocki, Foldbjerg, Eriksen, Videbæk 2014). Authors show that upgrading the indoor air quality in Danish schools to the level of Swedish schools could result in an increase in Denmark's Gross Domestic Product (GDP) of €173 million per annum, and in the public finances of €37 million per annum.

Even when the method used by Seppänen et al. (2006a) is robust and consistent, it would have been better to use Cohen's d to normalize the data so the different scales could be compared. However, mean and standard deviation were not properly reported in the published work, mainly in the older studies; therefore, it was not possible to use the Cohen's d approach. Thus, new studies should include the standard deviations, and as they are reported new normalizations using the Cohen's d should be perform.

It is not possible to extend the results of this study to climates different than temperate ones. Perhaps with a relation between performance and thermal sensation instead of temperature would be better. However, thermal sensation was not measured in most of the reviewed studies.

The relationship developed in the present work focus specifically on schools and learning, integrating all published data to date on the effects of temperature on learning and comparing the effects with well-defined reference conditions: 20°C. The selected approach in which the reference condition for performance is clearly defined allows a better interpretation of the results describing the effects on performance. It can be used in cost-benefit analyses when selecting the affordable and economically valid solutions that secure optimal conditions in elementary school classrooms, especially as regards the measures allowing avoidance of discomfort with thermal environment that were shown to have detrimental effects on learning.

The results provide a powerful argument for the decision makers and regulators to revise requirements in codes and standards so that the pupil, the teacher and the optimal learning environment will always remain in the center of attention independently of whether the aim is to design, renovate or operate the school buildings.

2.5. CONCLUSIONS

- Using data from 18 studies a relationship between classroom temperature and children school work performance was developed.
- Increasing classroom temperatures was shown to reduce the performance of psychological tests and schoolwork and number of pupils passing the final exam. Reducing temperature by 4 K from 26°C to 22°C is expected to increase the performance by 10%.
- All the studies were performed in non-tropical climatic zones, thus in areas with generally moderate rather than exceptionally high or extreme outdoor temperatures and relative humidities.
- The proposed relationship can only be used in temperate and cold climates and within the range of studied temperatures (21.8°C to 29.5°C).

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3. EFFECTS OF CLASSROOM'S TEMPERATURE ON TROPICALLY ACCLIMATIZED CHILDREN'S THERMAL PERCEPTION AND SCHOOL PERFORMANCE

3.1. INTRODUCTION

Considerable public and parental pressure has recently been exerted on ministries of public education and school administrations, asking them to provide children with better indoor thermal environments that enhance their academic performance (de Dear, Kim, Cândido, Deuble 2015; Vi Le, Gillott, Rodrigues 2017a; Sustainable Buildings Industry Council 2001). Consequently, the topic of how children perceive the indoor climate at schools has come into focus in recent years (Trebilcock, Soto-Muñoz, Yañez, Figueroa-San Martin 2017). Many new studies involving kindergarten and school children have been carried out (de Dear, Kim, Cândido, Deuble 2015; Trebilcock, Soto-Muñoz, Yañez, Figueroa-San Martin 2017; Teli, Jentsch, James 2012; Yun, Nam, Kim, Yang, Lee, Sohn 2014; Montazami, Gaterell, Nicol, Lumley, Thoua 2017). However, most of the research performed to date has been carried out in moderate climates, with only a few studies of tropically acclimatized children.

A summary of published studies that examined classroom temperatures and thermal comfort in the tropics is given in Table 3.1. Classroom thermal conditions in the Tropics were first studied by Kwok (1998) in Hawaii (18°N). The research included 3544 students (16.6 years average) from 19 naturally ventilated (N= 2181) and 9 air-conditioned classrooms (N= 1363). Optimum temperature was determined to be around 26.8°C (ET*) for naturally ventilated classrooms, and 27.4°C (ET*) for air-conditioned classrooms, while the preferred temperature (calculated from the thermal preference responses) was 2.5°C and 4°C lower, i.e. 24.3°C and 23.4°C respectively. In 2003 Wong and Khoo (2003) studied the thermal conditions in 15 classrooms in a secondary school in Singapore (1°N). Four hundred and ninety-three students between 13 and 18 years-old were surveyed on two mornings within

TABLE 3.1 Summary of field studies in naturally ventilated classrooms in the tropics examining thermal comfort of pupils

Study	Location	Climate	Population (schools and pupils)	Age of pupils	Temperature (°C)
Kwok 1998	Hawaii, USA	Tropical	19 classrooms in secondary schools (N: 2181)	13-19	26.8 (ET*)
Kwok and Chun 2003	Japan	Subtropical	1 classroom in a secondary school (N: 43)	13-17	Not calculated
Wong and Khoo 2003	Singapore	Tropical	15 classrooms in a secondary schools (N: 493)	13-17	28.8 (T_o)
Hwang et al. 2009	Taiwan	Subtropical	48 classrooms in 14 secondary schools (N: 944)	11-17	22.7- 29.1 (T_o)
Liang et al. 2012	Taiwan	Subtropical	48 classrooms in elementary and secondary schools (N: 1614)	12-17	22.4- 29.2 (T_o)
Vi Le et al. 2017	Vietnam	Tropical	97 classrooms in 3 elementary schools (N: 2145)	8-11	31.3 (T_a)

ET*: New effective temperature, T_o: Operative temperature, T_a: Air temperature a 3-day interval. They found that the neutral temperature was 28.8°C (To). The preferred temperature was also calculated using a Probit analysis of hot and cold discomfort and was found to be 3.5°C lower than neutral temperature (25.3°C). Vi Le et.al (2017b) performed a study in 97 naturally ventilated classrooms in 3 primary schools in Vietnam with 3960 children between 8 to 11 years old. Children felt thermally neutral at 31.3°C. These results show that children tolerated higher temperatures than the values recommended for adults in the applicable standards, suggesting that Vietnamese pupils have higher tolerance of thermal discomfort. Three additional studies by Kwok and Chun (2003), Hwang et al. (2009) and Liang et al. (2012) were carried out in naturally ventilated classrooms located in subtropical climates, two in the autumn and one in the summer. In the autumn, the neutral temperature was estimated to be between 22.4°C and 29.2°C but in the summer it was not calculated. In general, the studies summarized in Table 3.1 suggest that the optimal temperature for tropically acclimatized pupils is a few degrees higher than it is for pupils in moderate climates (Montazami, Gaterell, Nicol, Lumley, Thoua 2017; Teli, Jentsch, James 2012; Trebilcock, Soto-Muñoz, Yañez, Figueroa-San Martin 2017).

Thermal discomfort can have both long-term and short-term consequences for the learning process that affect not only school work but also the entry into working life. This has been clearly shown by Park (2016) who examined the impact of temperature on the results of exit exams in high schools (Regents exams). He showed that both elevated temperature on the day of the examination day and elevated temperatures in the months prior to it increased the probability of a poorer examination result. He estimated that performance was reduced by 0.19 standard deviations at 32°C in comparison with 22°C.

There have been 17 studies to date that examined the effects of thermal conditions on the performance of schoolwork by elementary and secondary school pupils. They are listed in Table 3.2 and briefly summarized in the following.

Holmberg and Wyon (1967) found that reading speed and comprehension were reduced by 31% to 40% when the temperature in a Swedish classroom was elevated from 20°C to 30°C. Performance of the same tasks decreased by 19% to 61% in a similar study when classroom temperatures were raised (Holmberg, Wyon 1967). In another study in the UK, Wyon (1969) showed that there were no changes in performance of routine school tasks when the temperature was raised from 20°C to 23.5°C, and then to 27°C; an analysis of sinus arrhythmia indicated however that significantly more effort had been exerted by pupils at the higher temperatures. Ryd and Wyon (1970) reported negative effects on 13-year-old pupils performing multiplication tasks when temperatures were raised from 20°C and 23°C to 25°C and 27°C. The results showed additionally that the less able pupils were most affected by the raised temperature. Similar results were found in tests applied in a language laboratory, in which answers were given verbally (Ryd, Wyon 1970). Auliciems (1972) carried out a study in 23 classrooms in England and derived two relationships that predicted a 15.5% decrease in continuous addition and 10% in cancellation if classroom temperature was increased from 16°C to 25°C. Schoer and Shaffran (1973) carried out three studies in two identical classrooms that were maintained at two different temperatures: 22.5°C and 26°C; lower temperatures were associated with better performance of schoolwork. Wyon et al. (1979) exposed Danish pupils to increasing temperatures in a laboratory and showed that sentence comprehension (grammatical reasoning) and the

TABLE 3.2 Summary of studies examining the effect of classroom temperature on the performance of schoolwork by children

Study	Location	Population (schools and pupils)	Age of pupils	Temperature range examined/reported temperature levels (°C)
Holmberg and Wyon, 1967	Sweden	3 classrooms in an elementary school (N: 50)	9	20, 27, 30
Holmberg and Wyon 1967	Sweden	4 classrooms in an elementary school (N: 80)	11	20, 30
Wyon, 1969	England	N/A (N: 48)	11	20, 23.5, 27
Wyon and Holmberg, 1969	Sweden	3 classrooms in an elementary school (N: 50)	9	20, 23.5, 27
Ryd and Wyon, 1970	Sweden	2 classrooms in an elementary school (N: 34)	13	20, 27
(2) Ryd and Wyon, 1970	Sweden	4 classrooms in an elementary school (N: 89)	13	23, 25, 27
Auliciems, 1972	England	23 classrooms in 19 elementary schools (N: 300)	11-16	12 - 25
(1) (3) Schoer and Shaffran, 1973	USA (Iowa)	2 classrooms in an elementary school (N: 44)	9	22.4, 24.9
(1) (4) Schoer and Shaffran, 1973	USA (Iowa)	2 classrooms in an elementary school (N: 22)	10	22.6, 26.1
(1) Schoer and Shaffran, 1973	USA (Iowa)	2 classrooms in an elementary school (N: 40)	11-12	22.3, 25.4
Johansson 1975	Sweden	N/A (N: 36)	10	23, 30, 36
Wyon et al., 1979	Denmark	N/A (N: 72)	17	20 - 29
(1) (5) Wargocki and Wyon, 2007	Denmark	2 classrooms in an elementary school (N: 44)	10-12	20, 23.6
(1) (6) Wargocki and Wyon, 2007	Denmark	2 classrooms in an elementary school (N: 44)	10-12	21.6, 24.9
(6) Bakó-Biró et al., 2012	England	2 classrooms in an elementary school (N:36)	9-10	23.1, 25.3
Haverinen-Shaughnessy and Shaughnessy, 2015 [13]	USA (Southwest)	140 classrooms in 70 elementary schools (N: 3019)	10	20 - 25
Park, 2016	U.S.A. (New York)	947 high schools (N: 1 million)	17-18	15.5 - 35
Jiang et al., 2018	China (Weinan city)	N/A (N:12)	11-13	10, 14, 15, 16, 18, 20

(1) Field intervention studies where air-conditioning was used to modify classroom's temperature.
Length of intervention studies: (2) 8 days over 2 months (3) 3 weeks (4) 9 weeks (5) 4 weeks (6) 2 weeks

performance of a multiplication task both decreased as classroom temperature increased from 23 to 28°C, while the performance of a memory task reached a maximum at 26°C before decreasing at higher temperatures, indicating that moderate heat stress decreases pupils' level of arousal. Wargocki and Wyon (2007b) performed two intervention studies in an elementary school in Denmark. In one study, average classroom temperatures were reduced from 23.6°C to 20°C, and in the other they were reduced from 25°C to 20°C. In both studies children performed language-based and mathematical tasks better, in terms of speed, at lower temperatures; there were no effects on accuracy. Bakó Biró et al. (2012) reported an experiment in a school in the UK in which neuropsychological tests were applied at two different temperatures; they showed that reaction time and the performance of a letter-search improved significantly at the lower temperature. Haverinen-Shaughnessy and Shaughnessy (2015) studied 140 classrooms in a field study in the USA and regressed measured classroom conditions against the scores on standardized maths, reading and sciences tests. They found that the average score in mathematics improved by about 0.5% for each reduction in classroom temperature by 1°C in the range of temperatures between 25°C and 20°C. Jian et. al (Jiang, Wang, Liu, Xu, Liu 2018) exposed 12 Chinese pupils to 6 different temperatures (10, 14, 15, 16, 18, and 20°C) in a controlled classroom environment using a balanced Latin-square design. Eleven to thirteen-year-old children participated in the experiment, wearing clothing with an insulation value of 1.5 clo. Attention, perception, comprehension and deduction were evaluated using 10 tests. Optimal learning performance was obtained when the thermal sensation votes were -1.4, i.e. on the cool side of neutral.

All of the studies in Table 3.2 showed benefits for the performance of schoolwork when elevated classroom temperatures were avoided. The studies suggest that classroom temperatures in elementary school classrooms located in moderate climates should be around 20°C and not higher than 23°C to create optimal conditions for learning by performing schoolwork. These temperatures are lower than temperatures that would be judged as neutral for thermal comfort in classrooms in the tropics (Table 3.1). The question then becomes which temperatures would be optimal in elementary school classrooms in the tropics.

Taking into account that nearly 40% of the world's population live in the tropics, where the temperatures and relative humidity are much higher than in other parts of the world, the information on how thermal conditions in school classrooms in this region affect thermal comfort and academic performance is clearly important. Most of the countries in the tropics have developing economies that cannot support technical solutions for reducing temperatures that would involve mechanical cooling. Nevertheless, school authorities and decision-makers should be aware of whether the currently very poor conditions in classrooms are having negative effects on children, and what conditions would be optimal for learning. The present study was a modest attempt to address some of these issues. The main purpose was to examine how reducing classroom temperature in the tropics would affect pupils' thermal comfort and their performance of schoolwork.

3.2. METHODS

3.2.1 Experimental design

A field intervention experiment was carried out in two similar and adjacent classrooms in the same elementary school in Costa Rica. The experiment was carried out between the last week of February and the first week of March during the dry season, which is characterized by a decrease of 95% in rainfall levels. It began a few days after the beginning of the 2017 school year.

A two-week 2x2 crossover intervention design was used, in which two different air temperatures were established in two adjacent classrooms. The pupils in Classroom 1 were exposed to reduced temperature the first week and normally occurring temperatures in the second week; the pupils in Classroom 2 experienced these conditions in the reverse order. During the experiment, normal teaching took place except for the 20-minute period during the third lesson when the pupils performed the tasks that assessed their ability to perform schoolwork and thus to learn, and rated the thermal conditions experienced in their respective classrooms. This period was scheduled to occur every day at the same time, i.e. from Monday to Friday during the two weeks of the experiments (Table 3.3); it thus occurred 10 times, 5 times at normal temperature and 5 times at reduced temperature. No other changes in school activities were made, so as to maintain the normal classroom and school routines.

The pupils were 5th grade eleven-year-old children. There were 18-19 pupils in each class and they all participated in the experiment; the number of pupils in the class was lower than the average in Costa Rican schools, which is about 25 pupils per class. Altogether, 37 pupils participated which is comparable to the size of populations studied in other experiments summarized in Table 3.2.

The interventions were made with the consent of school authorities and teachers and

TABLE 3.3 Schedule of experiments

Week	1	2	3	4	5
	Monday	Tuesday	Wednesday	Thursday	Friday
1	Mathematics: Multiplication (15 minutes)	Language: Reading and Comprehension (10 minutes)	Grammatical reasoning (4 minutes)	Language: Reading and Comprehension (8 minutes)	Mathematics: Addition and Subtraction (15 minutes)
2	Mathematics: Multiplication (15 minutes)	Language: Reading and Comprehension (10 minutes)	Grammatical reasoning (4 minutes)	Language: Reading and Comprehension (8 minutes)	Mathematics: Addition and Subtraction (15 minutes)

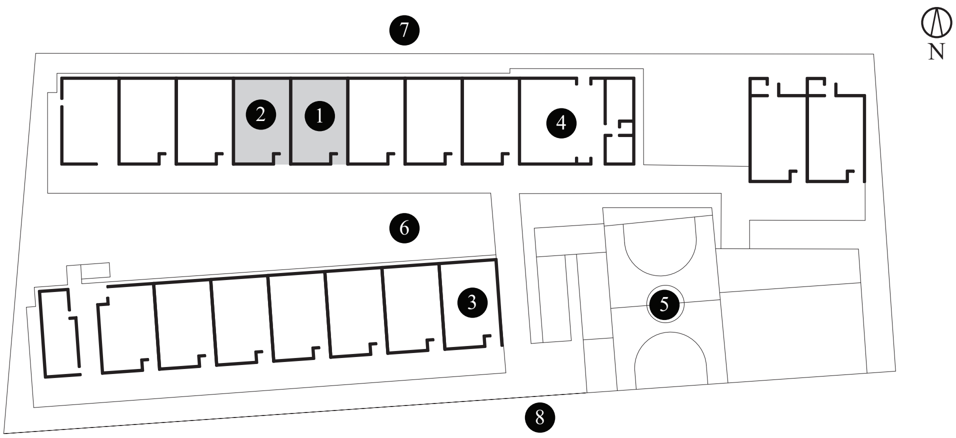
All tests were performed between the last week of February and the first of March, except Multiplication-Week 1 that was reschedule from the 20th of February to the 13th of March, due to a mistake in the tests given to the children.
All tests began between 9:15- 9:30 a.m.

were performed in collaboration with the teachers. The children were not informed about the experiments to ensure that they behaved normally but they were informed about the experiment and its purpose when the interventions had been completed. Throughout the experiment, an experimenter remained in the Principal's office, from which the entrance to the classrooms could be seen. He answered any questions from the teachers. There was no interaction between the experimenter and the pupils until the experiment had been completed, as the performance tasks and the questionnaires were administered by the teachers.

3.2.2 School

The school was located in a small country town in the north-western region of Costa Rica. It was at the confluence of two rivers, 15 meters above sea level, and mostly surrounded by sugarcane fields. It was an elementary public school run by the Costa Rican Ministry of Public Education (MEP) for children 5 to 12 years-old. At the time of experiment, the school had 334 pupils, in 2 kindergarten grades and 6 school grades. The average class size was about 19 pupils.

The single-storey 1500 m^2 school building was constructed in 2007 in a single stage, using an architectural prototype and a construction system that had been widely employed



(1) Classroom 1, (2) Classroom 2, (3) Principal's and teacher's office, (4) Dining hall, (5) Roofed basketball courtyard, (6) Courtyard, (7) Football field, (8) Main Street entrance.

(A) School's main entrance (B) Access to classrooms through open corridors (C) Classroom's interior

FIGURE 3.1 The school. Floor plan and pictures.

in Costa Rican public schools. It housed 13 classrooms for regular and complementary courses, a dining hall, a computer laboratory, a library, offices for the Principal and for the teachers, a roofed basketball courtyard and toilets for children and teachers (Figure 3.1). All rooms opened into two 2.5 m wide corridors that ran from east to west.

Except for the computer laboratory, where a split-cooling air conditioner (AC) unit was installed, there was no mechanical ventilation, and no mechanical cooling or heating system in the other spaces in the school. Two ceiling fans had been installed in each of the classrooms, although these were idled during the experiments. Most of the teachers and administrative staff had additional table-top fans for personal use.

3.2.3 Classrooms

The two classrooms that were used in the experiments were adjacent and equal in size, shape, and materials. They were part of a row of 7 classrooms that opened onto a straight corridor that ran from west to east and ended at the dining hall. Each classroom had a floor size of 6 x 9 m (54 m^2), and a volume of 160 m^3. It was designed for 27 pupils, i.e. 2 m^2 per child (Figure 3.2).

The external and internal walls were made of 4-cm-thick horizontal slabs of reinforced concrete, which were inserted between 12 x 12 cm vertical concrete columns. There was no insulation. The sloping roof was supported on metal beams and covered with a 5 mm reflective layer and corrugated metal sheets painted white.

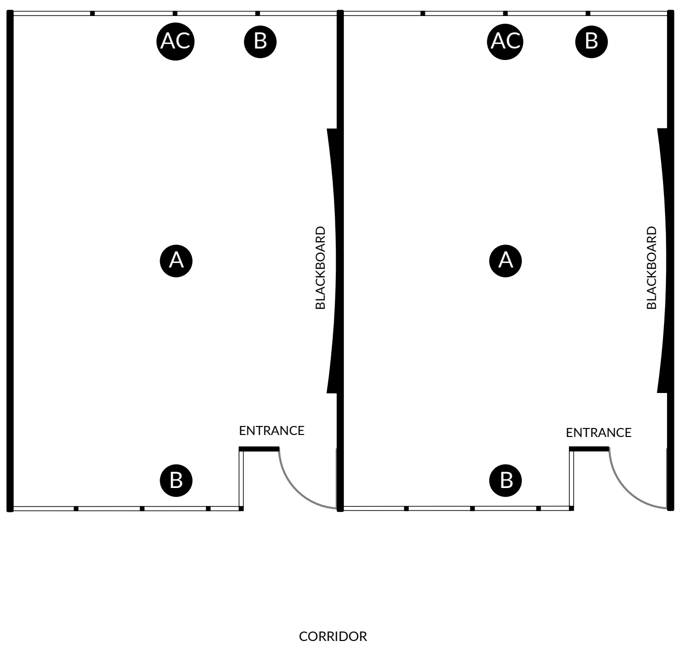


FIGURE 3.2 Floor plan of the classrooms where experiments were carried out showing location of measuring equipment and air-conditioners. (A) Air temperature, Globe temperature, Relative humidity, Air Speed, CO_2 concentration and light intensity, (B) Air temperature and Relative humidity, (AC) Air-conditioning unit

Windows were situated along the north façade, with a windowsill-height of 1.3 m, and in the upper quarter of the south façade, to provide cross-ventilation. 50% of the glass surface was of glass louvres that could be opened by occupants. The panes were of transparent 3 mm glass in an aluminium structure. The windows and walls were externally shaded from direct sun. There were no blinds.

The concrete floor was covered with ceramic tiles and there was a pitched ceiling made of PVC clapboards. There was no ceiling in the corridors. Typical school furniture with individual polypropylene seats and metal- polypropylene desks with a trapezoidal shape were employed. The thermal insulation of the chairs was considered negligible.

3.2.4 Weather

According to the Köppen-Geiger Climate Classification, the climate of the case study site corresponds to Tropical Savana Climate (Aw) (Peel, Finlayson, Mcmahon 2007), and according to the Costa Rican National Meteorology Institute (IMN), the area is located in the North Pacific Zone, Subregion 2 (PN2) which is characterized by a dry climate (Solano, Villalobos 2001).

The region experiences two climatic seasons of similar length. One season stretches from May to October and due to high rainfall, it is best known as the rainy season. The other season runs from December to April and is considered to be the dry period. The months of May and November can be classified as transition periods. Even though the climate of

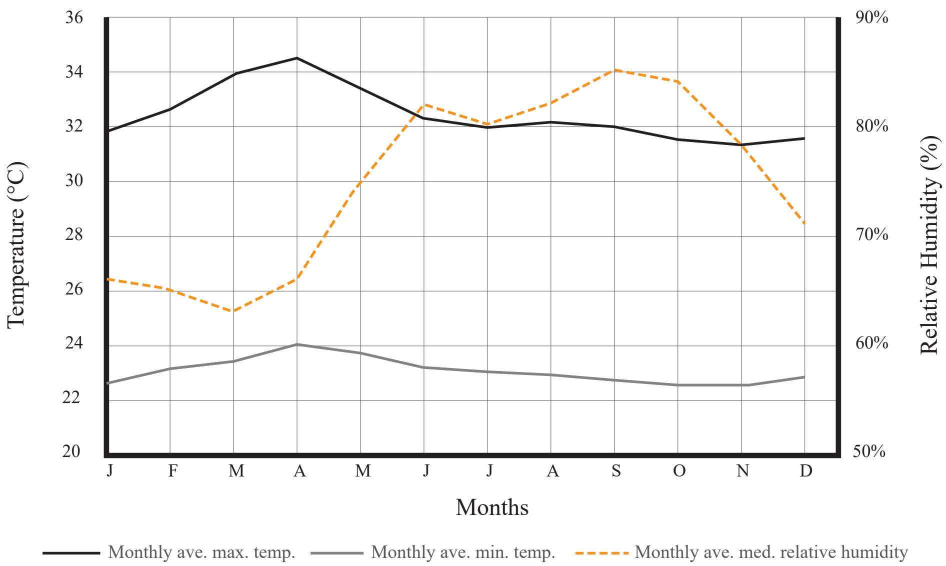


FIGURE 3.3 Monthly averages of climatic data based on information retrieved by the National Institute of Meteorology of Costa Rica (IMN) in the weather station Taboga Ingenio No. 76041 between 1984 and 2007

this region is classified as “dry” in comparison with Tropical Monsoon climates, the annual average precipitation exceeds 1,600 mm and the average number of days with rain is 142.

The lowest monthly average temperature is 22.5°C and occurs in October-November while the highest monthly average temperature of 34.5°C occurs in April; the average annual range of temperatures is about 11.9°C. The monthly average relative humidity varies throughout the year in close relationship with the rainfall regime. In the dry months, March and April, the monthly average is lowest and about 65% and in the rainy months, September and October, it exceeds 85%. The relative humidity is thus high compared with those of moderate climates, considering the average temperatures.

Figures 3.3 and 3.4 show the monthly averages of climatic data and changes in average outdoor air temperature.

Pupils Thirty-seven pupils participated, 18 in one class and 19 in the other. They were all dressed similarly. It is not required but common that pupils of both sexes wear t-shirts and that girls wear short pants under their skirts; in the present experiment 78% of pupils did the former and 38% of the girls did the latter. The children had few options to adaptively alter their clothing in schools during the day, for cultural and regulatory reasons. The thermal insulation of the clothing worn by pupils was estimated to be about 0.5 clo under both conditions. The metabolic rate of a seated child performing schoolwork was estimated to be equal to a typical office sedentary activity in the ASHRAE Standard 55- 2013, which corresponds to 1.2 MET (ANSI/ASHRAE 2013).

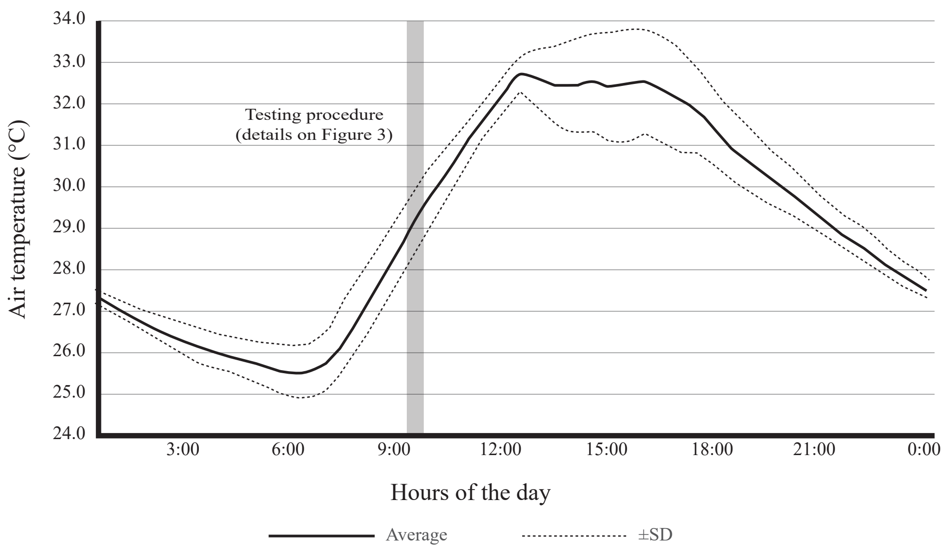


FIGURE 3.4 Changes in average outdoor air temperature on a typical day estimated by averaging 30-minute interval temperature records from 10 weekdays

3.2.5 Interventions

Using the Cooling Load Temperature Differences (CLTD) method (ASHRAE 1997), a cooling load of 15 kW was estimated to be sufficient to maintain temperature in the selected classrooms at 26°C with outdoor temperatures up to 32°C and the windows and door closed. The calculation took account of latent and sensible heat loads from 18 occupants per classroom and solar heat gains for the period of the year in which the experiments were scheduled. The average air temperature registered in the classrooms at the time the tests were scheduled to begin (10 a.m.) was 32°C in a preliminary study that was carried out in 2013. It was expected that 26°C would be rated by children as a neutral to slightly cool condition, based on the PMV method in ASHRAE 2013 (ANSI/ASHRAE 2013), and on studies by de Dear et al. (2015), Kwok (1998) and Wong and Khoo (2003) that found that the neutral temperature for tropically-acclimatized teenagers should be close to this temperature (Table 3.1).

Because the electrical system of the school did not have the capacity to support an additional 30 kW, and because of the high cost of 15 kW cooling equipment, it was decided to install units with a capacity of only 7 kW (approx. 24.000 Btu/h) and schedule the test period between 9:15 a.m. and 9:30 a.m. when the outdoor temperature was expected to be slightly lower (29-30°C). These smaller units were calculated to be able to maintain the intended temperature of 26°C.

A wall-mounted split-cooling air conditioning (AC) unit was chosen and installed in each of the experimental classrooms two weeks before the experiments began. The indoor unit was installed in the north façade and was connected to an outdoor unit consisting of the condenser and compressor and situated on the ground. It would have been preferable to install the indoor unit in the centre of the west wall, facing the blackboard, but this design was not authorized by the school's authorities. The AC units delivered their cooling effect during the reduced temperature condition and were otherwise operated in a placebo mode in which the fans were operating continuously while the cooling system was off. Neither teachers nor children were able to adjust the equipment at any time. The installed equipment produced a noise level of 43-48 dB (A). All indicators of temperature or relative humidity on the air conditioner were deactivated or covered to prevent teachers or pupils from reading them.

3.2.6 Measurements of Performance

The children performed only one task each day; altogether they performed 4 different tasks each week, as one task was performed twice (Table 3.3). The tasks examined skills in mathematics, logical reasoning and reading and comprehension. They were all presented in Spanish (the mother tongue of the pupils and the teachers). They were administered by the children's regular teacher, as mentioned earlier, during the third lesson, i.e. in the morning around 9:30 a.m.; teaching in the school started at 7 a.m.

In order to adapt content, difficulty, and type of exercises as much as possible to the curricula, skills and educational level of the students, the tests were prepared using the Ministry of Public Education official curriculum plans, school exams prepared by Costa

Rican teachers and course textbooks. The difficulty level of the tasks corresponded to what 4th grade pupils could manage even though they were to be performed by 5th grade pupils. The reason was that they were presented right at the beginning of the new school year. Before application in the planned experiments, the tasks were tested on another group of pupils and approved by the teachers.

The four tasks used were: multiplication; reading and comprehension; grammatical reasoning; and addition-subtraction. The reading and comprehension task was performed twice a week (Table 3.3). These tasks selected so that children would be likely to consider them as part of the normal teaching curriculum.

The multiplication task consisted of multiplying three-digit numbers by two-digit numbers. Every 3 units the three-digit numbers included a decimal (34.6 instead of 346). No zeros or fives appeared in the numbers. Fifteen minutes was allocated for this task, which was performed on Mondays.

In the reading and comprehension task, sixteen short texts with a range of 400 to 500 characters in 3 sentences were given to pupils. The order of the sentences did not necessarily correspond to a logical sequence. The task was to read and put the sentences in the right order. They had 10 minutes to complete the test on Tuesdays and 8 minutes on Thursdays.

A variation of the grammatical reasoning test developed by Baddeley (1968) was used. Each exercise consisted of a statement followed by a figure and two possible answers: True or False. Statements were positive, e.g. Figure A is inside, outside, bigger, smaller than Figure B, or negative, e.g. Figure A is not inside, outside, bigger, smaller than Figure B. Sixty-four statements were included in each test and the time allocated was 4 minutes; it was applied on Wednesdays.

In the addition-subtraction task performed on Fridays the pupils first added eight units and then subtracted 8 units. Pupils added six-digit numbers and subtracted six-digit numbers from seven-digit numbers. They had 15 minutes to complete this task.

The tasks were presented on two or more pages printed on both sides. They were written in Times New Roman Font size 11, and had a cover page containing the general information, the instructions and two examples. The exercises were distributed randomly on each page to remove any bias due to degree of difficulty.

Before the beginning of each task, the teacher gave a printed task version to every pupil and conducted a practice session. The words “examination” or “test” were not used at any time. Teachers began reading the instructions and asked children to write their full name on the exercise sheets, as they would normally do when performing any other school work. They also explained to pupils how to perform the exercises, using the examples provided. They performed the two examples on the blackboard and answered any questions from the children, who were instructed not to start the test or to look at the unsolved exercises until the instruction period had been completed. Teachers instructed pupils to perform as many exercises as possible. If a pupil did not know an answer or considered the question to be too difficult, he or she could leave it blank and continue with the next one.

The work period was so short and the tasks sufficiently long so that no one was expected to complete them in the time available. If anyone finished earlier, the teachers were asked to record the time.

The tasks were performed at least 30 minutes after the first morning break, which took place from 8:25 to 8:40 a.m. The pupils did not receive any payment, grades, awards, or extra points for completing the exercises. After the 10 days of experiment, researchers thanked the teachers and students by presenting them with a fruit-snack box.

Task performance was assessed by calculating the percentage of the answers that were correct (accuracy) and the number of correct answers provided in the time available (speed). The number of units attempted per unit time is often used (Wargocki, Wyon 2007b), but here the number of correct answers per unit time was used, following Petersen et al. (2015).

3.2.7 Measurements of classrooms' conditions

Outdoor temperature and relative humidity were measured in the corridor at a height of 150 cm above floor level with two HOBO U12-12 data loggers at 10-minute intervals. To measure indoor environmental parameters - air and globe temperature, relative humidity, air velocity and light intensity, the sensors and carbon dioxide monitors were deployed by researchers in three different places in the classroom (Figure 3.2): in the centre of the classroom (A), and on the north and south walls (B). All instruments were calibrated before use. Operative Temperature was assumed to be represented by globe temperature.

Two HOBO data loggers model U12-012 were used to monitor temperature (with a precision of ±0.35°C), relative humidity (with a precision of ±2.5%) and light intensity, every10 minutes at the north and south walls (B). Airspeed levels and globe temperature were recorded at 10-minutes intervals in the centre of the classroom (A) at two levels, 70 cm and 140 cm above the floor. For measuring the air velocity, two F900-L-P (precision ±0.05 m/s) sensors were used, and globe temperature was measured with a 40 mm diameter grey globe sensor that had a precision of ±0.3°C in the measuring range of 10–40°C (Simone, Olesen, Stoops, Watkins 2013). All 4 sensors were connected to a HOBO UX120-006 4-Channel analogue data logger. Carbon dioxide concentration was measured with a Vaisala model GMW22 (CO_2 range: 0-5000 ppm ±100 ppm, accuracy 2% of reading) attached to a HOBO data logger model U12-012 (signal range: ±2mV ± 2.5% of the reading) that also monitored temperature (with a precision of ±0.35°C), relative humidity (with a precision of ±2.5%) and light intensity.

All measurements indoors were performed during typical school hours, i.e. from 7 a.m. to 12 p.m., while measurements outdoors were recorded continuously (24/7).

3.2.8 Subjective measurements

The questionnaire used in the present experiments had been tested on more than 350 elementary school children in Costa Rica prior to the experiment. At the end of each test, the students completed a printed questionnaire containing questions on thermal acceptability (dichotomous Yes/No scale), thermal sensation (ASHRAE's seven-point scale) and thermal preference (seven-point scale); the scales are shown in the Appendix 3.2. The scales were especially developed to be understood by children and were based on a questionnaire used in an extensive field study in Chilean schools (Trebilcock, Soto-Muñoz, Yañez, Figueroa-San Martin 2017). Thermal preference was measured using the seven-point scale, instead of the common three and five-point scales, following the scales use by Teli et. al (2012) and Trebilcock et. al (Trebilcock, Soto-Muñoz, Yañez, Figueroa-San Martin 2017). It took pupils 2 or 3 minutes to answer the questions.

3.2.9 Statistical Analysis

The statistical analysis was conducted using R software (2016). First, a Normal Q-Q plot and a Shapiro-Wilks test with a p-value criterion of 0.05 were used to decide whether the residuals of the data subjected to statistical tests were normally distributed. Since the results showed that residuals in at least one of the conditions were not normally distributed, the non-parametric Wilcoxon matched-pairs signed-ranks test was used to examine the effects of classroom temperatures on different outcomes with the statistical significance set at $p=0.05$; 1-tail tests were used since results from moderate climates show that reducing classroom temperature improves the performance of schoolwork (Table 3.2). Fisher's method was used to combine the results from the reading and comprehension task that was performed twice (Winer 1970). Although the subjects were the same throughout and the Fisher test requires that data stem from independent experiments it was assumed that no bias was introduced since the tasks were performed on different days so that other factors affecting performance differed randomly.

3.3. RESULTS

3.3.1 Classroom conditions

Table 3.4 summarizes classroom conditions measured at the beginning of each task. Classroom temperature in the placebo condition with the AC cooling disabled (normal temperature condition) was between 29.5°C and 30.1°C, as predicted. Long-term measurements of classroom temperatures, not reported in this paper, confirmed that these were temperatures typically experienced by the children during the dry season. Measurements showed further that there were very small differences in classroom temperature between different days and between different classrooms. When the AC system was in operation, classroom temperatures in the experimental condition dropped to between 24.5°C to 26.0°C, again as predicted before experiments. The intervention thus reduced the classroom temperature by about 4 to 5°C. The measurements showed that during this condition the difference in temperatures between classrooms and on different days could be as high as 2°C; they were higher especially in the second half of the experimental week (Table 3.4). The globe temperature was about 0.5°C higher than the air temperature under both conditions examined in the present experiments and followed the changes in the air temperature. Figure 3.4 shows the outdoor changes in temperature and confirms that all

TABLE 3.4 Environmental monitoring. Measurements carried out at the beginning of the tests

	Air Temperature (°C)			Globe Temperature (°C)			RH (%)			CO_2 (ppm)			Light intensity (lux)			Air speed (m/s)		
	Normal	Reduced	Δ	Normal	Reduced	Δ	Normal	Reduced	Δ	Normal	Reduced	Δ	Normal	Reduced	Δ	Normal	Reduced	Δ
	Mean (SD)	Mean (SD)		Mean (SD)	Mean (SD)		Mean (SD)	Mean (SD)		Mean (SD)	Mean (SD)		Mean (SD)	Mean (SD)		Mean (SD)	Mean (SD)	
Multiplication	30.07 (0.3)	26.1 (0.2)	3.9	30.8 (0.5)	26.5 (0.3)	4.4	55.0 (5.7)	57.3 (5.7)	-2.3	458 (35)	523 (30)	-65	564 (33)	560 (117)	4	0.3 (0.1)	0.3 (0.0)	0.0
Reading & and Comprehension	29.9 (0.2)	25.4 (0.7)	4.5	30.4 (0.2)	25.6 (0.5)	4.8	54.4 (3.4)	58.7 (3.2)	-4.3	503 (99)	605 (1)	-102	445 (167)	516 (123)	-71	0.5 (0.3)	0.3 (0.1)	0.2
Grammatical reasoning	29.5 (0.7)	24.5 (2.0)	5.0	29.9 (0.6)	24.6 (2.2)	5.3	62.8 (5.2)	61.9 (1.4)	0.9	610 (251)	795 (269)	-185	670 (151)	761 (212)	-91	0.3 (0.0)	0.3 (0.0)	0.0
Reading & and Comprehension	29.6 (0.3)	24.8 (1.7)	4.8	30.0 (0.3)	25.3 (1.7)	4.7	62.6 (7.4)	61.5 (0.1)	1.1	493 (113)	654 (155)	-161	674 (45)	650 (67)	24	0.3 (0.2)	0.3 (0.1)	0.1
Addition & and Subtraction	29.9 (0.3)	24.7 (1.7)	5.2	30.5 (0.3)	24.9 (1.7)	5.5	59.8 (8.8)	59.6 (3.2)	0.2	549 (164)	781 (251)	-232	611 (33)	599 (28)	12	0.2 (0.1)	0.3 (0.1)	-0.1

Δ: Difference between Normal and Reduced conditions the performance tasks were scheduled (9:15 and 9:30 a.m.) before the warmest period of the day.

Relative humidity levels were not controlled and remained between 55% and 63% in both normal and reduced temperature conditions, and this is typical for the dry season. The difference in relative humidity between both thermal conditions examined in the present experiments did not exceed 5%.

Carbon dioxide concentrations measured in the classrooms were between 450 and 800 ppm. Under both normal and reduced temperature conditions, the light intensity at desktop level was above the classroom recommended level of 400 lux. Light intensity differences between the two thermal conditions were not higher than 90 lux. The average air velocity measured between the beginning of the school day (7:00 a.m.) and the onset of each task (9:15 a.m.) was about 0.3 m/s and very little difference in measured air velocities between the school days and the classrooms was observed.

Classroom's air temperature, relative humidity and carbon dioxide concentration during normal and reduced temperature conditions in the course of a day are presented in Figures 3.5, 3.6, and 3.7 respectively.

3.3.2 Pupils' ratings of thermal environment in classrooms

The ratings of thermal environment made by pupils under the normal and reduced temperature conditions are shown in Table 3.5. Pupils reported that they were on average

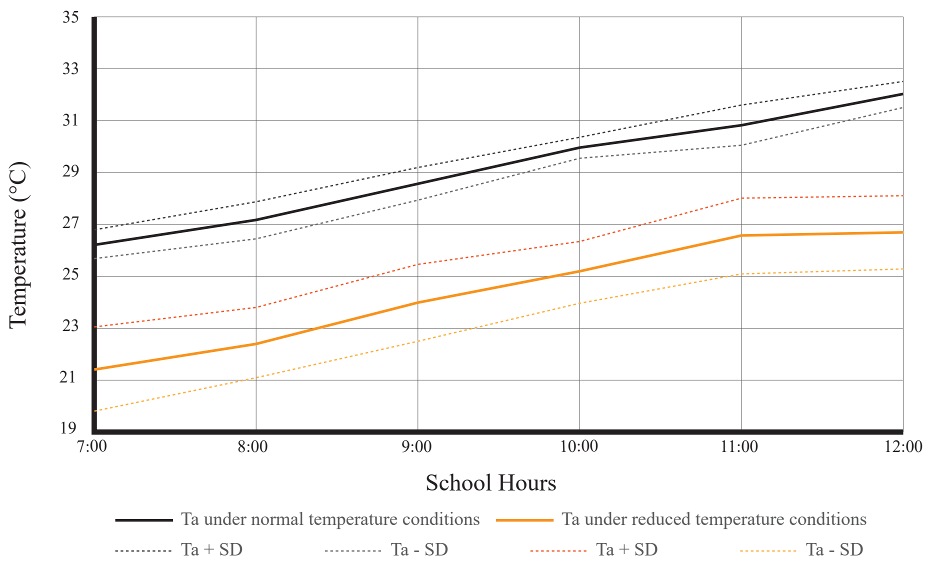


FIGURE 3.5 Changes in average air temperature on school hours under normal and reduced temperature conditions estimated by averaging 10-minute interval records from the 10 experimental days

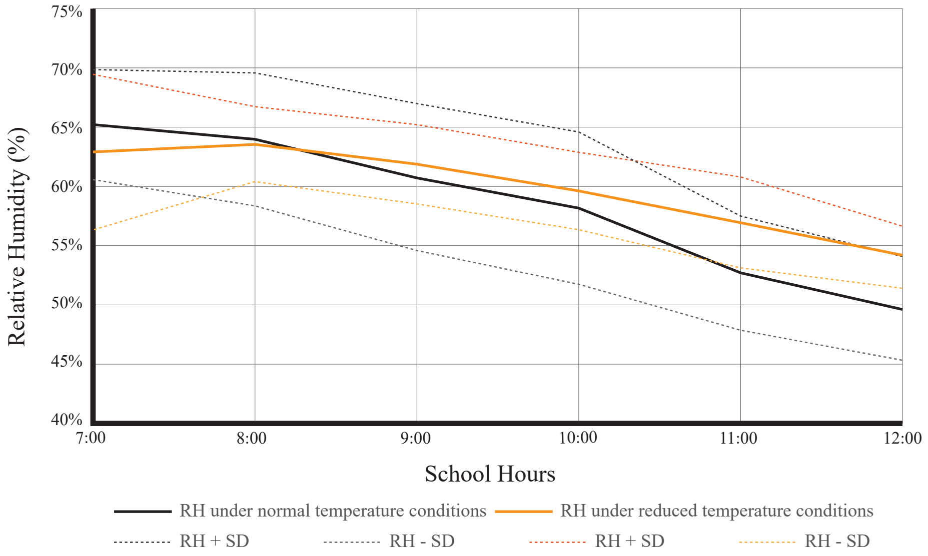


FIGURE 3.7 Changes in average relative humidity on school hours under normal and reduced temperature conditions estimated by averaging 10-minute interval records from the 10 experimental days

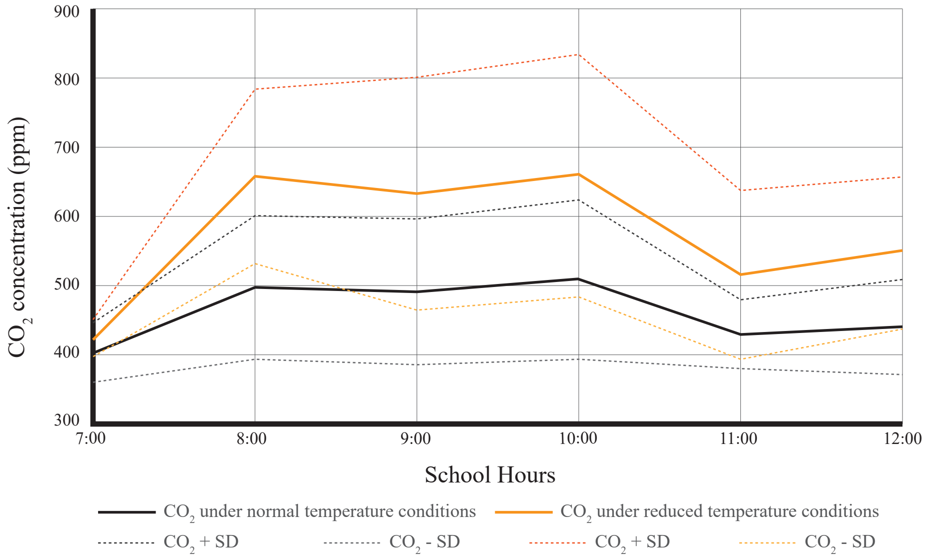


FIGURE 3.6 Changes in average CO_2 concentration on school hours under normal and reduced temperature conditions estimated by averaging 10-minute interval records from the 10 experimental days

hot (+2) at normal classroom temperatures, in which about 60% were dissatisfied with the thermal conditions, while they felt between neutral (0) and cold (-2) at the reduced temperatures, in which about 25% were dissatisfied with the thermal conditions. They always stated that they would have preferred a cooler environment, regardless of the temperature conditions in the classrooms.

Figure 3.8 shows the thermal sensation votes (TSV) and the predicted mean votes (PMV) plotted against measured operative temperatures in the classrooms; PMV was calculated using the CBE Thermal Comfort Tool (Tyler, Stefano, Alberto, Dustin 2017). Although based on data from subjects who were not heat acclimatized, PMV may be seen to underestimate the response of TSV to temperature, contrary to expectation. The figure suggests that in the present experiments the neutral temperature was 26.9°C. Probit analysis presented in Figure 3.9 showed a similar result.

Neutral temperature was also calculated with the Griffiths method of neutrality estimation, which results again agrees with all other estimations (Table 3.6). It uses a relationship between mean thermal sensation vote for a group (TSV), the mean operative temperature (To), and a constant thermal sensitivity coefficient, known as the Griffiths constant (G), which optimum value has been defined as 0.5 sensation scale unit/°C. This method is suitable when the sample of comfort votes and the range of temperatures are small (Nicol, Humphreys, Roaf 2012). One of the main critics is that it assumes a constant clothing insulation despite varying temperature (de Dear, Brager 2001), however in this study this assumption is true. It has been used to determinate thermal comfort temperature in other studies in school buildings (Trebilcock, Soto-Muñoz, Yañez, Figueroa-San Martin 2017;

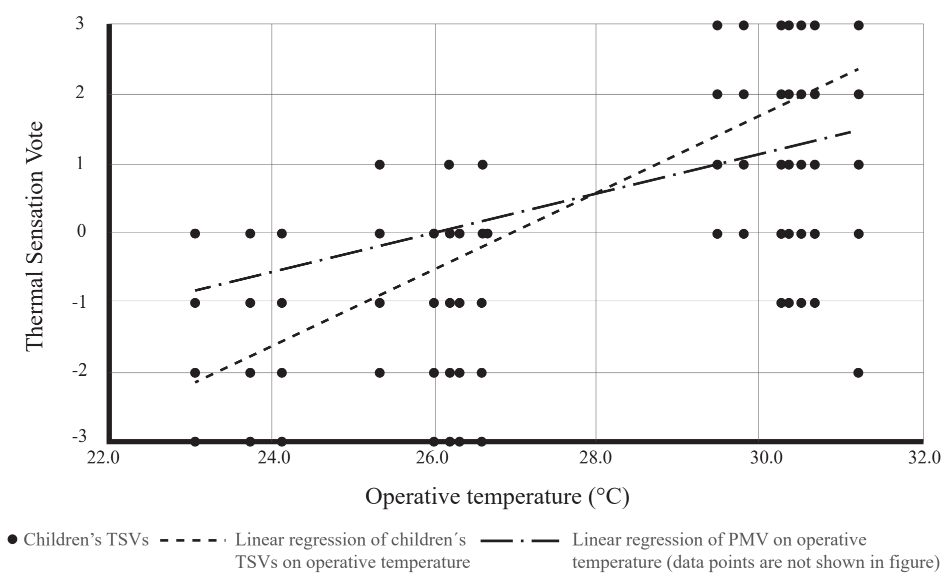


FIGURE 3.8 Thermal sensation votes as a function of classroom operative temperature; operative temperature was estimated using the measurements of globe temperature.

TABLE 3.5 Average (SD) ratings of pupils made under two conditions examined in the present experiments

	Number of pupils voting. Total (Class 1/2)*	Mean TSV (SD) (1)	Mean TPV (SD) (2)	Percentage of dissatisfied	Number of pupils voting. Total (Class 1/2)*	Mean TSV (SD) (1)	Mean TPV (SD) (2)	Percentage of dissatisfied
	Normal temperature conditions				Reduced temperature conditions			
Monday	34 (19/15)	2.0 (0.8)	-1.7 (0.9)	62%	30 (17/13)	-0.2 (1.5)	-1.2 (1.6)	27%
Tuesday	36 (18/18)	2.0 (1.0)	-1.3 (1.5)	69%	36 (19/17)	-0.7 (1.0)	-1.9 (1.3)	25%
Wednesday	37 (18/19)	1.9 (1.3)	-1.3 (1.6)	62%	36 (19/17)	-1.3 (1.0)	-2.0 (1.4)	19%
Thursday	31 (18/13)	1.7 (1.2)	-1.3 (1.2)	61%	33 (17/16)	-1.1 (1.1)	-1.9 (1.5)	24%
Friday	34 (17/17)	1.9 (1.0)	-1.5 (1.7)	62%	36 (19/17)	-0.9 (1.1)	-1.9 (1.5)	22%

(1) +3 Very hot, +2 Hot, +1 A bit hot, 0 Neutral, -1 A bit cold, +2 Cold, +3 Very cold.
(2) +3 Much hotter, +2 Hotter, +1 A bit warmer, 0 Any change, -1 A bit colder, +2 Colder, +3 Much colder.
*Total number of surveys: 343

Haddad, Osmond, King 2016).

Additional information about thermal sensation votes, thermal preferences and thermal comfort by classroom can be found in Appendix 3.3.

3.3.3 Performance of tasks representing schoolwork

The performance results are shown in Table 3.7; only the results from pupils who performed the tasks under both normal and reduced temperature conditions were included in the pairwise comparisons.

In the case of multiplication, the reduced temperature conditions improved both speed and accuracy but the changes did not reach statistical significance. The performance of reading and comprehension improved in terms of the speed at which the task was performed on Tuesday; the effect was significant ($P = 0.034$). There were no significant effects on accuracy. The performance of the same test also improved on Thursday but the effect did not reach significance ($P = 0.075$). One of the reasons was that nearly half of one class

TABLE 3.6 Comfort temperature under Griffiths method

Equation	Mean operative temperature (°C)	Thermal sensation votes mean	Griffiths constant	Estimated comfort temperature (°C)
T comf = To – TSV/G	27.8	0.51	0.5	26.8

*Total number of surveys: 343

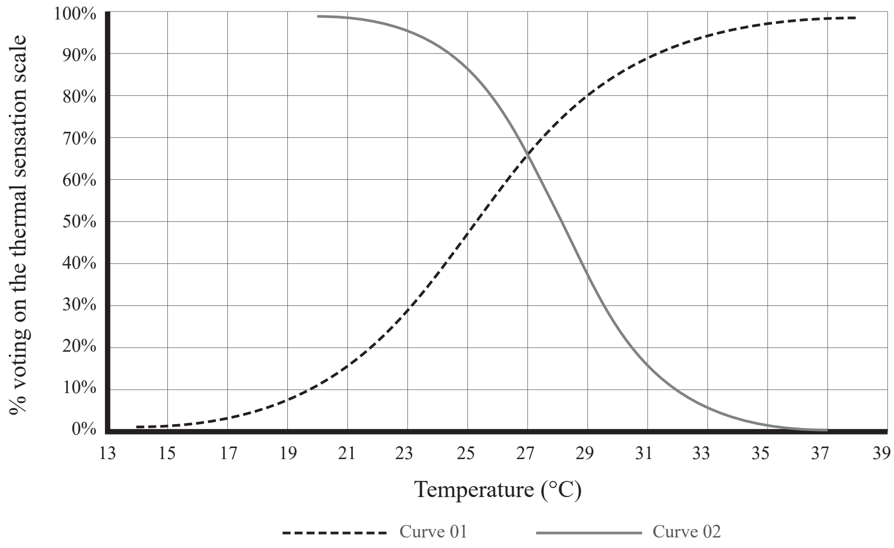


FIGURE 3.9 Probit regression models fitted to thermal sensation votes. Children thermal sensation votes were split into two groups for each sigmoid response curve. Curve 1 shows the percentage of children who would change their assessment from “ hotter than neutral” to “neutral or colder”. Curve 2 shows the change in the opposite direction, pupils who will change from “colder than neutral” to “neutral or hotter”

TABLE 3.7 The results of performance

Test	Day of the week when the test was applied	Performance Metric	Number of pupils Total (Class 1/2)	Performance		Fractional change in speed or accuracy per 1°C decrease in temperature	Effect size (Cohen's d)	Wilcoxon signed- rank test P<	Estimated number of pupils to reach statistical significance at beta 0.8 (1)
				Normal	Reduced				
				Mean (SD)	Mean (SD)				
Multiplication	Monday	Attempted units per min	27 (17/10)	0.06 (0.11)	0.06 (0.10)	0.25%	0.01	0.382	64 746
		Percentage of correct answers		14.3 (23.3)	16.3 (23.1)	0.47%	0.09	0.305	801
Reading & and Comprehension	Tuesday	Attempted units per min	33 (17/16)	0.39 (0.30)	0.53 (0.53)	7.54%	0.32	0.039	65
		Percentage of correct answers		24.2 (12.1)	24.2 (16.2)	0.00%	0.00	0. 448	N/A
Grammatical reasoning	Wednesday	Attempted units per min	36 (18/18)	4.11 (1.61)	5.18 (2.17)	4.91%	0.56	0.002	23
		Percentage of correct answers		70.4 (16.5)	69.7 (12.7)	-0.13%	-0.05	0.229	2 592
Reading & and Comprehension	Thursday	Attempted units per min	28 (17/11)	0.61 (0.33)	0.70 (0.35)	3.15%	0.27	0.075	91
		Percentage of correct answers		22.5 (15.7)	25.3 (16.9)	0.59%	0.17	0.059	226
Addition & and Subtraction	Friday	Attempted units per min	31 (17/15)	0.28 (0.21)	0.27 (0.19)	-0.43%	-0.03	0.299	7 196
					51.7 (31.6)	-0.77%	-0.13	0.388	385

(1) Power (1-β err prob) = 0.8, α err prob = 0.05

did not complete the task under one of the two conditions tested. If performance on the second day is regarded as an independent test of the same hypothesis, the P-values can be combined using Fisher's method (Winer 1970), yielding a significant effect of reduced temperature on the speed at which this test was performed (P = 0.020). In the grammatical reasoning task, the number of correct units completed improved significantly at the reduced temperature (P = 0.002). There was no significant effect on accuracy. Cohen's effect size as well as the number of pupils required to reach statistical significance at a power of 0.8 are also presented in the table and they match other statistical analyses. The number of skipped exercises was independent of the thermal conditions (Table 3.8).

Based on results presented in Table 3.7 the fractional change in performance caused by reducing the temperature in the classrooms was calculated, as was done by Seppänen et al. (2006b). They correspond to an increase of up to 8% in speed, and an increase of 3% in accuracy for each 1K reduction in classroom temperature.

An analysis of the performance of the most and less able pupils in terms of speed is presented in Tables 3.9 and 3.10; they were defined as those performing the tests best and worse than the 25th percentile for the entire class at normal temperature. Lest able pupils performed significantly better at reduced temperature in all the tasks except multiplication, while there were no significant effects of reduced temperatures on the most able pupils.

Although the data were not normally distributed and full independence between dependent variables was not observed, mixed ANOVA and multivariate analyses of the Reading and Comprehension tests was performed. The results of both analysis that can be seen in Appendix 3.4, confirm the results of the Wilcoxon test.

3.4. DISCUSSION

The present results are in agreement with the results of previous studies examining the

TABLE 3.8 Number of exercises skipped by children when performing tasks measuring their abilities to do schoolwork

Test	Day of the week when the test was applied	Thermal conditions in the classroom	Number of skipped exercises	Total number of exercises performed	Chi square test of independence P<
Multiplication	Monday	Normal	7	191	0.835
		Reduced	6	214	
Reading and Comprehension	Tuesday	Normal	3	479	0.308
		Reduced	0	407	
Grammatical reasoning	Wednesday	Normal	4	870	0.874
		Reduced	4	1282	
Reading and Comprehension	Thursday	Normal	2	465	1.0
		Reduced	1	438	
Addition and Subtraction	Friday	Normal	1	227	1.0
		Reduced	2	261	

TABLE 3.9 Results of performance of most able pupils. 25% of worst performers for each classroom and test under normal temperature were chose. Performance under normal and reduced temperature of least able children was compared as in Table 3.7.

Test	Day of the week when the test was applied	Performance Metric	Performance		Fractional change in speed or accuracy per 1°C decrease in temperature	Wilcoxon signed- rank test P<
			Normal	Reduced		
			Mean (SD)	Mean (SD)		
Multiplication	Monday	Attempted units per min	0.23 (0.09)	0.20 (0.10)	-3.0%	0.134
Reading and Comprehension	Tuesday	Attempted units per min	0.74 (0.38)	0.91 (0.64)	4.8%	0.171
Grammatical reasoning	Wednesday	Attempted units per min	5.95 (1.16)	6.23 (2.46)	0.9%	0.282
Reading and Comprehension	Thursday	Attempted units per min	1.16 (0.34)	1.06 (0.66)	1.9%	0.264
Addition and Subtraction	Friday	Attempted units per min	0.56 (0.14)	0.39 (0.21)	5.6%	0.110

TABLE 3.10 Results of performance of least able pupils. 25% of worst performers for each classroom and test under normal temperature were chose. Performance under normal and reduced temperature of least able children was compared as in Table 3.7.

Test	Day of the week when the test was applied	Performance Metric	Performance		Fractional change in speed or accuracy per 1°C decrease in temperature	Wilcoxon signed- rank test P<
			Normal	Reduced		
			Mean (SD)	Mean (SD)		
Multiplication	Monday	Attempted units per min	0	0	0%	-
Reading and Comprehension	Tuesday	Attempted units per min	0.13 (0.07)	0.24 (0.17)	21.7%	0.037
Grammatical reasoning	Wednesday	Attempted units per min	2.18 (0.84)	3.89 (1.33)	15.6%	0.011
Reading and Comprehension	Thursday	Attempted units per min	0.23 (0.23)	0.52 (0.47)	26.7%	0.012
Addition and Subtraction	Friday	Attempted units per min	0.03 (0.06)	0.17 (0.17)	76.9%	0.029

effects of elevated temperatures on the performance of schoolwork (Table 3.2). They show that elevated temperatures should be avoided because abilities that are important for optimal academic performance and learning are negatively affected. The present results extend previous findings to schools located in tropical climates. Improved performance was observed at about 25°C, which is higher than the temperatures at which performance improved in previous studies (Table 3.2).

It is possible that temperatures below 25°C would further improve the performance of schoolwork, but it is also possible that 25°C was too low for optimal performance, so future experiments with tropically acclimatized pupils should examine both of these possibilities. This study was not able to perform these estimations in the present work as only two conditions were tested and we do not know the shape of the dose-response relationship. What can be said for certain is that reducing temperatures below 30°C was beneficial for thermal comfort and the performance of schoolwork.

However, it is plausible that this temperature is close to being optimal for performance considering the results from previous studies (Roelofsen 2001; Kosonen, Tan 2004b; Willem 2006; Jensen, Toftum, Friis-Hansen 2009; Cui, Cao, Park, Ouyang, Zhu 2013; Geng, Ji, Lin, Zhu 2017; Jiang, Wang, Liu, Xu, Liu 2018; Lan, Lian 2009; Lan, Lian, Pan, Ye 2009; Lan, Wargocki, Lian 2011) that showed that optimum performance (in their case for office work) is achieved at temperatures slightly below those at which the thermal sensation is neutral, which was in the present experiment 26.9°C. As shown in Table 3.5 children in the present experiments were on average slightly cold in the reduced temperature condition. A plausible reason for this is that mental work imposes additional cooling requirements not accounted for in the thermal comfort studies that relate metabolic rate to physical activity (Law, Teen-onn; Fay 2009). In another study performed in a laboratory, Lan et. al. (2011) showed that avoiding thermal discomfort improves performance and this may be due to effects on physiological responses. Whether the same mechanisms occurred in the present study or whether the effects were merely due to distraction must be determined in future studies. It should be noted that about 25% of pupils were dissatisfied with the thermal environment in the reduced temperature condition and that this could be due to overcooling (Table 3.5). The present results seem to confirm McIntyre's hypothesis that subjective responses may have a climate-related semantic bias (Kwok 1998).

The improvement in performance was significant for the tasks requiring logical thinking and language skills, but not for the tasks requiring mathematical skills. In the studies summarized in Table 3.2 the performance of both types of task was improved when the temperature was reduced, but the children performed the numerical tasks very poorly under both thermal conditions (Table 3.7) and this has the effect of reducing environmental sensitivity.

The performance of the reading and comprehension task was analysed using the Fisher's method. It assumes that the measurements were independent of each other, while the performance that was compared between conditions was that of the same person. However, in the narrow context of combining P-values by Fisher's method, the important point is that the same hypothesis of better performance at lower classroom temperature was tested twice, each time comparing performance between conditions on the same weekday, using two sets of measurements, i.e. not comparing two days in one condition with one day in the other so that an anomalous value in the latter could affect both p-values. That is all that is meant by "independent" in the present context.

The magnitude of effects on performance per degree Celsius observed in the present study were close to those reported in other studies. Schoer and Shaffran (1973) reported 3.8% higher performance in the multiplication test. Wargocki and Wyon (2007b) found that performance speed increased between 0.5% and 8.9% in 15 of the 16 tests applied. Bakó-Biró et al. (2012) used psychological tests instead of school tasks and reported that performance changed by about 3%. It should be noted that the effects were on speed, not on accuracy, as has been reported many times before, , and that reduced speed of working in experimental exposures has been shown to predict the effect of raised classroom temperatures on learning over long periods as assessed by the results of end-of-year examinations (Park 2016).

Reducing classroom temperature had a significant effect on the performance of the less able children: they improved their performance in all tests except multiplication (Table 3.10). The mean performance of less able pupils at reduced temperatures was close to the mean classroom performance at normal temperatures. The present results imply that improving the indoor environment can be considered as an approach that will reduce inequalities, as the more able pupils have sufficient margins to overcome the negative effects of raised temperatures while the less able pupils do not. A larger negative effect of raised temperature on less able students was implied by the analysis performed by Park (2016) and had been noted by Ryd and Wyon (1970).

Thermal neutrality occurred at 26.9°C, which supports the results obtained by Kwok (1998) in naturally ventilated high-school classrooms in Hawaii, but is lower than the 28.8°C found by Wong and Khoo (2003) in Singapore. Studies performed with adults in tropical climates found that thermal neutrality could occur at temperatures as low as 25°C (Kameni, Tchinda, Orosa 2014) and as high as 28-29°C (de Dear, Leow, Foo 1991). Wong and Khoo (2003) suggested that the difference between thermal responses in Hawaii and Singapore might be due to adaptation: the climate in Hawaii does not have a warm season all year round, so children are not adapted to and do not tolerate as high temperatures. However, this is not the case in Costa Rica, where elevated temperatures are normal throughout the year. A plausible explanation for the lower thermal neutrality obtained in this study is that air conditioners installed in the classrooms during the experiment might have increased the psychological expectation of the children, i.e. that they were disappointed that it was not cooler. Fanger and Toftum (2002) argued that if given an opportunity, people from warm climates will prefer colder environments than the ones they are used to. Lower preferred temperatures could also be because the metabolic rate of the pupils was higher than it is normally assumed to be.

The present results were obtained using a crossover design in two identical and adjacent classrooms of the same school. This design makes it possible to achieve the same statistical power or precision with fewer subjects (pupils) compared with equivalent parallel designs (Piantadosi 2005). This is also the reason why a crossover design was used in many previous experiments examining the effects of classroom conditions on the performance of schoolwork by children; this design was shown in these studies to be sufficiently sensitive to detect differences in cognitive performance as a result of changes in temperature (Table 3.2) and air quality (Bakó-Biró, Clements-Croome, Kochhar, Awbi, Williams 2012; Wargocki, Wyon 2007a, 2007b). In this design each pupil serves as his/her own matched control (Piantadosi 2005). An advantage of the present design was that the tasks were always performed by pupils on the same day of the week and at the same time of day, removing any effect of increasing fatigue during the week or during the day or the effect of gradual improvement (learning) during the course of experiments. Figure 3.10 A and B documents that the effect of learning was negligible in the reading and comprehension test. This was not always the case in previous experiments (Bakó-Biró, Clements-Croome, Kochhar, Awbi, Williams 2012; Wargocki, Wyon 2007b). It should be noted that the effects were observed even though the children were presumably still "alert and fresh" in the morning and it might be expected that the effects would be even stronger if the effects of elevated temperatures had been examined later in the day, as this was found in an early Swedish experiment that specifically included time of day as one of the independent variables (Holmberg, Wyon 1967). The present study was performed at the beginning of a school year; the magnitude of the effects observed here cannot be extrapolated to later months during the school year without verification.

Due to time restrictions, there was no training week at the beginning of the experiment. Instead, before each task the teachers showed pupils how to perform the tasks using the examples provided. However, additional analyses (Figures 3.10 A and B) did not show any significant differences in performance of the tasks between classrooms and there was no

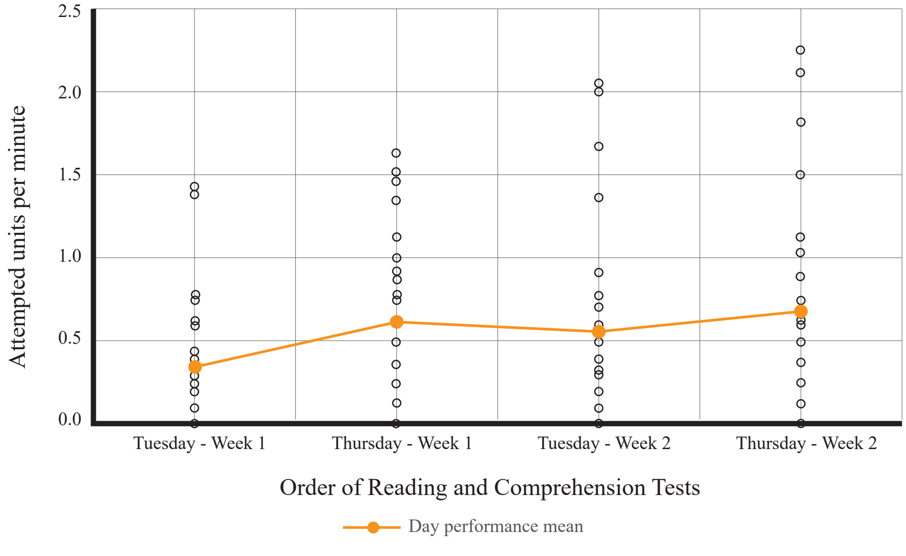


FIGURE 3.10 A. Changes in the mean attempted units per minute (speed) of Reading and Comprehension tests independently of condition during the experiment.

gradual change in performance with time in the course of the experiments, independently of the conditions established in the classrooms.

CO_2 concentration was about 60 to 230 ppm higher under the reduced temperature conditions. This indicates that the windows and door were open less frequently than under the normal temperature conditions (as shown by Wyon and Wargocki (2008) and Wargocki and Da Silva (2015)). This difference can probably be neglected, as the absolute concentration of CO_2 was 800 ppm and below, i.e. the classrooms were sufficiently ventilated and the air quality was at an acceptable level under both conditions. If anything, the observed increase in CO_2 level might have biased the results obtained at reduced temperature towards the null hypothesis by reducing the positive effect of reduced temperature, considering that other studies (Wargocki, Wyon 2007a; Bakó-Biró, Clements-Croome, Kochhar, Awbi, Williams 2012; Wargocki, Wyon 2007b) have shown that poor air quality has a negative effect on the performance of schoolwork by children.

In the reduced temperature condition, the cooling effect of operating a split-cooling air conditioner cannot have escaped the attention of the pupils. It might be that some effects on performance could have been caused by a spontaneously positive response to an air conditioner being in operation. This can only be ruled out if a similar experiment is conducted over an extended period of time to determine whether the observed effects on performance are sustained.

The present results suggest that cooling classrooms might yield significant economic benefits. However, they require verification in other schools and with other pupils.

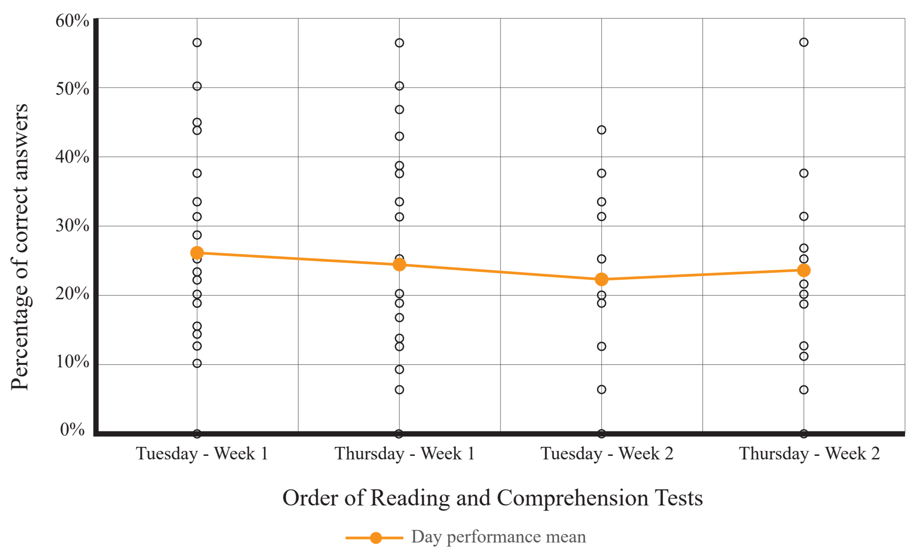


FIGURE 3.10. **B.** Changes in the mean percentage of correct answers (accuracy) of Reading and Comprehension tests independently of condition during the experiment

Additional studies could provide school authorities and decision makers with an empirical basis for the standards and guidelines that are required to ensure optimal learning conditions in schools located in tropical climates. Most of the schools in the tropics are in countries with developing economies, so if temperatures in schools are too high the children attending them must overcome even more difficulties than their counterparts in the developed parts of the world. Poor classroom conditions may be regarded as an additional factor that contributes to social inequality both nationally and worldwide.

Further studies are required to validate the present results. These studies should also examine whether long-term exposure to reduced classroom temperatures in tropical climates would provide any measurable benefit for other learning outcomes, including end-of-year examination results and national tests. They should also identify the optimal classroom temperature for learning, as this was not determined in the present experiment.

The design of schools must take into account the thermal environment in classrooms in order to create an optimal teaching environment. Given the influence that a building has on indoor thermal conditions, additional studies should be conducted to identify solutions capable of providing an optimal thermal environment for learning in the tropics.

3.4.1 Defining a maximum classroom temperature limit for learning

The experiment presented in this chapter was designed to determine whether the null

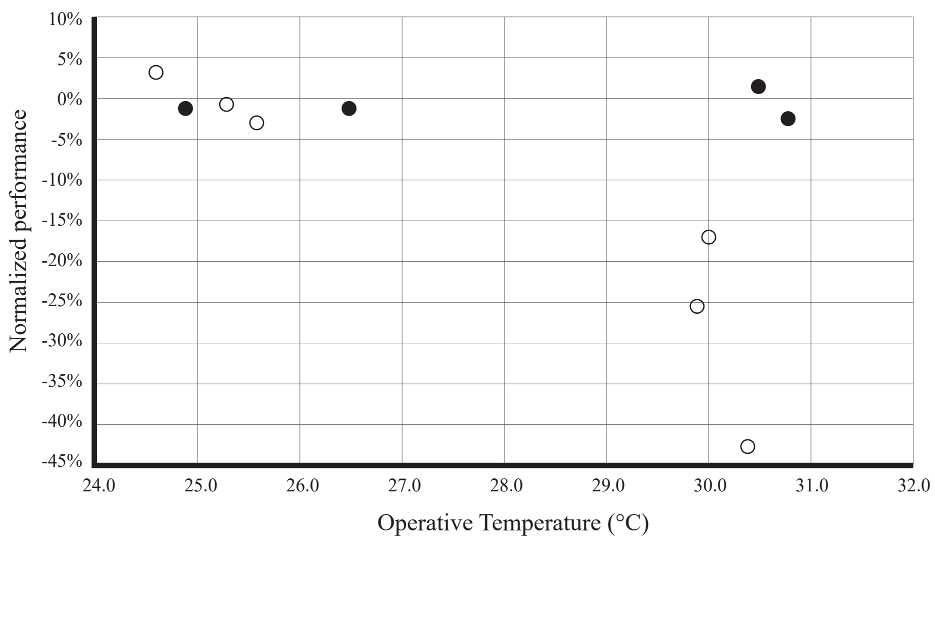


FIGURE 3.11 **A.** Performance of schoolwork as a function of classroom temperature. Performance is expressed in terms of speed. Dots show performance of individual tasks. Open dots indicate those tasks in which performance differed significantly between conditions.

hypothesis of no effect of temperature on school performance was true. Results show that it can be rejected at the P<0.05 level, i.e. that reducing normal classroom temperatures to 25°C improves the children's schoolwork performance (Figures 3.11 A and B). However, it was not possible to conclude which was the optimal temperature for learning because pupil's performance was tested at only two temperatures, so the shape of an empirical dose-response relationship could not be defined. Therefore from the experiment, is not possible to know if the optimal temperature is higher or lower than 25°C or if it is exactly 25°C. What it is known is that it is below 30°C.

Wargocki and Wyon (2013) proposed an empirical dose-response relationship between performance at school work and classroom temperature. A linear regression was fitted for the range of studied temperatures, between 20°C and 25°C. Figure 3.12 A and B shows that reducing classroom air temperature by 1°C would improve performance in terms of speed by about 2%. There was no improvement in terms of accuracy. Results from the curve proposed in Chapter 2 (Figure 2.2) shows that reducing temperature by 3K from 26oC to 23oC the speed performance is expected to increase by 10%. In this case the shape of the curve was not linear, perhaps because of the wider range of temperatures, tending to decrease faster at lower temperatures, while at high temperatures the fractional decrement is smaller. However as it was said before, this curves were done based on studies with moderate climate subjects, and cannot be used to infer the shape that the curve would have in the tropical climates.

The studies that had recently examined the effects of subjects thermal sensation votes on office work performance in tropical climates (Willem 2006) and school and office work

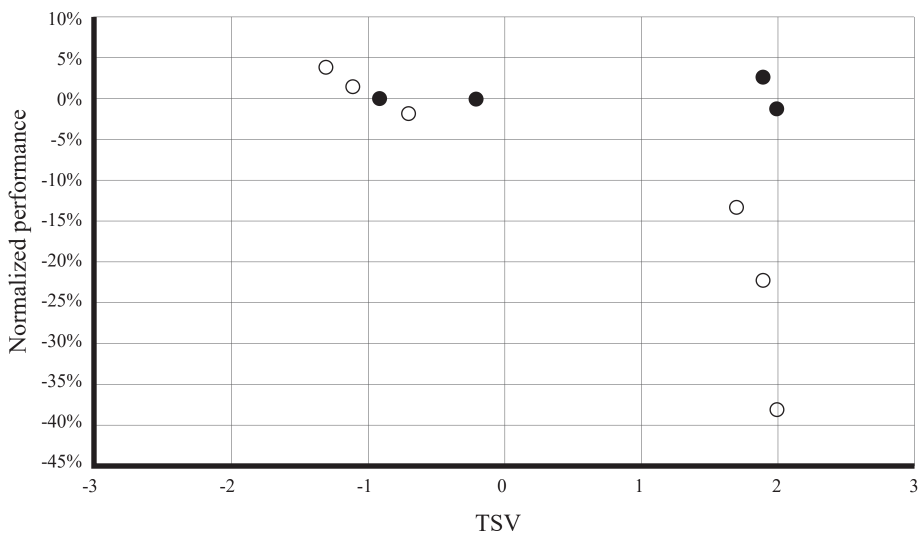
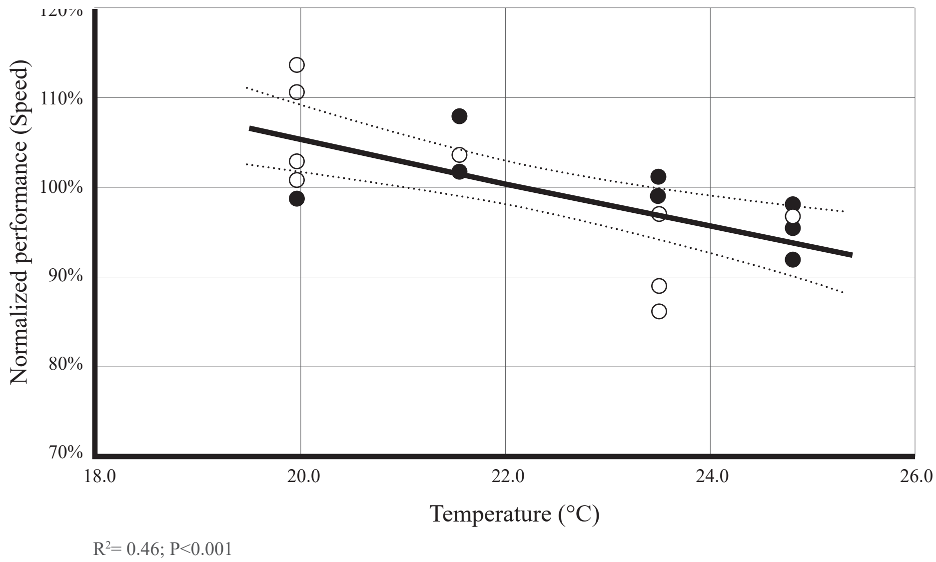


FIGURE 3.11. B. Performance of schoolwork as a function of the children's thermal sensation. Performance is expressed in terms of speed. Dots show performance of individual tasks. Open dots indicate those tasks in which performance differed significantly between conditions.



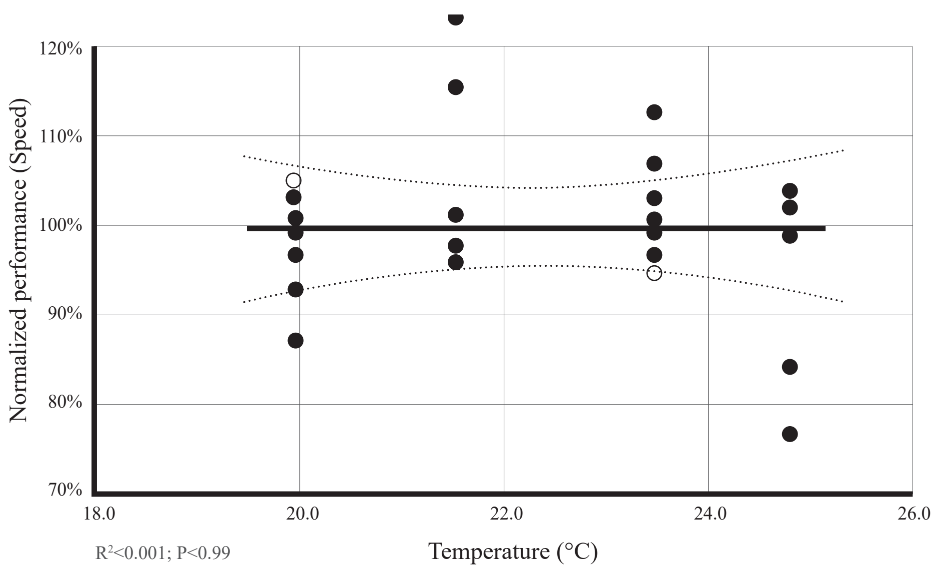


FIGURE 3.12 Performance of schoolwork as a function of classroom temperature. Performance is expressed in terms of the speed at which tasks were performed (top) and the percentage of errors committed (bottom); dots show performance of individual tasks (open dots indicate those tasks in which performance differed significantly between conditions) while lines show the regression (solid line) with 95% confidence bands (dashed line). Retrieved from Wargocki and Wyon 2013

performance in moderate climates (Lan, Wargocki, Lian 2011; Jiang, Wang, Liu, Xu, Liu 2018; Kosonen, Tan 2004b; Jensen, Toftum, Friis-Hansen 2009) show that the maximum performance is achieved when occupants feel the thermal environment between neutral (0) and slightly cool (-1) according to the ASHRAE's seven- point scale. Main studies are listed in Table 3.11 and summarized in below.

Roelofsen (2001) related the loss in performance with PMV using the data of Berglund (et al. (1990) and Loveday et al. (1995). The relationship exhibit an optimum relative performance between -0.5 to 0 on the seven- point ASHRAE scale. Kosonen and Tan (2004b) performed a theoretical study using Wyon's studies. Authors found that for thinking and typing the peak level of productivity occurs when the PMV value is −0.21. Willem (2006) carried out an experiment with 313 Singaporean adults from 3 air-conditioned call centers. The study intercalated temperatures of 22.5 and 24.5°C for nine weeks. Talk time from incoming calls and the number of concluded calls was used as performance measure. The preferred room air temperature was between neutral and slightly cool. Jensen et al. (2009) derived on the other hand the relationship between thermal sensation votes and performance (Figure 1); they adopted the Bayesian model taking into account probabilistic distribution of different factors influencing thermal sensation and used the data on performance of addition task (a component skill used to simulate office work) from several laboratory and field experiments when creating their relationship.(Lan, Wargocki, Lian 2012).

Lan et al. (2011) used data from their own laboratory experiments (Lan, Lian, Pan, Ye 2009; Lan, Wargocki, Wyon, Lian 2011; Lan, Lian 2009), where 21, 24 and 12 moderate climate subjects performed neurobehavioral tests and simulated office work at different temperatures. Results show that optimum performance for office work is achieved at about -0.25. Cui et al. (2013) recruited 36 university students and exposed a half of them to five different temperatures (22°C, 24°C, 26°C, 29°C, 32°C) and the other half to 26°C only, in a climate chamber. Memory typing and the number of correct letters was used to

TABLE 3.11 Summary of studies reporting the relationship between thermal sensation with occupant performance

Study	Location	Subjects		Thermal sensation were optimum performance is achieved
		Number	Age	
Roelofsen, 2001	NA	NA	NA	From -0.5 to 0
Kosonen and Tan, 2004	NA	NA	NA	-0.21
(3) Willem, 2006	Singapore	N: 313	13	From -1 to 0
(1)(3) Jensen, Toftum and Friis-Hansen, 2009	NA	N: 339	NA	From -1 to 0
(1) Lan and Lian, 2009	China	N: 21	19 (±1)	-0.25
(1) Lan et al., 2009	China	N: 24	25 (±3)	From -1 to 0
(1) Lan et al., 2011	Denmark	N: 12	23 (±2)	-0.25
(2) Cui et al. , 2013	China	N: 21	22.3	0.14
(1) Geng et al., 2017	China	N: 36	21.7 (±2.6)	From -1 to 0
(1) Jiang et al., 2018	China	N: 12	12.5 (±0.7)	-1.4

(1) Controlled environment (2) Climate chamber (3) Field studies

evaluate performance and a seven- point scale was used to evaluate working motivation. The optimum thermal sensation vote for performance was 0.14. Geng et al. (2017) carried out 7 groups of experiments in a controlled office environment in China. Nine females and 12 males, all adults, participated in the experiment. Subjective surveys and productivity tests were applied under different air temperatures ranging from 16°C to 28°C. The optimal productivity was obtained when people felt "neutral" or "slightly cool". Recently, Jiang et al. exposed 6 pairs of 12-year-old Chinese pupils to 6 different temperatures (10°C, 14°C, 15°C, 16°C, 18°C, and 20°C) in a climate chamber using a balanced Latin-square design (Jiang, Wang, Liu, Xu, Liu 2018). Children's clothing insulation was 1.5 clo and ten tests were applied to evaluate their performance. Optimal learning performance was obtained when the thermal sensation votes were -1.4.

It can be seen in all of these studies that there exists thermal sensation for optimal performance: there is a negatively affection of performance when occupants feel too cold or too warm (Lan, Wargocki, Lian 2012). However, Lan, Wargocki and Lian (2012) and Jiang et al. (2018), through summary of the studies carried out, showed that this effects are not symmetrical around thermal neutrality and they are somewhat skewed towards slightly cool sensation. This shift to the cold side can be seen in Figure 3.13, retrieved from the publication of Jiang et al. (2018).

The experiment developed in this chapter came to similar results: maximum performance was achieved when the pupils felt between neutral (-0.2) and slightly cool (-1.4). Thus, it is plausible that the optimum schoolwork performance in the tropics will be achieved at this thermal sensation range, meaning that temperatures above what is neutral to heat balance

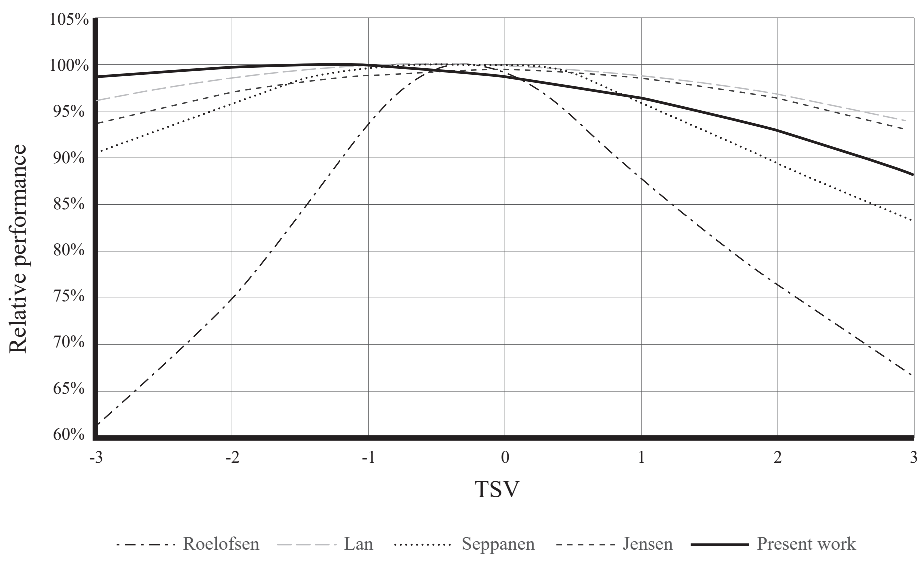


FIGURE 3.13 Comparison of the relationships between relative performance and TSVs proposed by different studies: Roelofsen 2001; Seppanen et al. 2006; Jensen et al. 2009; Lan et al. 2011; and Jiang et al. 2018. Retrieved from Jiang et al., 2018.

will have negative effects on the performance of schoolwork. Therefore, the maximum classroom temperature limit for learning, which will be called in this thesis To-max, was defined according to the equation 3.1.

$$T_{o\text{-}max} = T_n \quad (3.1)$$

3.5. CONCLUSIONS

- The results show that there was an improvement in the performance of schoolwork by tropically acclimatized children when normal classroom temperatures were reduced from 30°C to 25°C.
- Reduced temperature improved the performance of logical reasoning and reading and comprehension tasks for all pupils and the performance of all tasks for less able pupils.
- The speed at which the tests were performed was improved but there were no significant effects on accuracy.
- The less able pupils derived more benefit from the reduced temperatures.
- At 25°C pupils reported that their thermal sensation was neutral to slightly cold.
- The maximum classroom temperature limit for learning ($T_{o\text{-}max}$) was defined as equal to the neutral temperature (T_n)

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4. PROVIDING CLASSROOMS IN THE TROPICAL CLIMATES WITH AN OPTIMAL THERMAL ENVIRONMENT FOR LEARNING? A CASE STUDY

4.1. INTRODUCTION

The thermal environment of classrooms has a significant impact on school performance and children's health (Wargocki, Wyon 2007b, 2013). Studies that have examined the effects of thermal conditions on schoolwork and office work performance in moderate climates (Lan, Wargocki, Lian 2011; Jiang, Wang, Liu, Xu, Liu 2018; Kosonen, Tan 2004b; Jensen, Toftum, Friis-Hansen 2009) and office work performance in tropical climates (Willem 2006) show that the maximum performance is achieved when occupants feel a thermal environment between neutral (0) and slightly cool (-1) according to the ASHRAE's seven-point scale. The main studies are listed in Table 3.11.

The field intervention study performed with tropically acclimatized school children in **Chapter 3** reached similar conclusions: Maximum performance was achieved when pupils felt between neutral (-0.2) and slightly cool (-1.4), and even though additional studies should be performed to validate the results, it is plausible that the optimum schoolwork performance in the Tropics will be achieved within this thermal sensation range. Thus, it shows that temperatures above what is neutral to heat balance will have negative effects on the performance of schoolwork.

Warm humid climates are characterized by a combination of high temperatures, high humidity, and abundant rainfall (Givoni 1994). Seasonal variations throughout the year are scarce, the only one corresponding to periods of more or less rain. Air temperature during the day reaches maximum average values that range from 27°C to 32°C, and rarely exceeds the upper skin temperature (34°C). Annual and daily temperature fluctuations are very narrow, sometimes as low as 5°C, and rarely exceed 12°C; and relative humidity ranges between 50% to 100% throughout the year.

Nearly 40% of the world's population live in the Tropics, where warm humid climatic conditions prevail. Most of the countries located on this region have developing economies that do not allow them to provide mechanical cooling in public elementary schools; therefore, children and teachers depend on passive or low energy consuming cooling strategies to achieve optimal thermal conditions.

As a result, elementary schools in the tropical climates have traditionally been low-mass (light structure) naturally ventilated buildings. Elongated building plans with wide openings on opposite walls facilitate cross ventilation and pitched roofs with large overhanging eaves remove the abundant rain quickly, while protecting the interior and external walls from direct sun radiation (Szokolay 2006, 2004; Sevilla, Sanabria, Shedden 2010; ABNT 2003; Koenigsberger, Ingersoll, Mayhew, Szokolay 1977) (photographs of schools). The aim is to keep the internal temperature as near as possible to the outside air temperature (Szokolay 2004). These designs have the advantage of using little energy during the building operation phase and consequently GHG emissions are also low. However, how effective these design strategies are in providing optimal thermal environment for learning it is not that clear.

The purpose of this research was to study whether traditional lightweight construction classrooms with only window openings are able to provide pupils with an optimal thermal environment for learning in the tropics. A school located in Costa Rica was used as a case study.

Closing this gap will give school authorities, decision-makers and researchers the knowledge about how tropical school classrooms are performing thermally and whether additional studies should be conducted to identify solutions that are capable of providing children with a proper teaching environment. This will provide the empirical basis for the standards and guidelines required to ensure optimal learning conditions in tropical climates.

4.2. CASE STUDY INFORMATION

4.2.1 Weather/ climate description

According to the Köppen-Geiger Climate Classification, the climate of the case study site corresponds to Tropical Savana Climate (Aw) (Peel, Finlayson, Mcmahon 2007), and according to the Costa Rican National Meteorology Institute (IMN), the area is located in the North Pacific Zone, Subregion 2 (PN2) which is characterized by a dry climate (Solano, Villalobos 2001). For further details please refer to **Chapter 3**.

4.2.2 School building and classrooms

The school building chosen for the case study is the same as the one used in **Chapter 3** to perform the experiments. It was located in a small country town in the north-western region of Costa Rica, approximately 10 km west of the city of Cañas. The building was at the confluence of two rivers, 15 meters above sea level, and mostly surrounded by sugarcane

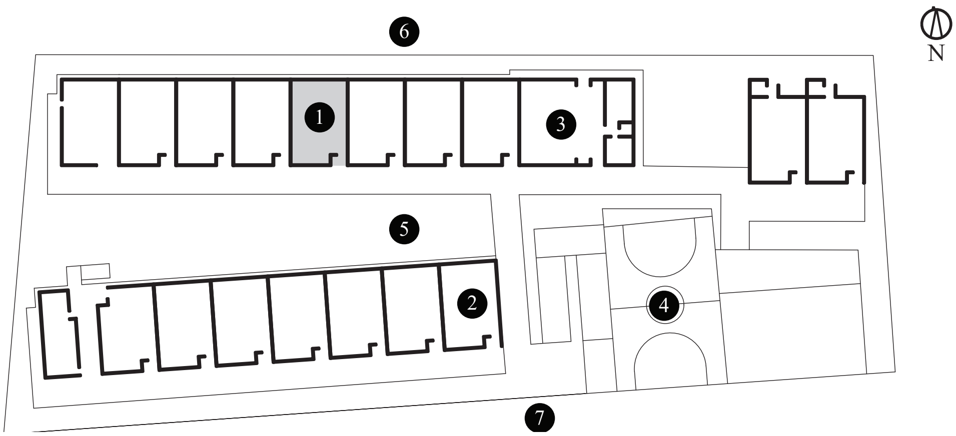


FIGURE 4.1 The school. Floor plan (1) Classroom 1, (2) Principal's and teacher's office, (3) Dining hall, (4) Roofed basketball courtyard, (5) Courtyard, (6) Football field, (7) Main Street entrance.

fields. It is a public elementary school run by the Costa Rican Ministry of Public Education (MEP) for children aged between 5 and 12.

This single-storey 1500 m^2 school has two wings connected by an open corridor. It was constructed in 2007 in a single stage and houses 13 classrooms for regular and complementary courses, a dining hall, a computer laboratory, a library, offices for the Principal and for the teachers, a roofed basketball courtyard and toilets for children and teachers (Figure 4.1). The whole site, except the basketball courtyard, was raised one meter above street level before construction, to protect it against flooding from nearby rivers.

Except for the computer laboratory, where a split-cooling air conditioning (AC) unit was installed, there is no mechanical ventilation, and no mechanical cooling or heating system in the other spaces in the school. To avoid overheating, two ceiling fans had been installed in each of the classrooms and offices.

The building selection criteria was the location, in a warm-humid climate; the characteristics of the building, low-mass naturally ventilated; the building condition and age, recently built and in good condition; and that it was built using an architectural prototype and a construction system that had been widely employed in other Costa Rican public schools.

A single regular classroom located in the centre of the North building was used for this study (Figure 4.2). The classroom had a floor size of 6 x 9 m (54 m^2), and a volume of 160 m3. Considering 2 m^2 per child, its design was for 27 pupils.

For further information and construction details, please refer to **Chapter 3**, Sections 3.2.2

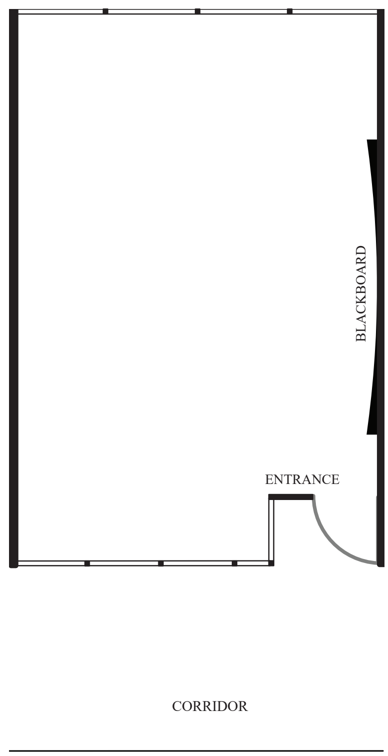


FIGURE 4.2 Floor plan of the classroom.

and 3.2.3.

4.2.3 School building adaptation to warm-humid climatic thermal conditions

Eighteen architectural solutions looking to adapt the Case Study school building to the site's thermal conditions were identified in the chosen case study school building. The description and image method was used (Nguyen, Tran, Tran, Reiter 2011). The solutions adopted in the design and construction phases encompass all the main climatic strategies for warm-humid regions recommended by the literature (Nguyen, Tran, Tran, Reiter 2011; Koenigsberger, Ingersoll, Mayhew, Szokolay 1977; Szokolay 1997, 2004). Therefore, to a certain extent, the building is adapted to the site's thermal conditions. Table 4.1 shows the architectural solutions found. They are classified according to Nguyen et al's. (2011) list of design guidelines for the tropics.

4.3. METHODS

4.3.1 Exceedance Hours method (EH) and the CIBSE TM52 criteria

The number of school year hours where the operative temperature of the selected classroom was above the upper defined limit ($T_{o\text{-}max}$) were estimated using the Exceedance Hours (EH) method, included in ASHRAE's 55-2013 standard (ANSI/ASHRAE 2013). The EH can be defined as the number of occupied hours within a time period where the thermal conditions of an indoor space are above a reference temperature (Equation 4.1). The number of EH accumulated in a year were used in this study as an indicator to evaluate how far the classroom's thermal environment is from the optimal thermal conditions for learning. The concept is similar to the Cooling Degrees Days (CDD); however, it is not an energy consumption proxy.

(4.1) $$EH = \Sigma\,(H > T_{o\text{-}max})$$

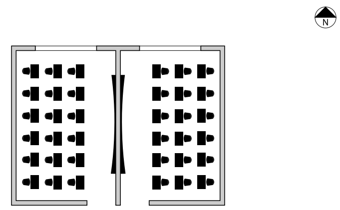
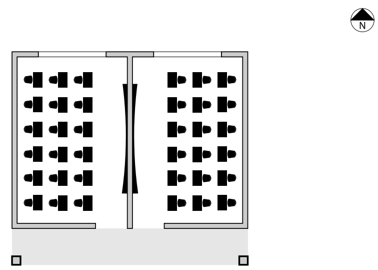
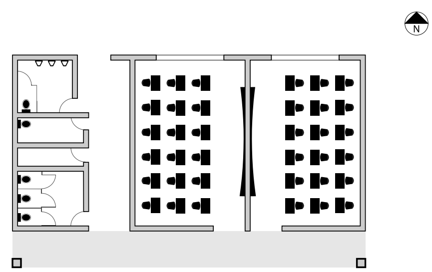
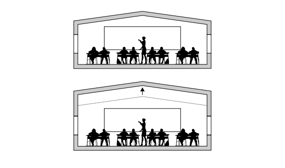
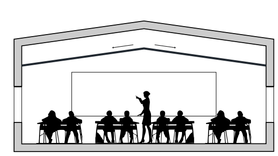
The other indicators used were the ones included in the CIBSE Technical Memorandum 52 which establishes the criteria for defining overheating that can be applied to European natural ventilated buildings (Nicol, Spires 2013). No similar standard is available for Costa Rica.

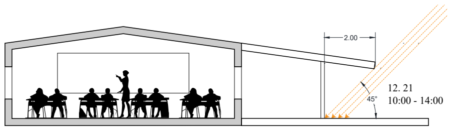
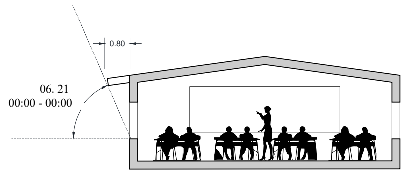
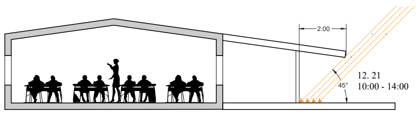
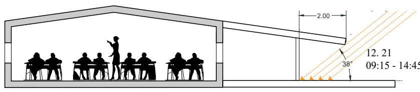
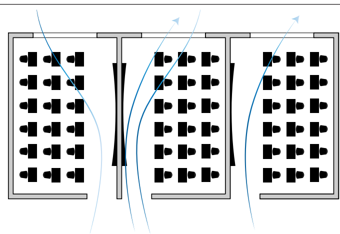
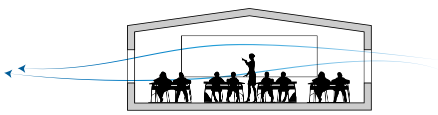
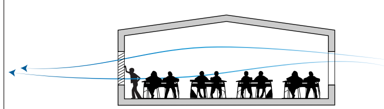
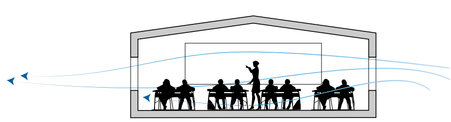
According to the CIBSE TM52, if the classroom fails any two of the following three criteria, then this is classed as overheating:

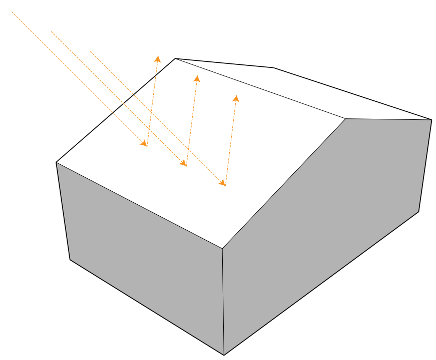
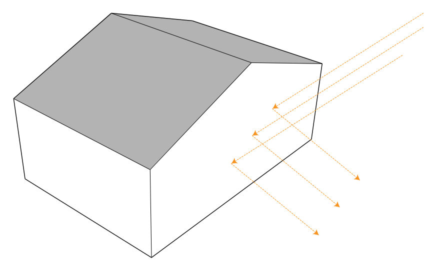
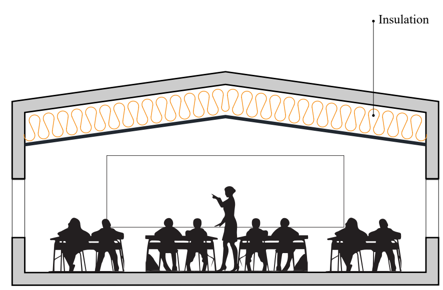
- (1) The percentage of Hours of Exceedance (H_e) where ΔT is greater than or equal to 1K shall be no greater than 3% during the occupied hours of a typical non-heating season (May 1st to September 30th, 5 months). Because high temperatures are common in warm-humid climates, it was considered that the non-heating season covers the entire year (January 1st to December 31st, 12 months). To estimate the H_e, equation 4.2 should be used.

(4.2) $$H_e = \Sigma\,(H > T_{o\text{-}max} + 1K)$$

TABLE 4.1 Architectural solutions by which the Case Study school building's design and construction have been adapted to the site's thermal conditions

Design guidelines	Architectural solutions	
Building orientation and shape	Elongated building shape with unilateral orientation where all the living areas are facing North to avoid direct solar radiation on main facades	
	Corridors and deep eaves protect the South façade from direct sunlight	
	Room arrangement: Toilets facing West and corridors facing South to protect classrooms from direct sun	
	Room height (30cm higher in warmer regions of Costa Rica) increases the indoor volume of air and separates the ceiling, normally warmer, from occupants	
	Pitched ceiling increases the indoor volume of air and separates ceiling from users	

Solar shading	The south façade is shaded all the time by the corridor roof that is 3.6 meter wide	
	Eaves (0.8m) protect the North façade from direct sunlight from during the time that the sun shines from the northern hemisphere (End of April to Mid-August).	
	Height of the front roof is minimized, producing an effective solar shading solution	 
Natural ventilation	Building shape with unilateral orientation, rooms in one row and narrow living spaces enhance cross ventilation	
	Open interior space with no partitions allows good ventilation	
	Large openings on opposite walls enhance natural ventilation. 36% of North and 25% of East façades are made of glass louvers that can be opened by occupants	
	Openings located at body level enhance the apparent cooling effect of air movement	

Light weight construction	Light weight construction using low thermal capacity materials	14. Light weight construction using low rec
Passive cooling by using color	Minimization of heat absorption by painting the roof white, which is a highly reflecting color.	
	Minimization of heat absorption by painting the façades in light, highly reflective colors	 16. Minimization of heat absorption by painting the facades in light colors with a high reflection XXX
Thermal insulation by material	Insulated roof: 5 mm of expanded polystyrene covered by a reflective surface	

- (2) The second criterion establishes a daily limit of acceptability. The Daily Weighted Exceedance (W_e) is the summation of all the exceeding degrees within the daily school hours. The objective is to measure the severity of the overheating within one day. This criterion sets that the maximum We shall be no more than 6 K. The estimation of We can be made using equation 4.3.

(4.3) $$W_e = (\Sigma H_e) \text{ X } WF$$

Where the weighting factor WF = 0 if $\Delta T \leq 0$, otherwise, WF = ΔT.

- (3) The Upper Limit Temperature (T_{upp}) sets an absolute maximum daily temperature for a room. Above this temperature, the level of overheating is unacceptable. To accomplish/fulfill this criterion, classroom temperature shall not exceed 4 K, the defined upper limit.

(4.4) $$T_{upp} = T_o - T_{o\text{-}max}$$

ASHRAE's Exceedance Hours (EH) should not be confused with the CIBSE TM52 Hours of Exceedance (H_e). The former is defined as the number of hours in which the thermal conditions of the classroom are above a reference temperature. While the second corresponds to numbers of hours when the classroom's temperature is 1 K or more over the reference temperature. In both, the measurement is made within the occupation period only.

4.3.2 Classroom's upper temperature limit ($T_{o\text{-}max}$)

The upper operative temperature limit (To-max) was estimated using the results of the field intervention study described in Chapter 3 and a wide body of literature which shows that temperatures above what is neutral for heat balance should be avoided because they have negative effects on schoolwork performance. Therefore, the classroom's maximum operative temperature ($T_{o\text{-}max}$) may not exceed the temperature where children feel neutral.

(4.5) $$T_{o\text{-}max} = T_n$$

ASHRAE's adaptive comfort model was applied as a rational basis (ANSI/ASHRAE 2013) and de Dear and Brager's (1998) formula was used to estimate the neutral temperature (Equation 4.6). It is known that ASHRAE's adaptive comfort model is based on adults' thermal responses and children might prefer cooler environments (Montazami, Gaterell, Nicol, Lumley, Thoua 2017; Trebilcock, Soto-Muñoz, Yañez, Figueroa-San Martin 2017; Teli, Jentsch, James 2012); however, a model considering children's thermal preferences has not been yet developed.

(4.6) $$T_n = 0.31\, T_{pma\ (out)} + 17.8$$

Different calculation methods, the number of sequential days prior to the day in question and exponential values were tested to estimate the prevailing mean outdoor temperature ($T_{pma\ (out)}$). Figure 4.3 shows that all the tested methods produce similar results; however, the exponentially weighted running mean method with α set to 0.8 and twenty sequential

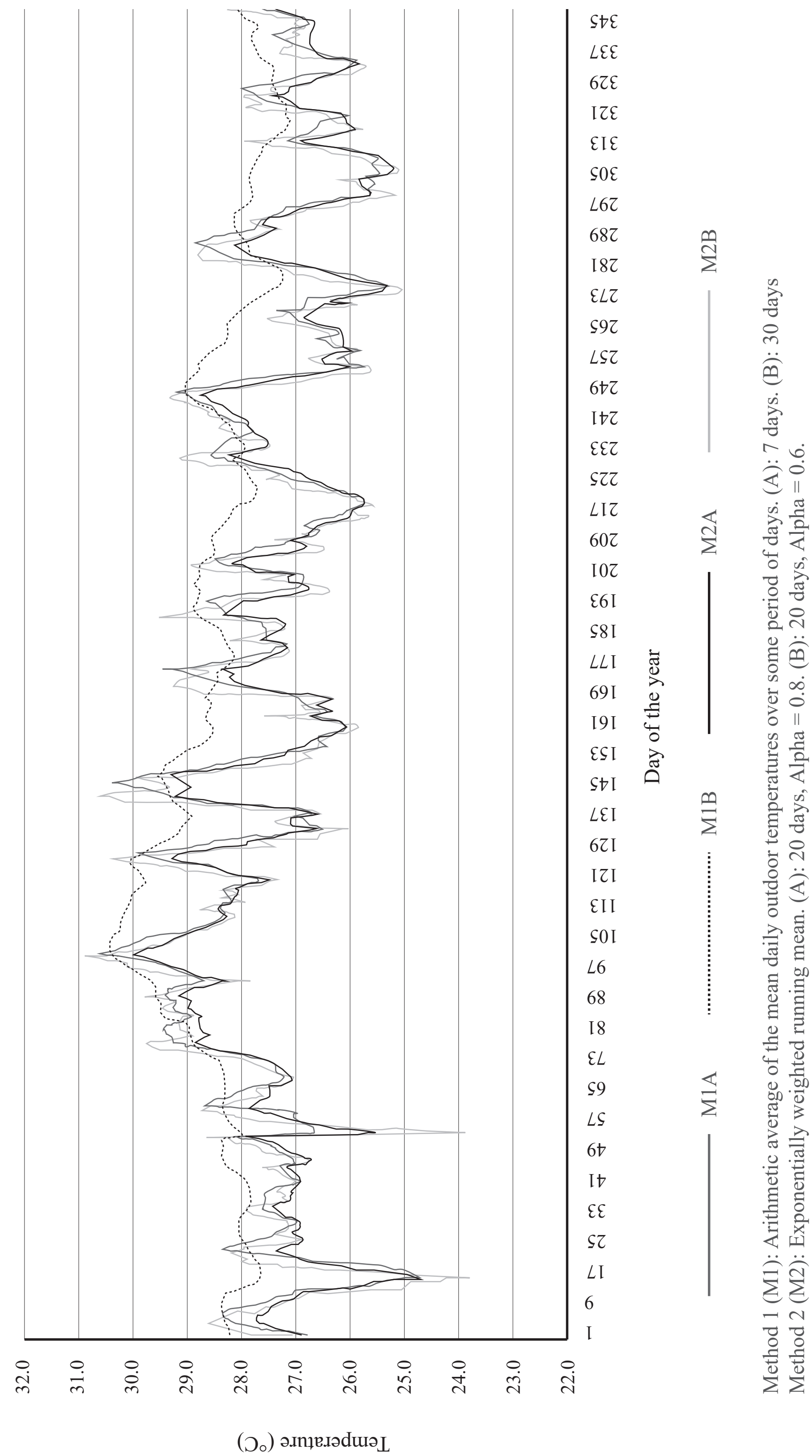


FIGURE 4.3 Estimation of the prevailing mean outdoor temperature $T_{pma\ (out)}$ for different calculation methods

days before the day in question, provides a conservative scenario that dampens temperature peaks. The number of days prior to the day in question avoids residual losses (de Vecchi, Sorgato, Cândido, Lamberts 2014) while a high α provides a slow response running mean, which is suggested by adaptive comfort theory as being more appropriate for climates where day-to-day temperature dynamics are relatively minor, such as in the humid tropics (ANSI/ASHRAE 2013).

Therefore, the classroom's maximum operative temperature was estimated using the following model:

$$T_{o\text{-}max} = 0.31\ T_{pma\ (out)} + 17.8 \qquad (4.7)$$

4.3.3 Meteorological data

A Typical Meteorological Year (TMY) for the Case Study location (10°22 N, 85°11 W) was generated by Meteonorm 7.0, interpolating the surrounding weather stations. Finally, hourly weather data file was exported using the Energy Plus Weather (epw) format.

Figure 4.4 shows that the monthly maximum and minimum averages of air temperature from the resulting file are similar to the ones registered by the local weather station, Taboga Ingenio No. 76041, between 1984 and 2007.

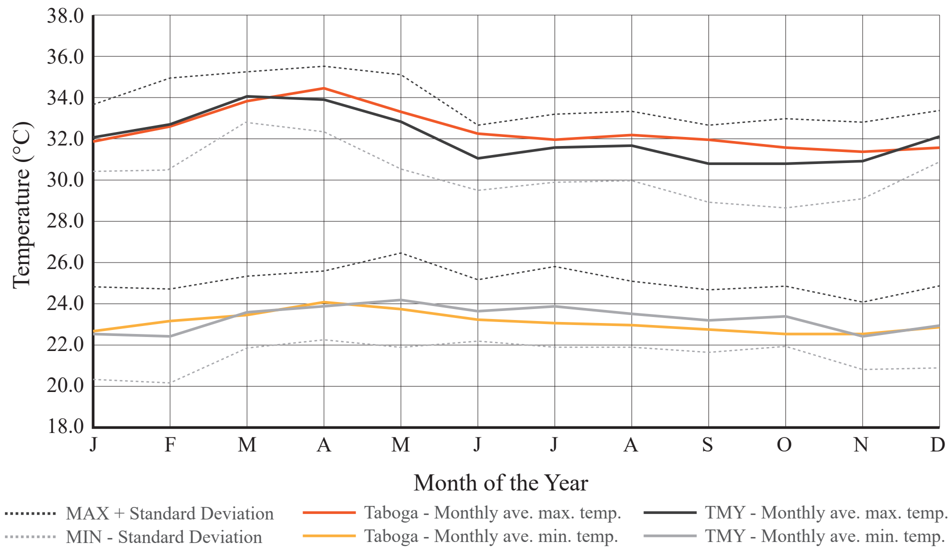


FIGURE 4.4 Comparison of the monthly average maximum and minimum air temperatures between the TMY developed for the Case Study location and a nearby weather station from the National Institute of Meteorology of Costa Rica (IMN): Taboga Ingenio No. 76041.

4.3.4 Classroom's thermal environment

The classroom's indoor thermal conditions were estimated using two approaches: a simplified method and a computational simulation method for validation purposes. Operative temperature was used as a proxy of the indoor thermal conditions.

4.3.4.1 Method 1: Simplified approach

The simplified approach is based on the argument that in tropical buildings, due to lightweight construction, walls and roofs have low thermal capacity and are not able to dampen the amplitude of the thermal wave, or delay it. During daytime hours when buildings are cross-ventilated, the indoor temperature tends to follow the outdoor pattern (Givoni 1994) and the inner surface temperatures of walls and roofs tend to stabilize at the same value as the air temperature (Koenigsberger, Ingersoll, Mayhew, Szokolay 1977). Thus, the indoor temperature cannot be cooler than the outside air (Szokolay 2006). This was corroborated by Mallick (1996), who showed that at high air velocities (0.45 m/s or above), the indoor globe and air temperature in lightweight construction tropical buildings tend to be similar. The same hypothetical situation was assumed by de Vecchi et al. (2014) when estimating the indoor temperatures for buildings located in two Brazilian cities.

Therefore, first of all, it was assumed that the classrooms' operative temperature was equal to the outdoor air temperature ($T_o = T_{out}$). Thus, the dry bulb air temperature data of the interpolated Typical Meteorological Year (TMY) was used as an estimation of the indoor operative temperature. However, a three-month monitoring period performed in the case study's classrooms showed that the temperatures recorded inside were lower than the ones recorded outside, and that this difference followed a daily pattern (Appendix 4.1).

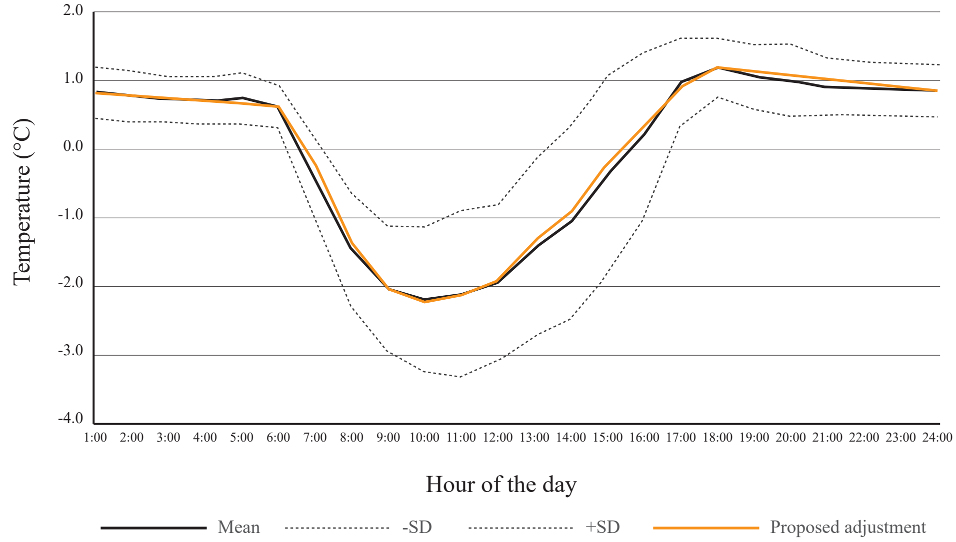


FIGURE 4.5 Air temperature differences between outdoor and indoor conditions. Estimated by averaging 30-minute interval temperature records from September 9th 2016 to December 9th 2016

Therefore, a correction was introduced to the TMY dry bulb temperatures using Equation 4.8.

$$T_o = T_{out} \pm T_{corr} \quad (4.8)$$

Where Tcorr is a temperature correction in degrees Celsius. The correction temperature was estimated for each hour, averaging the hourly air temperature difference between the outdoor and indoor conditions recorded (Figure 4.5).

4.3.4.2 Method 2: Computational simulation approach

The classroom's operative temperature was also estimated using a computational simulation model. The thermal behavior of the classroom was simulated for a whole year using the software, Design Builder version v5.3.0.14, which uses Energy Plus 6.0 for its calculations.

A single classroom in the center of the North wing was chosen and modelled (Figure 4.2). The side walls and ground floor were considered adiabatic. The corridor that runs in front of the classrooms was excluded from the analysis. However, overhangs and the corridor's roof were included as shading structures. The interpolated TMY was used as the simulation weather file. The model's main settings are presented in Table 4.2 and the

TABLE 4.2 Model's main settings

Setting		Details
Occupation density	0.37 persons/m^2	19 children + 1 adult divided by the classroom area (54m^2)
Schedule	7 a.m. to 5 p.m.	According to the official school calendar
Metabolic activity	Light office work/ Standing/ Walking	Light office work multiplied by a factor of 0.75 which corresponds to children
Clothing	0.5 clo	Estimation based on the field study performed in **Chapter 3**. Winter and summer.

TABLE 4.3 Thermal characteristics of the school classroom's enclosure

Roof						
Simple composition	Ep	λ	D	Cp	U	R
Corrugated metal sheets	0.04	113	7000	390	2.11	0.48
Expanded polystyrene	0.5	0.04	15	1400		
Air gap	15					
PVC clapboards	0.8	0.16	1380	1000		
Floor						
Simple composition	Ep	λ	D	Cp	U	R
Concrete floor	20	1.4	2100	840	2.83	0.35
Walls						
Simple composition	Ep	λ	D	Cp	U	R
Cast concrete walls	5	1.3	2000	840	3.24	0.31

Ep: Thickness - cm
Λ: Conductivity - W/(m K)
D: Density - kg/m^3
Cp: Specific heat capacity - Wh/(kg K)
U: Coefficient of surface transmission - W/(m^2.K)
R: Thermal resistance - (m^2.K)/W

material description for the selected classroom can be found in Table 4.3.

The simulation model was validated using ASHRAE Guideline 14 (ANSI/ASHRAE 2014), which is one of the most widespread validation processes (Royapoor, Roskilly 2015). The hourly temperature data, following the guideline, was used for calibration. Simulated and measured dry bulb temperature for indoor and outdoor conditions were compared. ASHRAE Guideline 14 considers a model as validated if it has a Mean Bias Error (MBE) that is not larger than 10%, and the Variation Coefficient of the Root Mean Square Error (CV(RMSE)) is not greater than 30%.

The data measured was recorded during 2016. The air temperature was recorded at 10-minute intervals in two identical classrooms of the chosen school building with four HOBO data loggers, U12-012 (± 0.35°C) model. Indoor temperature was monitored for three months between September 9th 2016 and December 9th 2016 for a total of 2192 hours of monitoring, approximately 25% of the hours of 2016. While outdoor temperature was monitored for 7266 hours (September 9th 2016 to February 7th 2017, and February 21st 2017 to July 22nd 2017).

Table 4.4 shows that both values fall below the 10% recommendation for hourly comparisons. In this case, MBE is 0.81% indoors and 2.47% outdoors. CV (RMSE) is also below 30%, both for indoors (4.44%) and outdoors (0.38%). Thus, the base case model is validated and can be used to predict the thermal behavior of the classroom.

4.3.5 Academic year school hours

The Costa Rican school year annual hours were estimated using the official public school calendar. The number of school weeks were estimated by subtracting the holiday periods: Easter week, Midterm holidays (two weeks at the beginning of July) and summer holidays (8 weeks that run from mid-December to the first week of February). National or local holidays within the school terms were not taken into account. The school days were estimated by multiplying the school weeks by the school weekdays (5) and dividing them by the weekdays (7). During school days, classrooms are commonly used from 7 a.m. to 5 p.m. by one or more groups of children. Thus, the yearly school hours were calculated by multiplying school days by 10. The total annual school hours were estimated to be 2060.

(4.9) Academic year school hours = (365 – holiday periods) * 5/7 * daily school hours

TABLE 4.4 Validation of the model

	Internal		External	
	Simulation	Monitoring	Simulation	Monitoring
Average temp. (°C)	27.2	27.4	27.9	27.5
Sum of temp. (°C)	59652	60141	254514	206328
Sum of the differences (°C)	489.57		-5104.34	
MBE (%)	0.81		-2.47	
RMSE	1.21		0.11	
CV(RMSE) (%)	4.44		0.38	

4.4. RESULTS

4.4.1 Approach 1: Simplified method

Figure 4.6 shows the indoor operative temperature and the outdoor air temperature and their standard deviations during a typical school day. The curves were estimated by averaging the hourly results from the 206-day school year. Indoor operative temperature fluctuated from 25.3°C (SD ± 1.8°C) at 6 a.m. to 33.1°C (SD ± 2.6°C) at 4 p.m. Indoor values were similar to outdoor temperatures (24.8°C (SD ± 1.9°C) at 5 a.m. to 33.0°C (SD ± 2.6°C) at 3 p.m.). However, indoor temperature curves are shifted one hour to the left, meaning that the building was not able to dampen the indoor temperatures, but rather delay them one hour.

The classroom's maximum acceptable annual mean operative temperature ($T_{o\text{-}max}$) was estimated to be 26.7°C (SD ± 0.5°C). Figure 4.7 presents the fluctuation of the operative temperature upper limit through the school year and the corresponding indoor temperatures. Zones with no data correspond to the holiday periods. From a total of 2060 school hours, 1647 were over the $T_{o\text{-}max}$, meaning that children spend 80% of their time in a classroom, which does not provide them with an optimal environment for learning.

A measure of the severity of the Exceedance Hours (EH) is presented in Figure 4.9. The exceeding degrees from the proposed limiting maximum acceptable temperature (ΔT) are shown binned into 0.5°C intervals. The exceeding degrees can reach up to 10°C and 71.2% of the school time that the classroom's temperature is 1°C or more over the $T_{o\text{-}max}$.

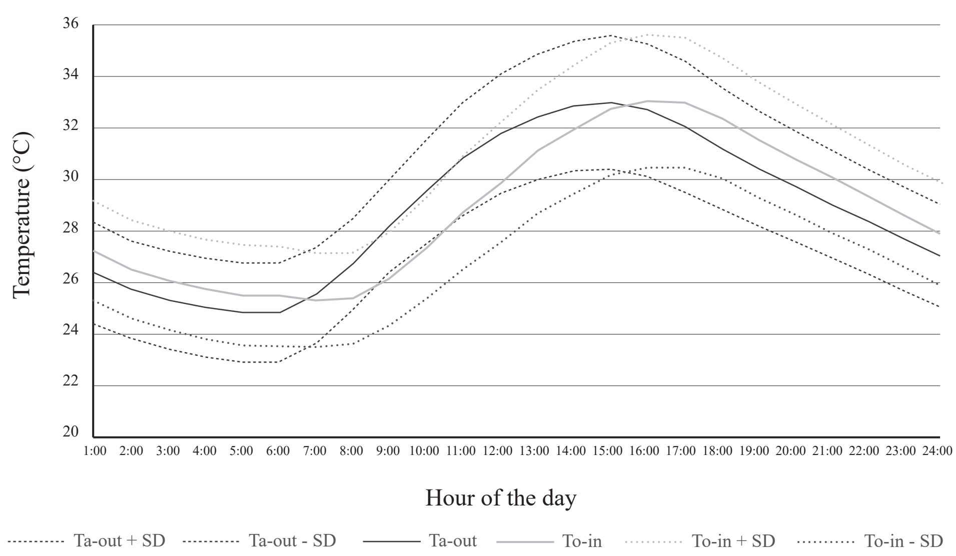


FIGURE 4.6 Approach 1. Classroom's operative temperatures during a typical school day. Estimated by averaging hourly data from the 206-day school year. Outside air temperature is presented as a reference.

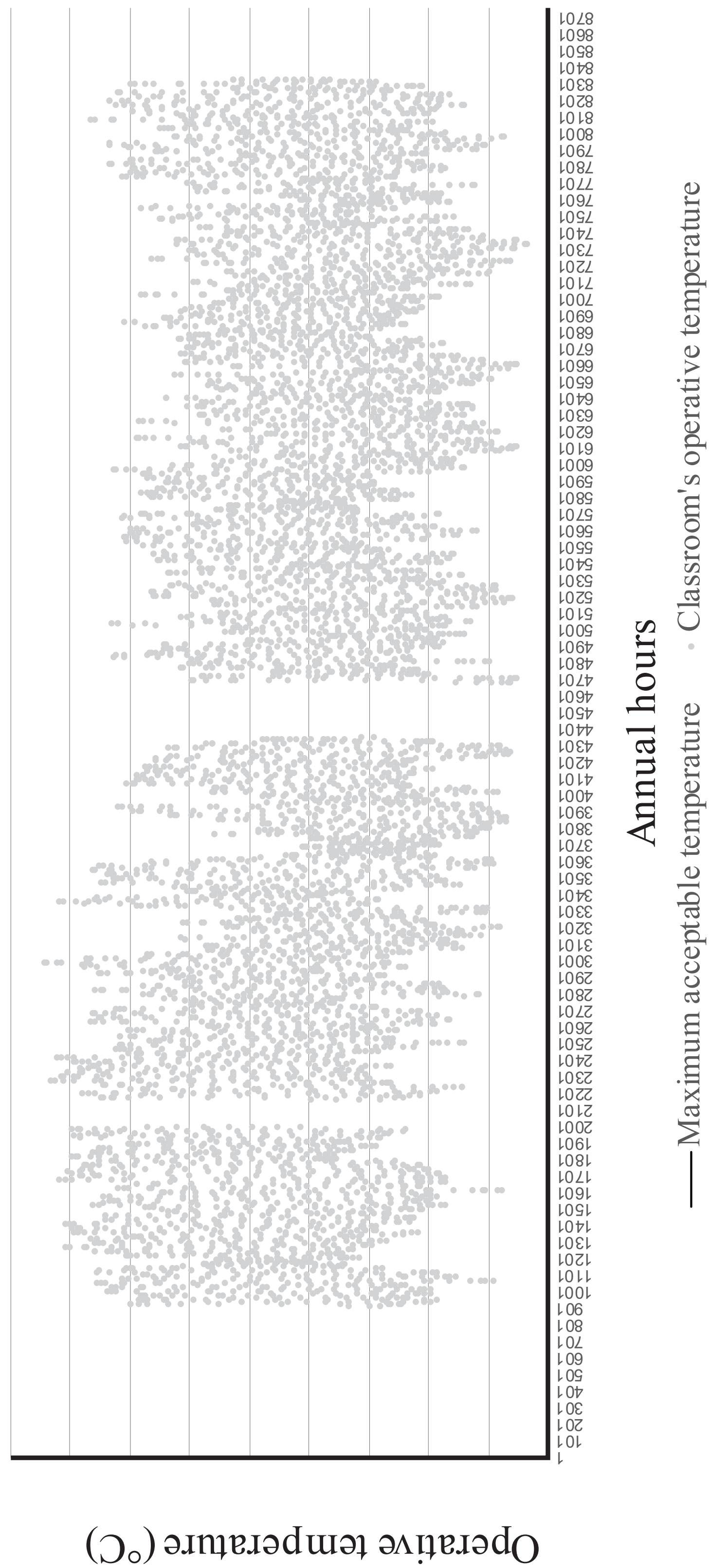


FIGURE 4.7 Approach 1. Fluctuation of the classroom's operative temperature upper limit ($T_{o\text{-}max}$) through the school year and the corresponding classroom's operative temperature

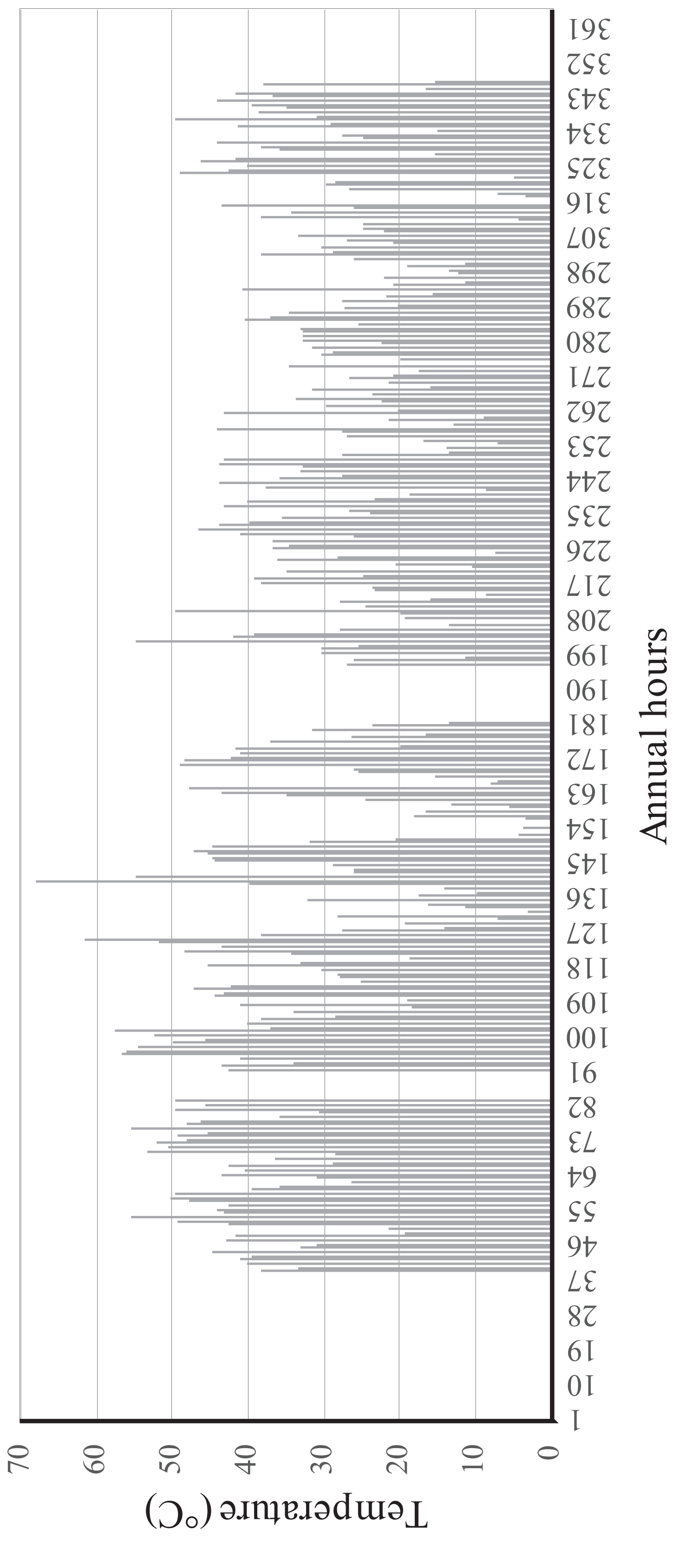


FIGURE 4.8 Approach 1: Daily Weighted Exceedance (W_e). Estimated by adding all the exceeding degrees (ΔT) of a school day

The variation of the Daily Weighted Exceedance (W_e) through the school year is presented in Figure 4.8. The We mean was estimated to be 29.1°C (SD ± 13.0°C). However, peaks of 57.3°C were achieved. Considering the 10 school hours per day results, show that the temperature in the classrooms was on average 3°C over $T_{o\text{-}max}$.

4.4.2 Approach 2: Computational simulation approach

Figure 4.10 shows the behavior of the indoor operative temperature and the outdoor air temperature and their standard deviations during a typical school day. The curves were estimated by averaging hourly results from the 206-day school year. Indoor operative temperature fluctuated from 23.1°C (SD ± 1.6°C) at 5 a.m. to 31.5°C (SD ± 2.2°C) at 3 p.m. Indoor values were between 1.6 and 2.5°C lower than outside temperatures (24.8°C (SD ± 1.9°C) at 5 a.m. to 33.0°C (SD ± 2.6°C) at 3 p.m.). However, indoor temperatures closely followed the outside temperatures' pattern as expected to occur in a naturally ventilated-light construction building located in the tropics.

The classroom's maximum acceptable annual mean operative temperature ($T_{o\text{-}max}$) was estimated to be 26.7°C (SD ± 0.5°C). Figure 4.12 presents the fluctuation of the operative temperature upper limit through the school year and the corresponding indoor temperatures. Zones with no data correspond to the holiday periods. From a total of 2060 school hours, 1718 were over the To-max, meaning that children spend 83% of their school year in a classroom that does not provide them with an optimal environment for learning.

A measure of the severity of the Exceedance Hours is presented in Figure 4.11. The exceeding degrees from the limiting maximum acceptable temperature (ΔT) are shown binned into 0.5°C intervals. The exceeding degrees can reach up to 9°C and 74% of the

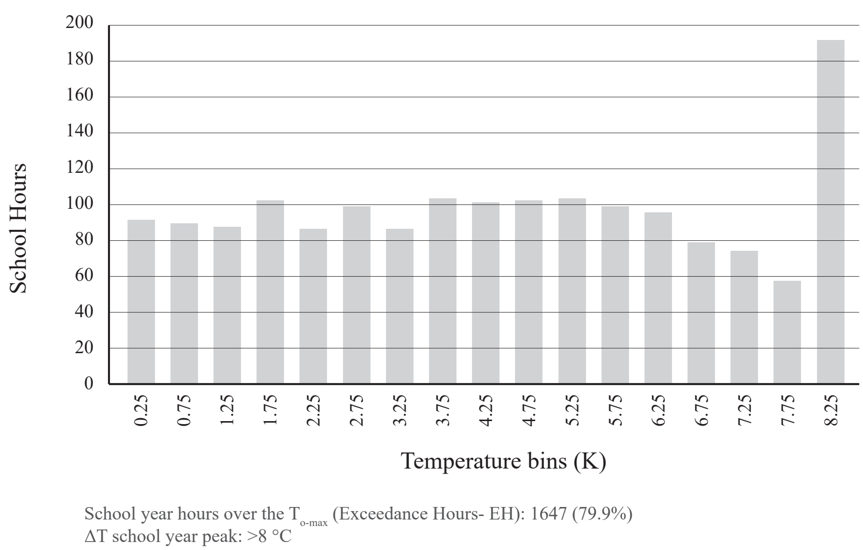


FIGURE 4.9 Approach 1: Exceeding degrees (ΔT). For each hour the number of degrees over the $T_{o\text{-}max}$ was estimated and binned into 0.5°C intervals

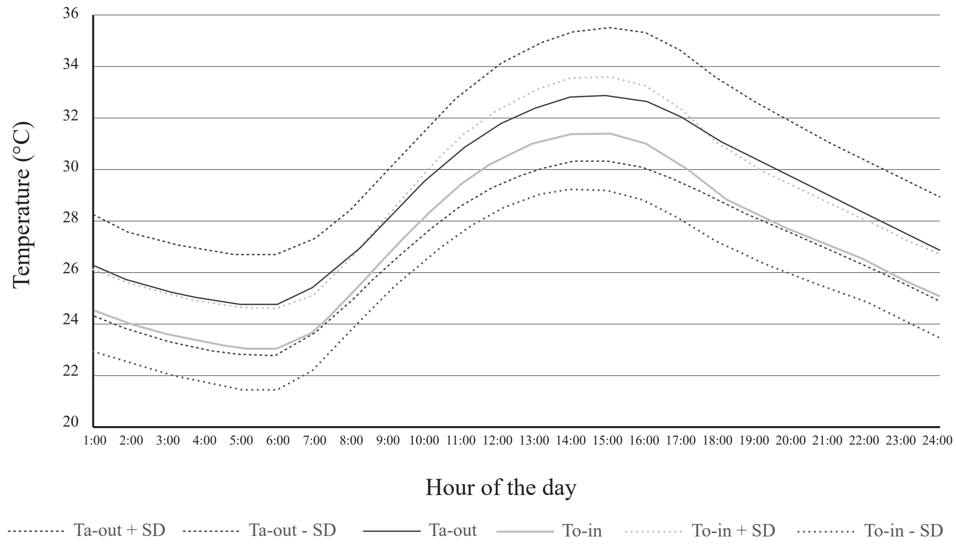


FIGURE 4.10 Approach 2. Classroom's operative temperatures during a typical school day. Estimated by averaging hourly data from the 206-day school year. Outside air temperature is presented as a reference.

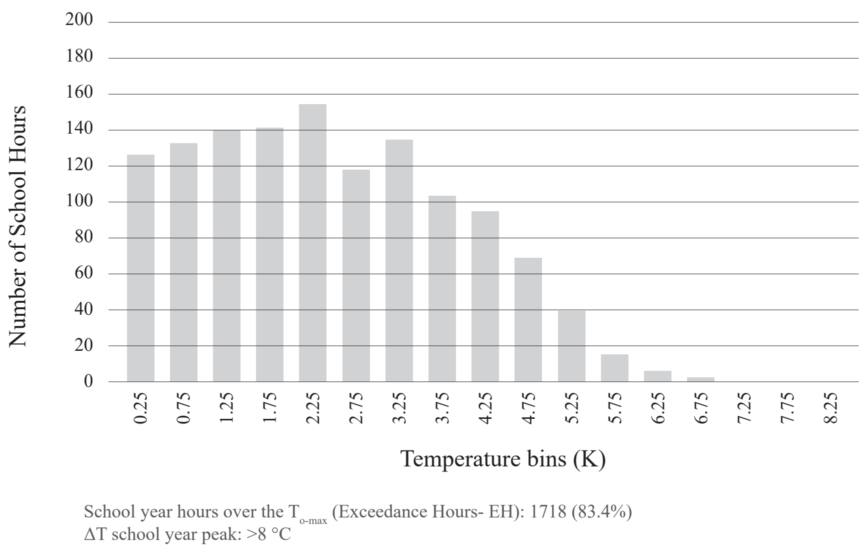


FIGURE 4.11 Approach 2: Exceeding degrees (ΔT). For each hour the number of degrees over the $T_{o\text{-}max}$ was estimated and binned into 0.5°C intervals

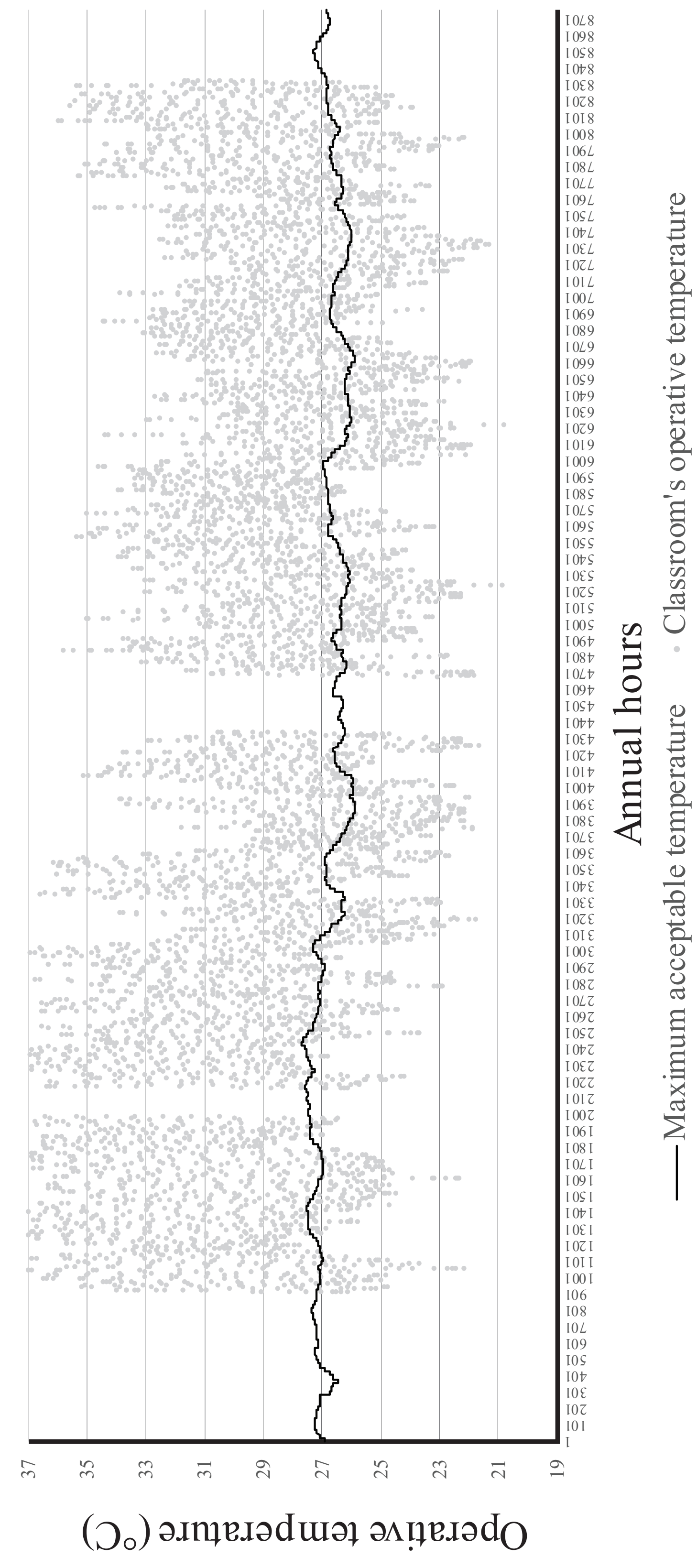


FIGURE 4.12 Approach 2. Fluctuation of the classroom's operative temperature upper limit ($T_{o\text{-}max}$) through the school year and the corresponding classroom's operative temperature

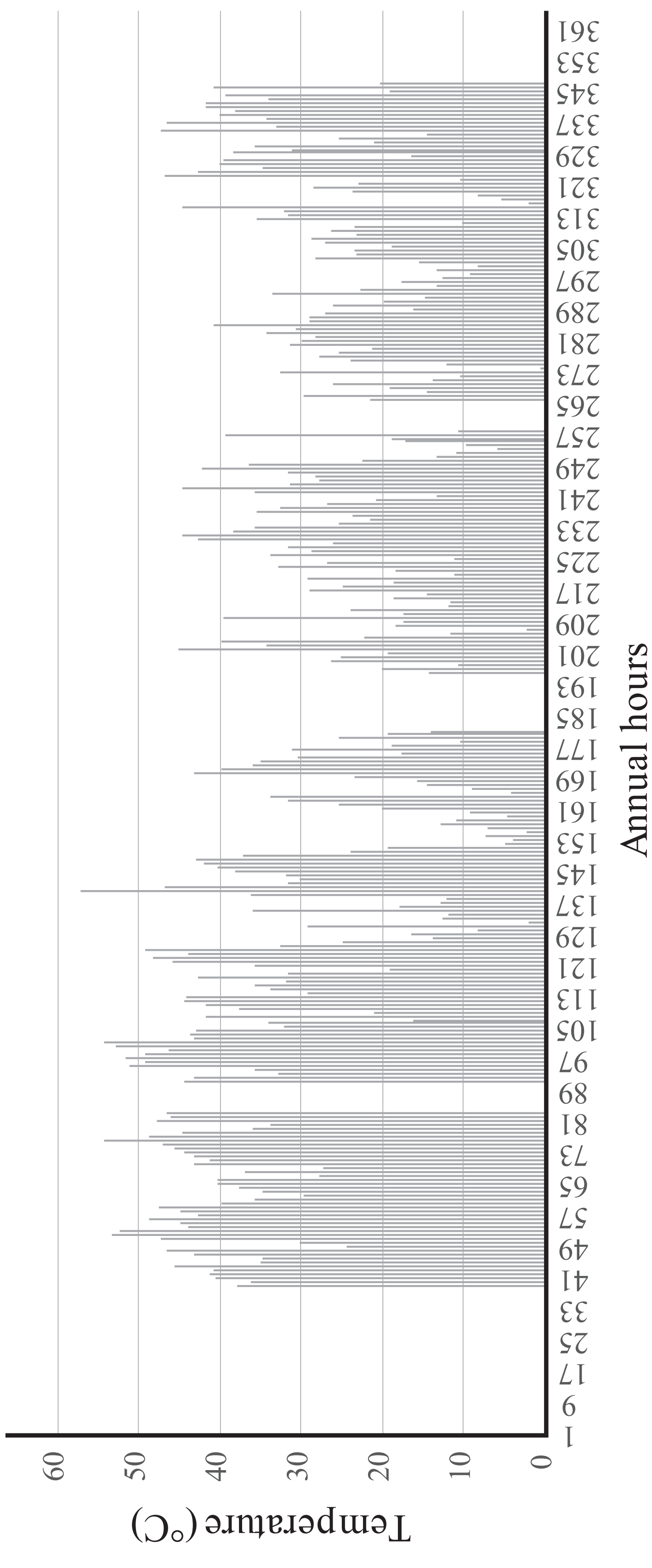


FIGURE 4.13 Approach 2: Daily Weighted Exceedance (W_e). Estimated by adding all the exceeding degrees (ΔT) of a school day

school time the classroom's temperature is 1°C or more over the To-max.

The variation of the Daily Weighted Exceedance (W_e) through the school year is presented in Figure 4.13. The We mean was estimated to be 31.6°C (SD ± 13.2°C). However, peaks of almost 70°C were seen.

The classroom was originally simulated with 19 students and one teacher, which were the number of students found during the monitoring period and the experiments. However, classrooms in Costa Rica seem to be more crowded. Therefore, a simulation model with an occupancy factor of 0.5 (26 pupils and one teacher) was performed. Results show that the percentage of EH with 19 or 26 students are similar.

Some administrative changes regarding to the school schedule were also explored. For example in Thailand, school holidays are in March and April to avoid the hot, peak temperatures of the year. Therefore, a computational simulation was run, changing the traditional January-February summer holidays of the southern hemisphere to March and April. However, warm thermal conditions are present at the school site all year round, so this change only represented a 1% reduction in the number of EH.

Starting the school day earlier, at 6 a.m., was also analyzed and it would only mean a reduction of 9.5% in the number of school hours over the maximum acceptable limit (EH).

There is a difference in the percentage of EH if children attend school in the morning (7 a.m. to 12 p.m.) or in the afternoon (12 p.m. to 5 p.m.) schedule. During the mornings, 68.9% of the hours are over the proposed limit (EH), while in the afternoons, this percentage increases to 97.9%. Therefore, children that attend school in the afternoons experience a worse thermal environment.

TABLE 4.5 Case Study overheating indicators compared with the CIBSE TM52 criteria

Criteria	Approach 1 (1)	Approach 2 (1)	CIBSE TM52 criteria
Hours of exceedence (H_e)	73.0%	71.2%	The number of hours where To is 1 K over To-max should be less than 3% of the occupied hours during the period May to September (Northern hemisphere's summer)
Daily weighted exceedence (W_e)	Mean: 29.1°C (SD ± 13.0°C)	Mean: 31.6°C (SD ± 13.2°C)	The sum of the daily exceeding degrees shall be equal or less than 6 K
Upper limit temperature (T_{upp})	>8°C	>8°C	The difference between To and To-max shall not exceed 4 K

(1) Estimated air speed: >0.4 m/s

4.5. DISCUSSION

The results show that indoor temperatures were over the upper temperature limit for more than 80% of the school time. During school hours, temperatures were on average 3°C above $T_{o\text{-}max}$. However, peaks differences over 8-9°C were common during the warmer days.

Table 4.5 shows that under both approaches, the (1) percentage of Hours of Exceedance (H_e) at which ΔT is greater than or equal to 1 K, (2) the Daily Weighted Exceedance (W_e), and (3) the Upper Limit Temperature (T_{upp}), are substantially over the limits suggested by the CIBSE Technical Memorandum 52, which establishes the criteria for defining overheating that can be applied to European natural ventilated buildings (Nicol, Spires 2013). No similar standard is available for Costa Rica. Therefore, if the CIBSE TM52 criteria is used, the selected school classroom cannot guarantee a suitable thermal environment for learning.

Administrative changes were studied regarding the school schedule. Changing the holiday's period to the warmer months showed no impact on the percentage of EH. However, when starting the school earlier (6 a.m.), a reduction close to 10% was seen.

These results disagree with many of the studies performed in the tropics. (Vi Le, Gillott, Rodrigues 2017b) found that in naturally ventilated elementary school classrooms in Vietnam, the children's neutral temperature was 31.3°C (T_a). Authors concluded that Vietnamese children tolerate higher temperatures than the values recommended for adults in the standards and that the benchmark for overheating calculations should be moved to 33°C.

However, the experiment performed in **Chapter 3** shows that even when children would tolerate this classroom's conditions, a decrease in school work performance should be expected, due to the number of hours (1815 hours, 88% of the school year) where indoor conditions were equal or over 30°C, temperature at which the children showed a considerable decrease in performance.

The reason for the disagreement could be endorsed to the fact that this study evaluated the classroom's thermal conditions based on a human response model that sets a lower maximum temperature limit than the ASHRAE's or UNE-EN's adaptive thermal models. Achieving the thermal conditions for optimal teaching might be harder due to the high temperatures that prevail in the tropics. However, designing to a threshold comfort temperature might not be enough to ensure that the most effective learning environments are delivered (Montazami, Gaterell, Nicol, Lumley, Thoua 2017).

The results under both approaches, simplified or computational simulation, were similar. The difference between the methods was only 3% of the school year which corresponds to 60 hours. Therefore, the simplified method can be used to assess classroom thermal environment in other tropical locations.

The results also show that the passive strategies towards adapting the school building to the warm humid conditions were not enough to achieve the desired thermal environment. Even when eighteen architectural solutions were identified. Nguyen et al. (2011) had already showed that under extreme weather conditions, traditional building design might not be sufficient to maintain indoor thermal comfort.

However, the indoor temperature was lower than the outdoor temperature under both research approaches and this could be a consequence of the passive strategies and architectural solutions applied. Without strategies like the building's East-West orientation, the longitudinal shape, the cross ventilation and the solar shading, the classroom's thermal conditions could have been worse.

Further studies should be made to know which passive or low energy consumption strategies with high cooling potential are missing or undeveloped in the case study's school building. For example, the average air speed in the classrooms was 0.3 m/s. Since the Adaptive Comfort Model in ASHRAE's 55-2013 standard allows speeds of up to 1.2 m/s, it is still possible to improve the thermal conditions by increasing the air velocity by means of envelope design or by using fans.

This study focused on classrooms where children spend most of their school time and where main cognitive activities are carried out. The aim is to provide an optimal teaching thermal environment in these spaces. In other school spaces (i.e. dining rooms), the estimation of EH can be done based on ASHRAE's adaptive model or any other comfort model.

The main limitation of this study is that the assumption, that the To-max should be not higher than the neutral temperature, is based on limited data. Very few studies were performed with children and only one, the one presented in **Chapter 3**, was developed with tropically acclimatized pupils. Therefore, additional studies in this field would contribute to validate and adjust these results. However, through a scientific analysis, it questions the effectiveness of the design and constructive solutions of traditional free running tropical classrooms focused on improving the thermal environment in school buildings in warm-humid climates. This is the first step towards developing the empirical basis for the standards and guidelines required to ensure optimal learning conditions in these regions.

4.6. CONCLUSIONS

- The estimation of the EH and H_e under the simplified and the computational simulation approaches produce similar results. The difference between the methods was only 3% of the school year, which corresponds to 60 hours. Therefore, the simplified method can be used to assess classroom thermal environments in other tropical locations. However, further studies should focus on how to adjust the outdoor air temperatures to make them similar to real indoor temperatures.

- Children spend more than 80% of their school time in a classroom that does not provide them with an optimal teaching environment. This is far above the percentage of occupied hours that the CIBSE TM52 criteria establishes as a tolerance margin for overheating in naturally ventilated buildings.

- Indoor classroom conditions are better than outdoor conditions. It is plausible that this could be a consequence of the architectural solutions that have already been incorporated in the Case Study's school building (i.e. East-West orientation, longitudinal shape, cross ventilation and solar shading)

- Changing the holiday's period to the warmer months showed no impact on the percentage of EH. However, when starting school earlier (6 a.m.) a reduction close to 10% was seen.
- The number of children in the classroom, 19 or 26, does not have a major or important effect on the EH number.

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5. TOWARDS OPTIMAL THERMAL CLASSROOM ENVIRONMENTS IN TROPICAL CLIMATES: STRATEGIES FOR ARCHITECTURAL DESIGN

5.1. INTRODUCTION

The results from the Case Study (CS) developed in **Chapter 4** show that children spend more than 80% of their time in a classroom that does not provide them with an optimal teaching environment. The classroom's operative temperature was above the recommended maximum temperature limits 1700 school hours, of a total of 2060. This is far above the 3% that the CIBSE TM52 criteria establishes as a tolerance margin for overheating in naturally ventilated buildings.

However, unsuitably high temperatures are common in classrooms (Wargocki, Wyon 2007b). Therefore, a considerable public and parental pressure has been placed recently on Public Education Ministries and school administrations asking them to provide children with better indoor thermal environments that enhance their academic performance (de Dear, Kim, Cândido, Deuble 2015; Vi Le, Gillott, Rodrigues 2017a; Sustainable Buildings Industry Council 2001). As a result, some schools are considering or have adopted the use of air-conditioners (Vi Le, Gillott, Rodrigues 2016; Kwok 1998).

Air conditioning systems are a reliable cooling source and are considered the most advanced and effective way to reduce temperature (International Energy Agency (IEA) 2018). Their penetration is increasing continuously (Santamouris 2006; Santamouris, Kolokotsa 2013). Worldwide, there wer around 1.6 billion air-conditioning units by 2018 and this number is predicted to grow to 5.6 billion by mid-century (International Energy Agency (IEA) 2018). However, air-conditioners have potentially adverse effects on children's health and performance (Vi Le, Gillott, Rodrigues 2016; Santamouris 2006; Santamouris, Kolokotsa 2013) and will exponentially increase the use of energy in the tropical school buildings and peak electricity loads: air conditioning represents between 50 and 60% of the energy use in the acclimatized buildings located in the tropics (Law, Teen-onn; Fay 2009; Katili, Boukhanouf, Wilson 2015; Gonzalez Cetz, Gomez Azpeitia 2018).

Because of the global use of fossil fuels (coal, oil, and gas) has dominated world energy supply since the mid-eighteenth century (Akpan, Akpan 2012), more energy needs will mean an increase of the anthropogenic greenhouse gas emissions (GHGE). In the world, buildings are responsible for almost 50% of energy and heating production, 12% of the carbon dioxide equivalent emissions recorded in 2010 (FAO 2018). And thanks to GHGE, the world is getting very warm, very fast. The global average temperature has risen by almost a degree since 1880, 20 times faster than in the last 10,000 years. In order to mitigate climate change and the associated climatic disasters, the Paris Agreement set a maximum global temperature increase of 1.5°C compared to the pre-industrial levels for 2030, which will be hardly met (FAO 2018).

Therefore, a collective responsibility has been set to minimize building's operational energy use and the environmental impacts (de Dear, Kim, Cândido, Deuble 2015; Santamouris, Kolokotsa 2013). School buildings are built to last more than 50 years, thus architects must design buildings to minimize their dependence on the energy to remain habitable. As a result, it is important to achieve a good and healthy indoor environment, but this does not exclude saving energy (Larsen, Heiselberg 2008). Developing thermal conditions for an optimal learning environment without using mechanical cooling is an important task for the building construction sector and researchers.

As it was shown in Chapter 4, Section 4.2.3, the selected CS school has already adopted 18 architectural solutions towards adapting the building to the site's thermal conditions. These solutions encompass all the main climatic strategies for warm-humid regions found in the literature (Nguyen, Tran, Tran, Reiter 2011), but it does not seem to be enough to achieve an optimal thermal environment. Therefore, further steps are needed.

The aim of this chapter is to identify passive or low energy consuming design guidelines and architectural solutions, that individually or jointly, are capable of providing an optimal thermal teaching environment in the tropics.

5.2. METHODS

The literature was surveyed to find articles and books reporting which are the most effective design strategies and architectural solutions for non-residential small buildings in tropical climates. Strategies towards minimizing external heat gains, modulating heat gains and removing internal heat were identified, listed and classified. Only passive or low energy consuming strategies were considered. A brief summary of the pros and cons found in the literature for each of the design guidelines was developed. This summary was used as the basis to classify the design strategies according to their cooling potential.

The same Case Study school building as in **Chapter 4** was selected and qualitatively investigated and evaluated using the description and image approach (Nguyen, Tran, Tran, Reiter 2011), to identify which of the most effective strategies were missing or underdeveloped. Those design guidelines with a high cooling potential that were not considered under the design and construction processes of the Case Study school building were selected for further analysis.

The highest cooling potential, in degrees, was estimated or identified through a combination of international standards, published studies and computer simulation modelling were used to make this estimation.

Finally, the combination of strategies with the highest cooling potential in degrees were applied for the Case Study's school building and the number of school year hours in which the classrooms' operative temperature was over the maximum acceptable operative temperature limit ($T_{o\text{-}max}$) was recalculated using the ASHRAE's Exceedance Hours (EH) method (ANSI/ASHRAE 2013).

5.3. RESULTS

5.3.1 Identifying the most effective passive cooling strategies for warm-humid climates

Five publications showing the most effective passive cooling strategies for warm and hot environments that were written in the last decade were retrieved from a wide body of literature. A short description of each one of them is presented below.

Santamouris (2007) edited a book in 2007, where specialized researchers fully addressed six passive cooling techniques: urban heat islands, solar control, ventilation for cooling, ground cooling, evaporative cooling and radiative cooling. Authors presented the fundamentals, calculation methods and showed different solutions. The pros and cons were discussed for each strategy and examples of successful cases were presented.

In the same year, Santamouris et al. (2007) published a paper where the potential of the most promising new developments in the field of passive cooling were investigated. The focus of the research was to improve the indoor and outdoor conditions of low-income households in warm areas and as a consequence, discourage the use of air conditioning. The strategies addressed were classified under three techniques: Urban microclimate (green areas, the use of appropriate materials, and colored highly reflective coatings), solar and heat protection techniques (cool reflective coatings), and heat dissipation techniques (ground cooling, cooling effect of air movement, night cooling, and stack ventilation). However, authors did not classify the strategies according to climate.

Nguyen et al. (2011) made a study on climate responsive design strategies of vernacular housing in Vietnam. The authors, as one of the results, presented a classification of popular climatic strategies used in the built environment in hot humid regions, categorizing them as 17 architectural solutions. This classification focuses on climate responses as a whole and not only on cooling strategies; therefore, aspects like storm and flood prevention were included. Six traditional houses located in three different cities of Vietnam were analyzed looking for the most used strategies. Authors found that natural ventilation was the most commonly used, while passive solar and ground cooling were not employed at all, perhaps due to the challenges presented by the technical requirements.

Geetha and Velraj (2012), developed a review where the best known methods for the passive cooling of buildings were described and classified. The representative applications of each method were also discussed generally. The paper focuses on all the available techniques; therefore, only some of them were fully developed with references to examples of successful cases. Authors divided the cooling methods in three, using a framework that is widely accepted: Prevention of heat gains, modulation of heat gains and heat dissipation. Geetha and Velraj (2012) did not differentiate the methods according to the climate or the use of the building.

One year later, Santamouris and Kolokotsa (2013) published a study where they underline and review the recent state-of-the-art technologies for passive cooling dissipation. The aim was to study the disposal of a building's excess heat to a lower temperature sink, like the ambient air, water, ground and sky. Therefore, the pros and cons of ground cooling, evaporative cooling and cooling ventilation were fully explored in the paper and referenced to different studies performed in all types of climates and buildings.

The cooling strategies identified in each one of the publications were summarized in Table 5.1, and a brief description is presented below:

> **Microclimate:** Microclimate controls are the deliberately produced changes/variations in the microclimate around a building. They have two main purposes: (1) to control the ambient conditions (sun, wind) of outdoor spaces; (2) and to improve the outdoor conditions adjacent to the building (Szokolay 2004). Appropriate landscaping techniques like green areas, water surfaces and ground materials can be applied at an urban and building site level (Givoni 1991a; Geetha, Velraj 2012).

TABLE 5.1 Passive cooling methods/techniques identified in the selected publications

Techniques		Studies				
		(1)	(2)	(3)	(4)	(5)
Reduce Heat Gains						
Microclimate		X	X	-	X	-
Solar control		X	X	X	X	-
Modify Heat Gains						
Thermal mass	With thermal energy storage	-	-	-	X	-
	Without thermal energy storage	-	-	X	X	-
Night ventilation		X	X	-	X	X
Remove Internal Heat						
Natural ventilation	Cross ventilation	X	X	X	X	-
	Stack ventilation	X	X	X	X	-
	Single- sided ventilation	X	-	X	X	-
Natural cooling	Evaporative cooling (direct)	X	-	X	X	X
	Ground or earth cooling	X	X	X	X	X
	Radiative cooling	X	-	-	X	-

Selected published work on passive cooling strategies from the last decade:	
(1) Advances in passive cooling (Santamouris 2007)	Book
(2) Recent progress on passive cooling techniques: Advanced technological developments to improve survivability levels in low-income households (Santamouris et al. 2007)	Journal- Review
(3) An investigation on climate responsive design strategies of vernacular housing in Vietnam (Nguyen et al. 2011)	Journal- Study
(4) Passive cooling methods for energy efficient buildings with and without thermal energy storage– A review (Geetha and Velraj 2012)	Journal- Review
(5) Passive cooling dissipation techniques for buildings and other structures: The state of the art (Santamouris and Kolokotsa 2013)	Journal- Review

The impact of green areas has been widely studied, including in the tropical climates. Results show that while high temperature differences can be expected in surface temperatures, their impact on ambient temperature is moderate, not surpassing 3-4°C. The lot's dimensions are a constraint for this cooling technique; however, architectural solutions like green roofs, pergolas, and green walls are very efficient and low land/terrain demanding.

Microclimate control benefits were not considered in the CS school building, and even when a moderate impact can be expected, they should help to cool down the outdoor air before it enters the classrooms.

Solar control: The control of solar loads is considered a pre-condition of passive cooling. According to Santamouris (2007), due to the limited heat capacity of buildings and natural heat sinks, the effective control of solar loads should be a pre-condition for the successful operation of the passive cooling concept. A building that admits too much solar radiation will always be harder to cool. Solar control denotes the complete or partial, permanent or temporary exclusion of solar radiation from the building's envelope by appropriate glazing, combination of orientation and shape of the openings, and sun shading devices. In low rise buildings located in the tropical belt, special attention should be placed on the roof, because it is the part of the envelope that receives most of the solar radiation (Harimi, Harimi, Kurian, Bolong, Zakaria, Gungat 2005; Jayasinghe, Attalage, Jayawardena 2003). Also, the fact that the daily maximum outdoor temperature coincides with the maximum radiative power on a west façade, makes this part of the building particularly critical (Santamouris 2007).

Solar control was fully developed in the CS. The building is oriented from east to west to avoid direct solar heat gains, with the main façades facing north and south. For some reason, the classroom's main windows are facing north. A 0.8 meter overhanging eave provides shade to the north windows during the time that the sun shines from the northern hemisphere (End of April to Mid-August). The south façade is shaded all the time by the corridor's roof that is 3.6 meter long.

Thermal mass without thermal energy storage: Thermal mass is the ability of a body to store thermal energy. It is equivalent to thermal capacitance or heat capacity. In architecture, thermal mass is a property of the mass of a building which allows thermal energy storage. The benefit of the thermal mass to indoor thermal comfort is the potential to dampen indoor air temperature and, therefore, reduce internal temperature peaks (Aste, Angelotti, Buzzetti 2009; Gauthier, Teli, James, Stamp 2017). A mass building fabric can absorb the heat from the solar radiation and air during the day and release it at night, providing "inertia" against temperature fluctuations.

Good ventilation in the evening or at night can improve the removal of heat that flows from the heavy walls and slabs. Therefore, the thermal mass strategy has been widely combined with night cooling ventilation (Shaviv, Yezioro, Capeluto 2001;

Givoni 1998; Yang, Li 2008). Due to the low day-night temperature differences (night temperatures remain elevated), it is widely believed that in hot humid climates, the use thermal mass is not effective as a passive cooling design strategy (Shaviv, Yezioro, Capeluto 2001).

Thermal mass with thermal energy storage: Thermal mass with and without thermal energy storage works in a similar way. However, in the former, Phase Change Materials (PCM) are integrated into building fabrics to enhance the thermal storage effect. The main applications of PCM are on wallboards, roofs and ceilings and building blocks, among others.

Night ventilation: Night ventilation is the removal of the heat that the building fabric has been absorbing during the day by using natural or mechanical ventilation. Through this technique, indoor conditions can be modified during the day by: (1) reducing peak air temperatures, (2) reducing air temperatures, in particular, during morning hours, (3) reducing slab temperatures, and (4) creating a time lag between external and internal temperatures (Santamouris 2007). The successful application of night ventilation techniques will be influenced by the outdoor temperature, relative humidity and wind speed (Santamouris, Kolokotsa 2013). Night ventilation is more effective in buildings with high thermal mass where heat can be absorbed during the day (See thermal mass). However, the thermal mass is not a recommended strategy for warm-humid climates, due to the low day-night temperature swing, it (Shaviv, Yezioro, Capeluto 2001; Nguyen, Tran, Tran, Reiter 2011; Givoni 1991b).

Cross- ventilation: Cross ventilation occurs where there are pressure differences between one side of a building and the other. Two or more openings on two or more façades with different pressures are needed. When using cross-ventilation in buildings, it is expected that cooler exterior air enters with high pressure on the windward side and is drawn out of the building on the low pressure leeward side. Higher air speeds can be achieved through cross-ventilation. Maximum air velocity is achieved when the inlet opening is much smaller than the outlet (Szokolay 2004). It can be used to remove heat by air exchange and to produce in occupants, a physiological cooling effect by enhancing the evaporation from the skin temperature.

Cross-ventilation is generally only suitable for narrow buildings. A rule of thumb for effective ventilation says that the building's length should be less than five times the floor to ceiling height (Chu, Chiang 2014). This cooling technique was applied in the CS school building, but it was not fully developed. The air speeds measured in the classrooms are low; therefore, the physiological cooling effect of air movement can be increased.

Single-sided ventilation: According to Mohamed et al. (2011), single-sided ventilation can be defined as a condition where one or more openings exist only on one façade of a sealed room. As a result, it provides a local ventilation solution and generally has a worse natural ventilation performance than cross-ventilation (Mohamed, King, Behnia, Prasad 2011; Emmerich, Dols, Axley 2001). This is because the driving forces tend to be relatively small and highly variable, due to the limited pressure differences developed on a single façade. An effective ventilation is generally achieved in zones close to the openings, while at the back of the rooms, the air remains still. It is only recommended when there is no possibility of having cross-ventilation.

Stack ventilation: In stack ventilation, the air moves by temperature differences. When the air gets warmer, it becomes less dense and tends to rise. In buildings, cooler air from the outside is drawn indoor at a lower level and when it becomes warmer it rises and goes out through a vent located at a higher level. If the temperature difference of the stack is high enough, a positive pressure area will be created at the top of the building and negative pressure area at the bottom. However, air speed is generally low. Thus, stack ventilation works quite well replacing the indoor hot air by the cooler outdoor air, but has a low physiological cooling effect.

This process has the advantage that it takes place without wind. However, the temperature difference and the height of the building are important.

Evaporative cooling: In the evaporative process, air is cooled by the evaporation of water into the air. Sensitive heat is converted into latent heat at a constant wet bulb temperature. Maximum cooling is achieved when the air becomes saturated (dry-bulb and wet-bulb temperatures are equal); however, the cooling potential decreases as the dew point is approached. Therefore, the benefits of evaporative cooling are very limited in warm-humid climates (Santamouris 2007; Giabaklou, Ballinger 1996)

Ground or earth cooling: The ground cooling uses the soil as a heat sink. Ground changes its temperature more slowly than the ambient air and at a certain depth, the ground remains at an almost steady temperature level that is slightly higher than the yearly mean ambient air temperature (Santamouris 2007). Therefore, in the hotter hours of the day it will be cooler than the air temperature.

Two main cooling techniques are used. Direct contact, where a significant proportion of the building envelope is in contact with the soil, and earth to air heat exchangers (EAHE or EAHX), which consist of pipes buried in the soil while an air circulation system forces air through the tubes (Santamouris, Kolokotsa 2013; Givoni 1991b).

This cooling strategy is more efficient when there is a high temperature swing between night and day, which is not a characteristic of warm-humid climates. Nguyen et al. (2011) argued that ground cooling, thermal mass and night ventilation are not appropriate strategies for the Vietnamese climatic conditions, classified as warm and humid. However, results from (Sanusi, Shao, Ibrahim 2013) showed that EAHE can provide low energy cooling in Malaysia. (2007). They argued that ground cooling has no geographic limits due to the soil's capacity to store heat and to attenuate the temperature variations of outdoor air temperature.

Radiative cooling: Considering the incoming solar radiation that can reach an intensity of over 1000W/m^2 in tropical latitudes, and the balance between long-wave radiation emitted by building surfaces and long-wave radiation received from the sky, the impact of the radiative cooling is low. Building cooling radiators use the sky as a heat sink, which is typically colder than most terrestrial surfaces. However, in warm-humid climates, the atmospheric humidity and the presence of clouds through most of the year are the major environmental factors affecting the net radiative flux.

Some of the strategies identified were dismissed because they were not suitable or had low cooling potential for warm-humid climates (night ventilation, evaporative cooling, thermal mass, and radiative cooling), mainly because of the low swing between day-night temperatures. For others, authors mentioned a low cooling potential (single- sided ventilation, stack ventilation). Finally, solar control was discarded because it has already been fully addressed in the Case Study's school building. Therefore, the four cooling guidelines left were selected for further research:

- (S1) The cooling effect of ventilation also known as the physiological cooling effect of air movement
- (S2) Roof's thermal properties and shading
- (S3) The ground cooling using earth air heat exchangers (EAHE- EAHX)
- (S4) Microclimate controls through the use of appropriate landscaping techniques, especially green areas

5.3.2 Estimation of the Exceedance Hours method (EH) and the CIBSE TM52 overheating indicators after applying the selected cooling strategies independently.

5.3.2.1 Apparent cooling effect of air movement (S1)

There are few passive cooling strategies in warm-humid climates beyond the prevention or reduction of heat gains. The most effective one is the physiological cooling effect of air movement (Szokolay 2004; Koenigsberger, Ingersoll, Mayhew, Szokolay 1977). Air movement can increase heat convection between the human body and the ambient environment promoting heat dissipation from the skin. When air flows around the body at a temperature below the mean skin temperature, it takes away heat by evaporating perspiration (Santamouris, Wouters 2006). To promote heat dissipation from the skin, the air velocity at the body's surface is critical because the increase of air velocity can speed up the evaporation rate (Szokolay 2004). At higher air speeds, higher body cooling effects can be achieved (Santamouris, Wouters 2006). Therefore, providing air movement is an important method to increase thermal comfort by cooling down the human body, with low or null energy consumption.

A correct estimation of the apparent cooling effect of air movement is a major issue because of its influence on the success of passive thermal controls in the humid tropics (Szokolay

1997). As a result, multiple studies have been made over the past 70 years to estimate how far the limits of acceptable temperatures can be extended by the physiology cooling effect of air. Szokolay (2006) selected and summarized 12 of them (Table 5.2) and proposed a polynomial fit to the tabulated values' average, equation 5.1, where v is the average air velocity.

$$dT = 5.9331\ v - 1.2844\ v^2 - 1.0136 \quad (5.1)$$

According to the proposed equation, air velocities of 0.5, 1.0 and 1.5 m/s will be equivalent to an apparent cooling effect of 1.8, 3.7 and 4.8 K respectively. However, such a high cooling effect has not been accepted yet in any of the main thermal comfort standards: ASHRAE 55, EN 15251 and ISO 7730.

As of today, the ASHRAE's adaptive comfort model permits a maximum 2.2°C extension of the 80% acceptability limits if the indoor operative temperature is above 25°C, the metabolic rates range from 1.0 to 1.3 met, and if occupants are able to directly control the air speed, and adapt their clothing to the thermal conditions within a range of 0.5-1.0 clo (Equation 5.2). Therefore, if the prevailing mean outdoor temperature is 33.5°C, the operative temperature's upper 80% acceptability limit (U_{80}) can be extended from 31.7°C to 33.9°C by increasing air velocity from 0.3 to 1.2 m/s.

$$T_{o\text{-}max\ 1.2} = T_{o\text{-}max} + 2.2°C \quad (5.2)$$

To estimate the highest cooling potential of the air movement in the case study's school building, the air speed in two classrooms were monitored between February 20th and March 3rd 2017. Results show that the average air speed during the school time mornings (7 a.m. to 12 p.m.) was 0.3 m/s. An additional estimation was made using a computer simulation

TABLE 5.2 The apparent cooling effect of air movement (°C). Retrieved from Szokolay, 2006

	0.5 m/s	1 m/s	1.5 m/s	2 m/s	Author	Function fitted
1	1.6 K	3.4 K	-	-	Drysdale 1952	dT = 3.6 (v - 0.05)
2	3	6.3	-	-	Drysdale 1975	dT = 6.7 (v - 0.05)
3	0.5	1.6	2.63 K	3.7 K	Rohles et al. 1974	dT = 2.09 (v - 0.24)
4	2.25	4.5	-	-	Rohles et al. 1983	dT = 4.5 v
5	0.9	2.7	4.5	6.3	ASHRAE st. 55-1981	dT = 3.6 (v - 0.25)
6	1.65	2.8	3.6	-	ASHRAE st. 55-1992	$dT = -1.9755\ v^2 + 6.0502\ v - 1.0829$
7	1.5	3.6	5.3	6	Arens et al. 1981, at 50% RH	$dT = -1.2648\ v^2 + 6.1661\ v - 1.2254$
8	1.7	4.1	5.8	6.5	Arens et al. 1981, at 30% RH	$dT = -1.5361\ v^2 + 7.0835\ v - 1.4704$
9	2	4.9	6.8	7.5	Arens et al. 1981. Psychrom., at 12 g/kg	$dT = -1.9938\ v^2 + 8.6097\ v - 1.7074$
10	2.9	4.8	6.1	6.5	Khedari et al. 2000	$dT = -1.2547\ v^2 + 5.7631\ v - 0.2426$
11	1.6	2.9	3.7	4	Smith & Tamakloe 1970	$dT = -1.1265\ v^2 + 4.445\ v - 0.4019$
12	2.48	3.4	-	-	Nicol 2004	dT = 1.4845 Ln(v) + 3.4556
Total Ave	22.0 1.8	45.0 3.7	38.4 4.8	40.5 5.8		

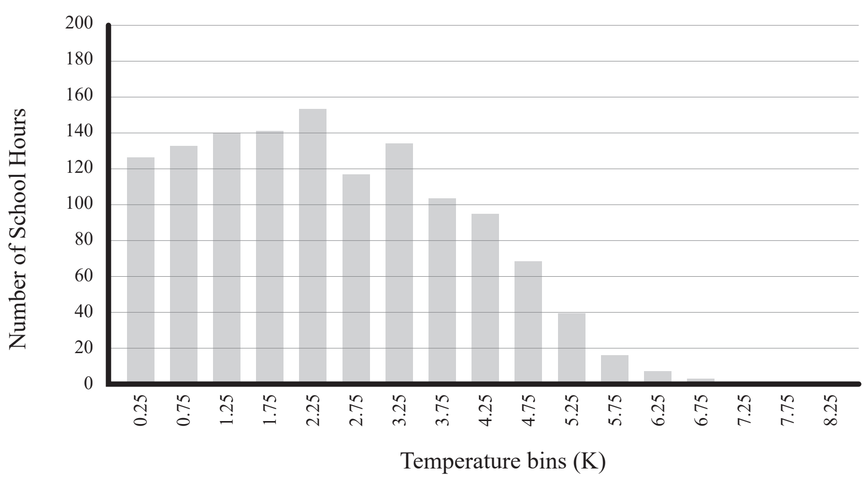
approach with Design Builder which showed similar results, 0.4 m/s (Appendix 5.1). Thus, it is possible to increase the airspeed from current values to 1.2 m/s, using natural ventilation or fans, and extend the upper operative temperature limit ($T_{o\text{-}max}$), 2.2°C

Figure 5.2 presents the fluctuation of the $T_{o\text{-}max}$ and the extended upper limit ($T_{o\text{-}max\ 1.2}$) through the school year and the corresponding indoor temperatures. Zones with no data correspond to the holiday periods. From a total of 2060 school hours 1263 were over the $T_{o\text{-}max}$, meaning that children spend 62% of their time in a classroom that does not provide them an optimal environment for learning.

The exceeding degrees from the limiting maximum acceptable temperature (ΔT) are shown in Figure 5.1 binned into 0.5°C intervals. The exceeding degrees can surpass 7°C.

The variation of the Daily Weighted Exceedance (W_e) through the school year is presented in Figure 5.3. The We mean was estimated to be 16.3°C (SD ± 9.9°C). However, peaks up to 47°C were seen.

Increasing the air speed in the classroom could lead into a 22% reduction in the EH. However, there are still 62% of the school hours where the temperature inside the classrooms is over the optimal temperatures for learning. The building does not meet the CIBSE TM52 criteria to prevent overheating either, because during 49% of the school time, indoor temperatures are 1°C over the $T_{o\text{-}max}$ (H_e). Additionally, it will be necessary to subtract the hours where the external air temperature is above 34°C, the approximate skin temperature at high temperature conditions (Wyon, Andersen, Lundqvist 1979), where the process is reversed, causing heat to flow from the air into the body (Nicol, Humphreys, Roaf 2012)



School year hours over the $T_{o\text{-}max}$: 1269 (61.6%)
ΔT school year peak: <7.0°C

FIGURE 5.1 Model 1: Exceeding degrees (ΔT). The number of degrees over the $T_{o\text{-}max}$ was estimated and binned into 0.5°C intervals for each hour. The apparent cooling effect of air movement (S1) was applied as a passive cooling strategy

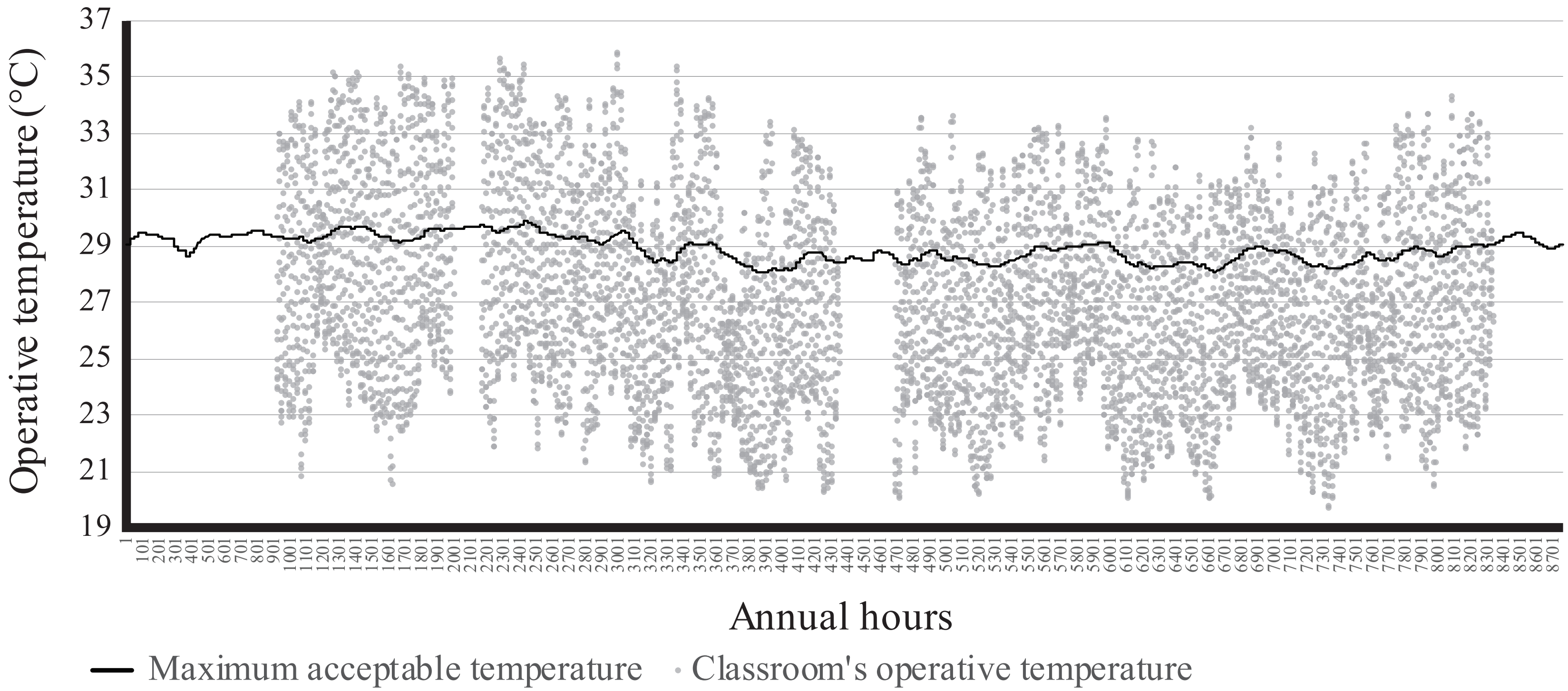


FIGURE 5.2 Model 1: Fluctuation of the operative temperature upper limit ($T_{o\text{-}max}$) through the school year and the corresponding classroom operative temperatures. The apparent cooling effect of air movement (S1) was applied as a passive cooling strategy

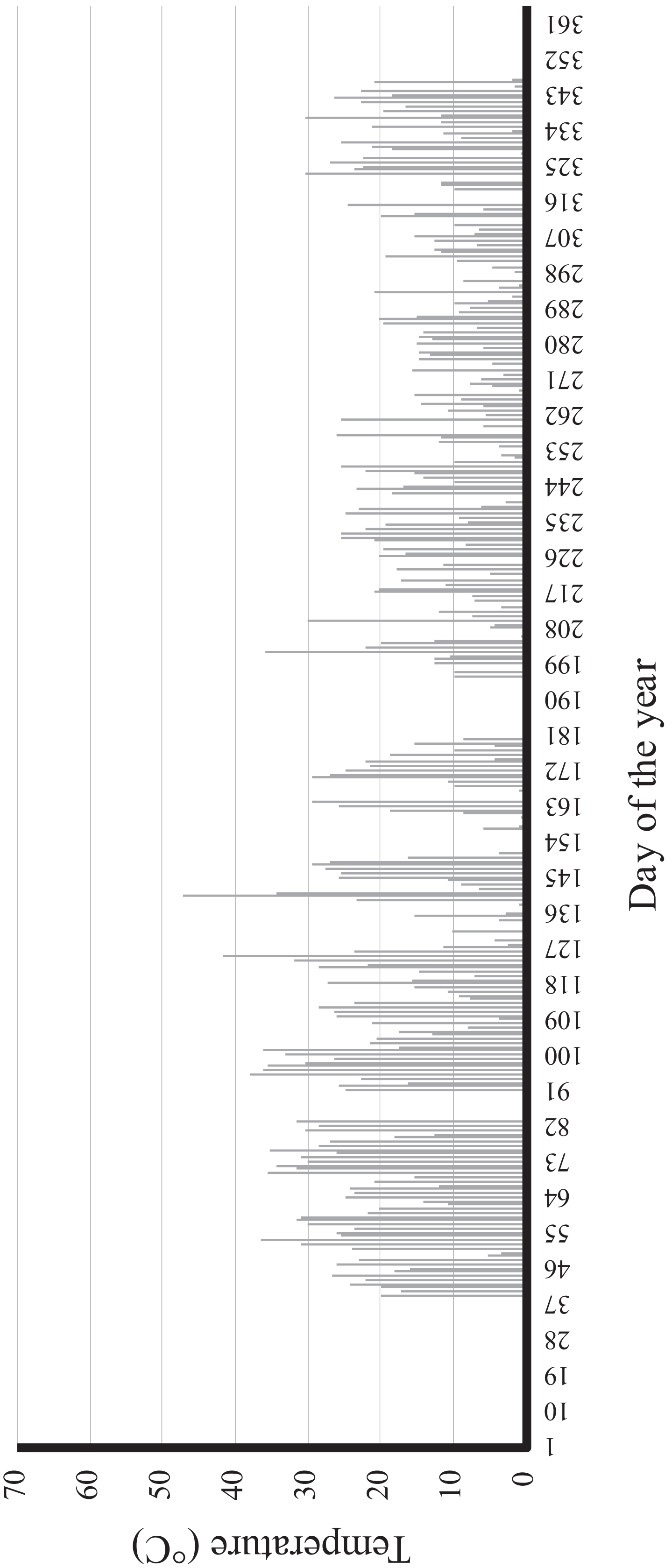


FIGURE 5.3 Model 1: Daily Weighted Exceedence (W_e). Estimated by adding all the exceeding degrees (ΔT) of a school day

If equation (5.1) proposed by Szokolay (2006) from the studies presented in Table 5.2 is used, a extension of the $T_{o\text{-}max}$ of 4.8°C would be obtained with an air speed of 1.5 m/s and the number of hours about the maximum temperature limit (EH) would be reduced to 26.7%, concentrated in the hottest months and hottest hours of the day. However, additional studies would need to be made with children in the tropics to validate the assumptions. Therefore, the results shown that the apparent cooling that the air movement under the current standards provokes (ASHRAE 55-2013) does not provide enough cooling load for the classroom's environment to be felt within suggested levels.

5.3.2.2 Roof's thermal properties and shading (S2)

The building envelope plays a fundamental role in the heat transfer that occurs between the exterior and interior spaces (Barrios, Huelsz, Rojas, Ochoa, Marincic 2012). In low rise buildings, like most of the schools in the tropics that are one or two storeys, the roof represents the biggest proportion of the envelope and receives more solar radiation than walls (Harimi, Harimi, Kurian, Bolong, Zakaria, Gungat 2005; Jayasinghe, Attalage, Jayawardena 2003). In this region, the sun's path goes through high altitudes all year-round, subjecting the roofs to 6–8 hours of intense sun radiation. During these hours, the solar irradiance can reach up to 800–1000 W/m^2. Therefore, the roof area is the most critical part of the building that is exposed to heat caused by high solar radiation (Roslan, Ibrahim, Affandi, Mohd Nawi, Baharun 2016).

According to the Intergovernmental Panel on Climate Change (IPCC) in tropical climates, the roof is responsible for approximately 30% of heat gains inside the building. A similar result, 40%, was obtained when calculating the classrooms' cooling load for the field experiment detailed in Chapter 3- Section 2.3 (Appendix 3.1).

The heat that enters the building through the roof is one of the main causes of thermal discomfort in warm-humid climates (Jayasinghe, Attalage, Jayawardena 2003; Roslan, Ibrahim, Affandi, Mohd Nawi, Baharun 2016). During the daytime, the roof's surface is heated to high temperatures, the ceiling radiates this heat into the rooms below, which

TABLE 5.3 Optimization of the roof's thermal insulation. Characteristics of the evaluated roof types

Roof type	U-Value (K m²/W)	Insulation (1)		Roof-ceiling air gap (cm)	Roof/ ceiling materials
		Thickness (cm)	Material		
Base case	2.1	0.5	Expanded polystyrene	15	Corrugated metal sheets/ 0.8 cm PVC clapboards.
1	0.1	30.8			
2	0.25	14.6			
3	0.5	6.6			
4	1.0	2.6			
5	1.5	1.27			
6	4.0	0.23	Standard insulation (3)	0	
7 (2)	2.1	0.5	Expanded polystyrene	15	

(1) The insulation thickness and material was adjusted according to the U-Value
(2) Shaded roof
(3) Standard insulation: Conductivity: 0.04 W/m- K, specific heat: 840 J/Kg- K, density: 12 Kg/m^3

increases the indoor temperature and affects the thermal comfort level of the occupants (Harimi, Harimi, Kurian, Bolong, Zakaria, Gungat 2005; Roslan, Ibrahim, Affandi, Mohd Nawi, Baharun 2016; Vecchia, Givoni, Silva 2001).

Garde et al. (2004) studied the effect that various solar protection devices (roofing, walls and windows) have on temperature and thermal comfort and found that the solar protection of the roof remains one of the main points in the thermal design of buildings in a tropical climate.

From a thermal point of view, a good wall or roof is one that contributes to thermal comfort conditions inside the building without using heating or cooling air-conditioning systems or using them with minimum energy consumption (Barrios, Huelsz, Rojas, Ochoa, Marincic 2012).

The thermal transmittance (U), and its reciprocal thermal resistance (R), are the most widely used parameters for wall/roof thermal evaluations (Barrios, Huelsz, Rojas, Ochoa, Marincic 2012). It is considered that the smaller the U (the bigger the R), the better the thermal performance (ASHRAE 2013). Even when this cannot be generalized, estimates performed in Chapter 3-Section 2.3 using the Cooling Load Temperature Differences (CLTD) method (ASHRAE 1997) showed that replacing a roof with an U-Value of 3.3 with a much more insulated one (U = 2.0) could lead to a decrease in the classroom's cooling load (Appendix 3.1).

To estimate the effects that the roof's thermal properties have on the classroom's thermal performance, different roof types were tested using the software, Design Builder version v5.3.0.14. The model was calibrated following the procedure detailed in Chapter 4-Section 4.2.4 and the thermal performance of the Case study's School classroom (base case) was used as a reference point. Table 5.3 shows the characteristics of the roof types evaluated

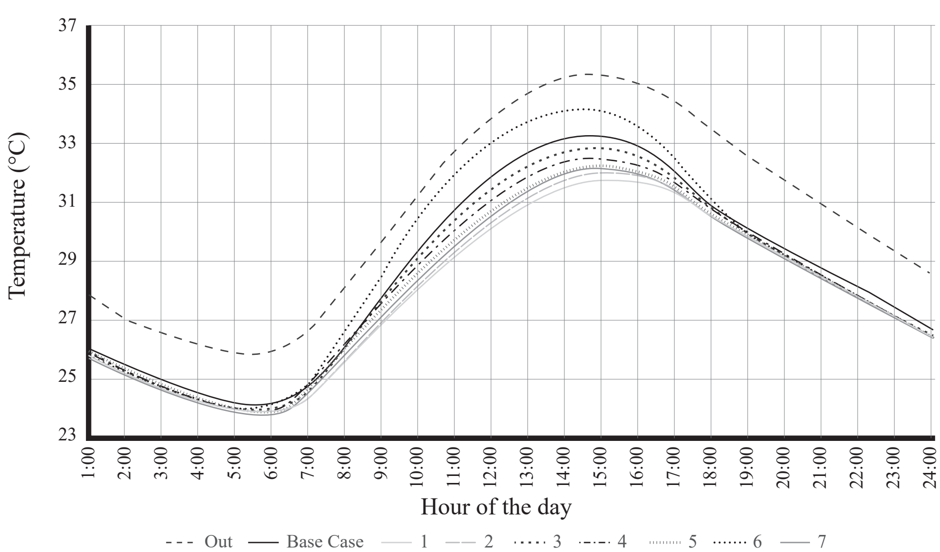


FIGURE 5.4 Indoor classroom's temperatures (T_o) on a typical day of the hottest month using different roof types. Estimated by averaging hourly temperatures of the 30 days of the month

with present and proposed U-Values. The thickness of the polyethylene foam insulation was changed accordingly to achieve the proposed U-Values.

A typical day of the hottest month (April) for each one of the proposed roof types is presented in Figure 5.4. The estimation was made by averaging the hourly operative temperatures of the 30 days of the month. Figure 5.5 shows the temperature differences during a typical day between the proposed roof types and the reference case. Both figures show that increasing the thermal resistance of the roof leads to a better thermal performance, especially in the hottest hours of the day where the indoor temperature can be up to 1.7°C below the base case.

The U-Value of each one of the roof types evaluated was regressed against the maximum temperature differences using a polynomial fit (Figure 5.6A). A maximum difference of 2.1°C was achieved when the U-Value was 0.14 K m²/W. An equivalent of 27 cm of expanded polystyrene insulation will be needed to achieve this U-Value. However, Figure 5.6B shows that the U-Value and the insulation thickness have an exponential relationship. Therefore, reaching increasingly lower U Values becomes increasingly difficult. Thus, a heat transfer rate of 0.25 (14.6 cm de polyethylene foam insulation) was preferred instead of 0.14 K m²/W. The expected maximum cooling potential was around 1.5-1.7°C.

Shading the roof of the base case classroom was also explored using the Design Builder software. A standard component block was constructed 30 cm above the existing roof (Figure 5.7). It was treated as a shading surface without any zones. Results presented in Figure 5.5 show that the maximum temperature difference between roof types 3 and 7 are

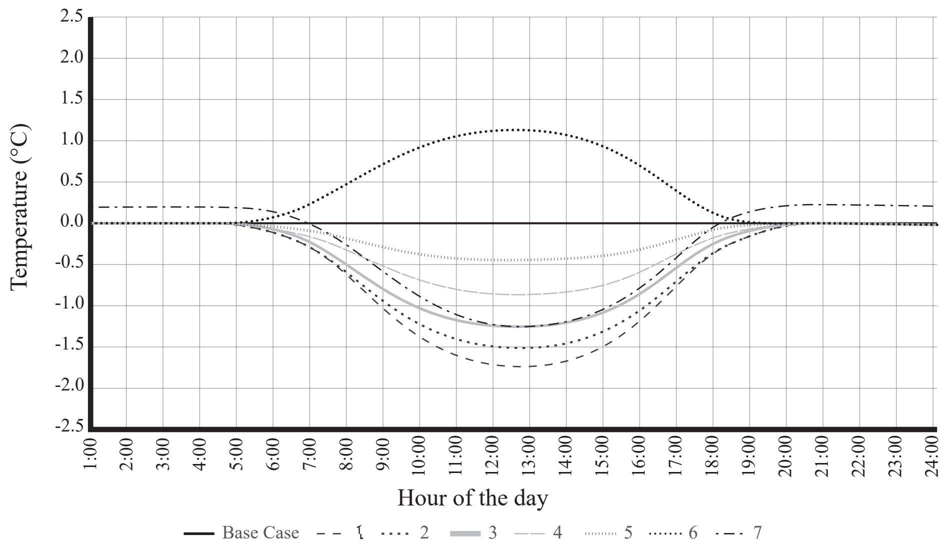


FIGURE 5.5 Indoor temperature differences during a typical day of the hottest month between the proposed roof types and the reference case

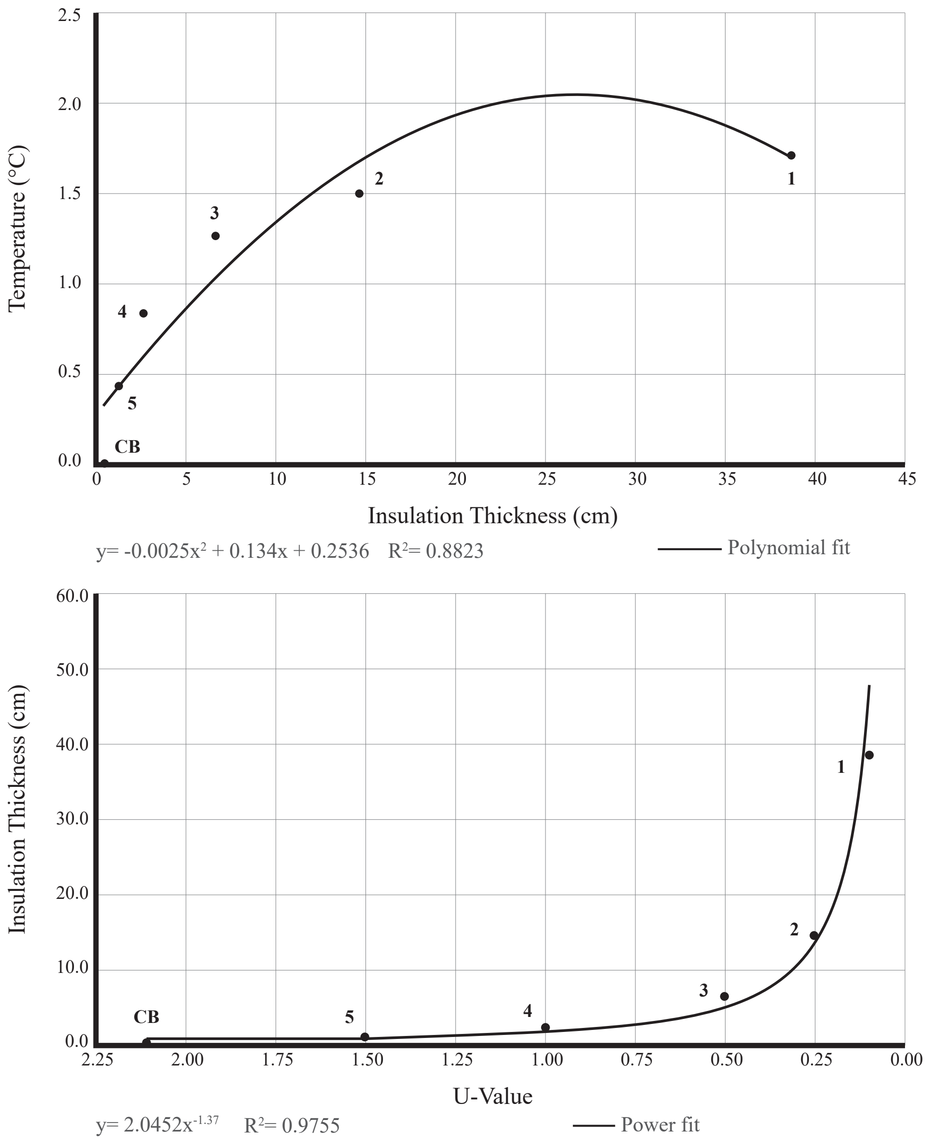


FIGURE 5.6 **A.** (Top) Maximum classroom temperature differences between the proposed roof types and the Base Case as a function of the insulation thickness. **B.** (Bottom) Roof insulation thickness as a function of the U-Value

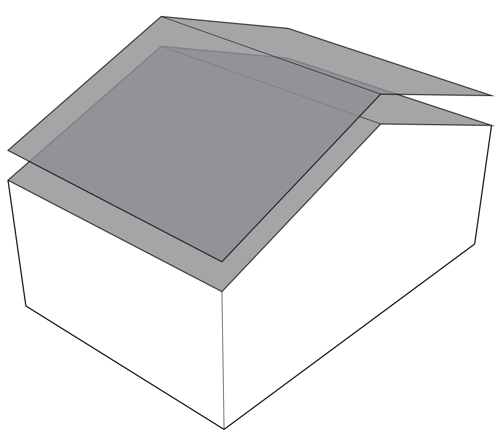


FIGURE 5.7 Shading surface 30 cm over existing roof.

similar during the day. Therefore, shading the roof will be equivalent to adding 6.1 cm of polyethylene insulation. However, this is a general estimate for comparative purposes only, because the Design Builder software cannot consider some heat transfers that occur between the shading surface and the existing roof.

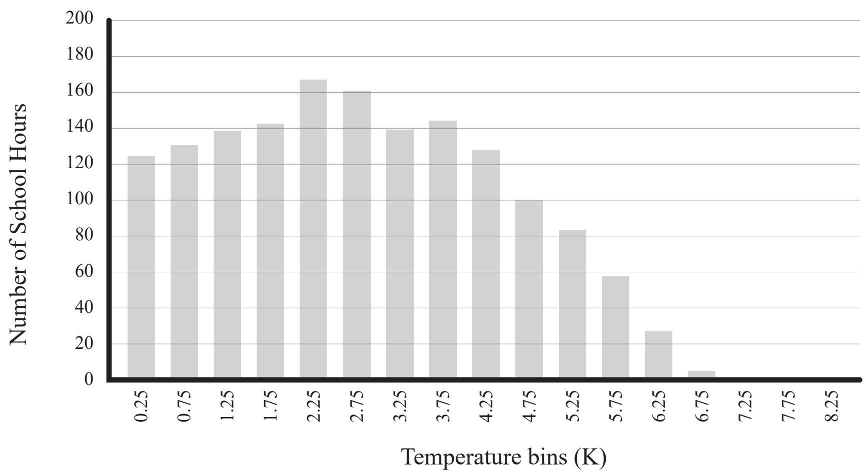
The classroom's indoor thermal conditions were finally simulated using a roof U-Value of 0.25. The operative temperature outcome was used to estimate the EH and the CIBSE TM52's overheating indicators.

Figure 5.9 presents the fluctuation of the $T_{o\text{-}max}$ and the upper classroom's temperature limit ($T_{o\text{-}max}$) through the school year and the corresponding indoor temperatures. Zones with no data correspond to the holiday periods. From a total of 2060 school hours, 1540 were over the $T_{o\text{-}max}$, meaning that the classroom's temperature was above the reference temperature 75% of the time. Thus, lowering the roof's U-Value from 2.1 to 0.25, which means adding 14 cm polyethylene insulation, could lead to an 8.6% reduction of the EH.

The exceedance degrees (ΔT) are presented in Figure 5.8 and the Daily Weighted Exceedance (W_e) through the school year is presented in Figure 5.10.

5.3.2.3 Ground or earth cooling (S3)

The ground cooling is a heat dissipation technique based on the use of the ground as a heat sink. The ground changes its temperature more slowly than the ambient air and at a certain depth the ground remains at an almost constant temperature level that is slightly higher



School year hours over the $T_{o\text{-}max}$ (Exceedance Hours- EH): 1541 (74.8%)
ΔT school year peak: <7 °C

FIGURE 5.8 Model 2: Exceeding degrees (ΔT). The number of degrees over the $T_{o\text{-}max}$ was estimated and binned into 0.5°C intervals for each hour

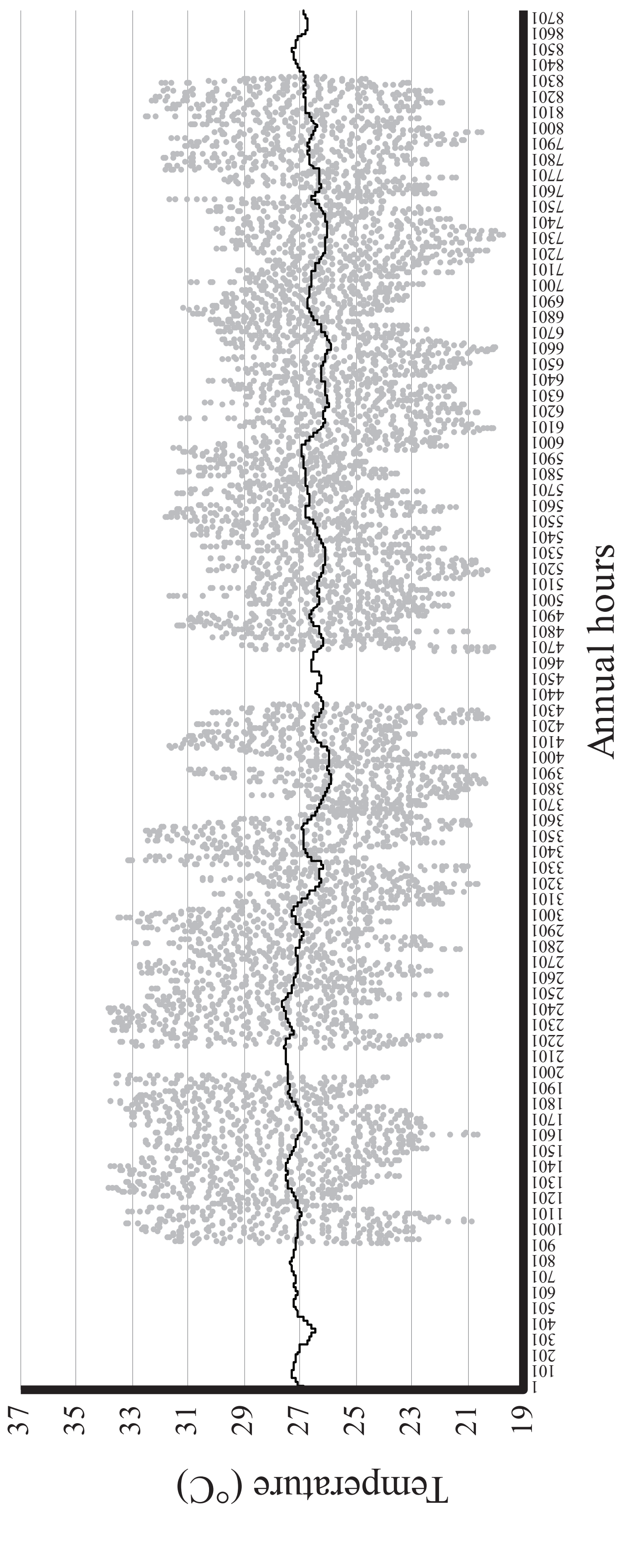


FIGURE 5.9 Model 2. Fluctuation of the operative temperature upper limit ($T_{o\text{-}max}$) through the school year and the corresponding classroom operative temperatures. Roof insulation was applied as a passive cooling strategy

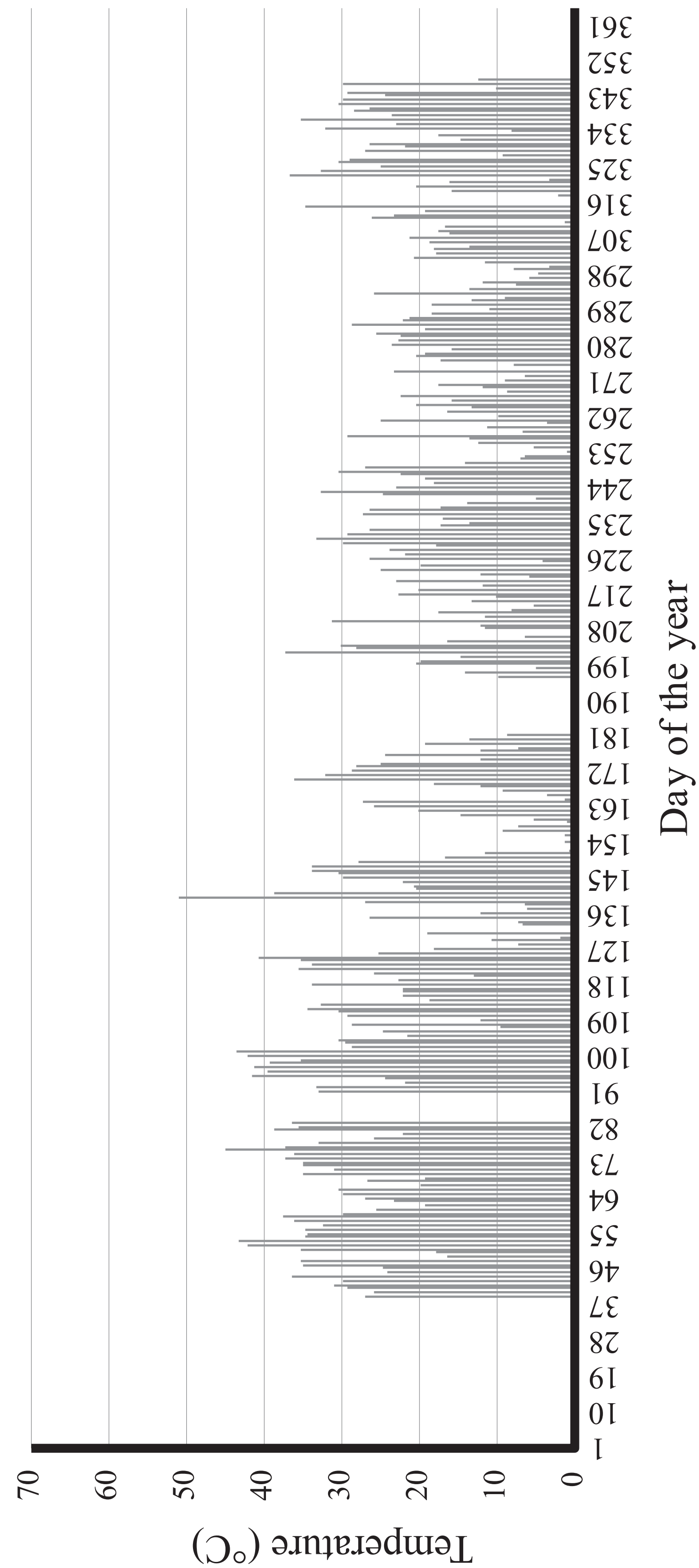


FIGURE 5.10 Model 2: Daily Weighted Exceedance (W_e). Estimated by adding all the exceeding degrees (ΔT) of a school day

TABLE 5.4 Soil heat transfer estimations according to the site's climate conditions and the characteristics of the ground above and surrounding the tubes. Estimations were performed with the software CalcSoilSurfTemp developed by Energy Plus

		Soil condition surrounding the Earth Tube											
		1- Heavy and Saturated			2- Heavy and Damp			3- Heavy and Dry			4- Light and Dry		
		Annual Average Soil Surface Temperature	Amplitude of Soil Surface Temperature	Phase Constant of Soil Surface Temperature	Annual Average Soil Surface Temperature	Amplitude of Soil Surface Temperature	Phase Constant of Soil Surface Temperature	Annual Average Soil Surface Temperature	Amplitude of Soil Surface Temperature	Phase Constant of Soil Surface Temperature	Annual Average Soil Surface Temperature	Amplitude of Soil Surface Temperature	Phase Constant of Soil Surface Temperature
Condition of the ground surface above the earth tube	1. Bare and wet	24.801	2.150	232	24.801	2.161	232	24.801	2.166	232	24.801	2.173	231
	2. Bare and moist	26.233	2.236	229	26.233	2.251	228	26.233	2.257	228	26.233	2.266	228
	3. Bare and arid	30.053	2.532	211	30.053	2.555	210	30.053	2.566	210	30.053	2.580	210
	4. Bare and dry	32.608	2.735	210	32.608	2.766	209	32.608	2.781	209	32.608	2.799	208
	5. Covered and wet	26.342	2.224	223	26.342	2.238	222	26.342	2.244	222	26.342	2.252	222
	6. Covered and moist	27.634	2.318	222	27.634	2.335	221	27.634	2.343	221	27.634	2.353	221
	7. Covered and arid	30.915	2.627	208	30.915	2.653	207	30.915	2.664	207	30.915	2.680	207
	8. Covered and dry	32.608	2.735	210	32.608	2.766	209	32.608	2.781	209	32.608	2.799	208

than the yearly mean ambient air temperature (Santamouris 2007). Therefore, in the hotter hours of the day, it will be cooler than the air temperature.

The ground's cooling potential can be used by (1) direct contact when a significant proportion of the building envelope is buried, (2) water-driven heat exchangers or (3) horizontal earth-to-air heat exchangers (Santamouris 2007). However, the most common technique to couple buildings with the ground is the use of underground air tunnels, known as earth to air heat exchangers (EAHE- EAHX). Earth to air heat exchangers consist of pipes, usually made of plastic, which are buried in the soil, while an air circulation system forces the air through the pipes (Santamouris, Kolokotsa 2013; Givoni 1991b)

(Sanusi, Shao, Ibrahim 2013) conducted an experimental study in Malaysia and reported that the temperature difference between the pipe inlet and outlet was up to 6.4°C and 6.9°C depending on the season of the year. Givoni (1991b) demonstrated that the difference between the outdoor maximum air temperature and the cooled earth temperature in mid-summer can be up to about 14-16 K in arid regions and up to 10-12 K in some hot-humid regions. Patel and Ramana (2016) estimated that a typical horizontal loop with a 35-60 m long pipe is needed for each kilowatt of heating or cooling capacity.

However, the performance of the EAHE system varies as a function of its characteristics

TABLE 5.5 Optimization of the EAHE system. Characteristics of the EAHE systems tested

EAHE system	Pipe-ground contact area (m^2)	Length of the pipe (m) (1)	Pipe depth under ground surface (m)	Required area (m^2) (2)	Outdoor air volume (ac/h)
A. Different pipe-ground contact areas					
A1	94.3	200	1	400	40
A2	188.5	400		800	
A3	282.7	600		1200	
A4	377.0	800		1600	
A5	471.2	1000		2000	
B. Different outdoor air volumes					
B1	282.7	600	1	1200	10
B2					20
B3					40
B4					80
B5					160
C. Different pipe depths					
C1	282.7	600	0.5	1200	40
C2			1.0		
C3			1.5		
C4			2.0		
C5			3.0		

(1) The length was estimated according to a pipe radius of 7.5 cm
(2) The required area was estimated assuming that distance between pipes is one meter
The pipe's thermal conductivity is 0.5 W/m- K (polyethylene)
The operation schedule of the EAHE is from 7 a.m. to 6 p.m.
The EAHE is the classroom's only ventilation source. Therefore, natural ventilation in the Design Builder was set to the OFF mode
The characteristics of the soil are Heavy Saturated and Bare and Wet

such as the area of the pipe, the air flow rate, the depth of the tunnel below the ground, the thermal characteristics of the soil, and the pipe's material, among other factors (Kamal 2012; Sanusi, Ahmad Zamri 2014; Jacovides, Mihalakakou, Santamouris, Lewis 1996; Mihalakakou, Santamouris, Asimakopoulos 2010, 1994; Sanusi, Shao, Ibrahim 2013)

Therefore, to estimate the highest cooling potential that the EAHE system would have, four aspects that affect its efficiency were first optimized using the software CalcSoilSurfTemp and Design Builder: (1) the ground's characteristics, (2) the contact area between pipes and the ground, (3) the outside air volume, and (4) the deepness at which the pipes are buried. (Sanusi, Shao, Ibrahim 2013) had already shown that Energy Plus simulation results correlate well with the field work data.

Characteristics of the ground: Table 5.4 shows (1) the annual average, (2) the amplitude and (3) the phase constant of the soil surface temperature for different combinations of soil around and over the tubes. The estimations were made accordingly for the site's climatic conditions (**Chapter 4**-Section 4.3.3) using the Calculation of the Soil Surface Temperature software (CalcSoilSurfTemp) developed by Energy Plus. It can be seen that major changes are due to the characteristics of the ground surface above the air tube.

The soil that presents the best heat transfer conditions is the one characterized as Heavy Saturated and Bare and Wet. Therefore, it is the one that will be used in the subsequent analysis.

Contact area between pipes and ground: EAHE systems with different pipe-ground contact areas were tested using the Design Builder software, version v5.3.0.14. Table 5.5 shows the characteristics of the evaluated EAHE systems with the proposed pipe-ground contact areas. Again, the model was calibrated following the procedure

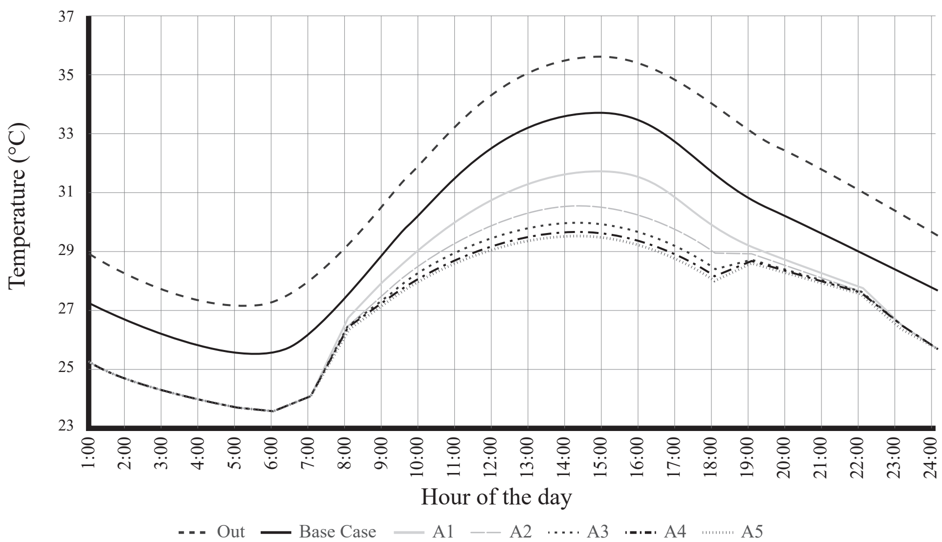


FIGURE 5.11 Indoor classroom's temperatures (T_o) on a typical day of the hottest month using different EAHE pipe- ground contact areas. Estimated by averaging hourly temperatures of the 30 days of the month

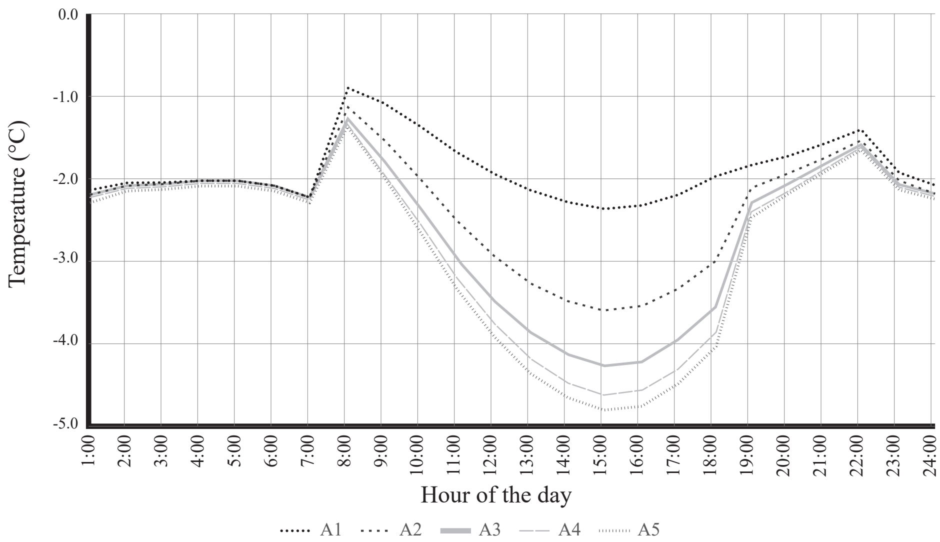


FIGURE 5.12 Classroom temperature differences during a typical day of the hottest month between the proposed EAHE pipe-ground contact areas and the Base Case

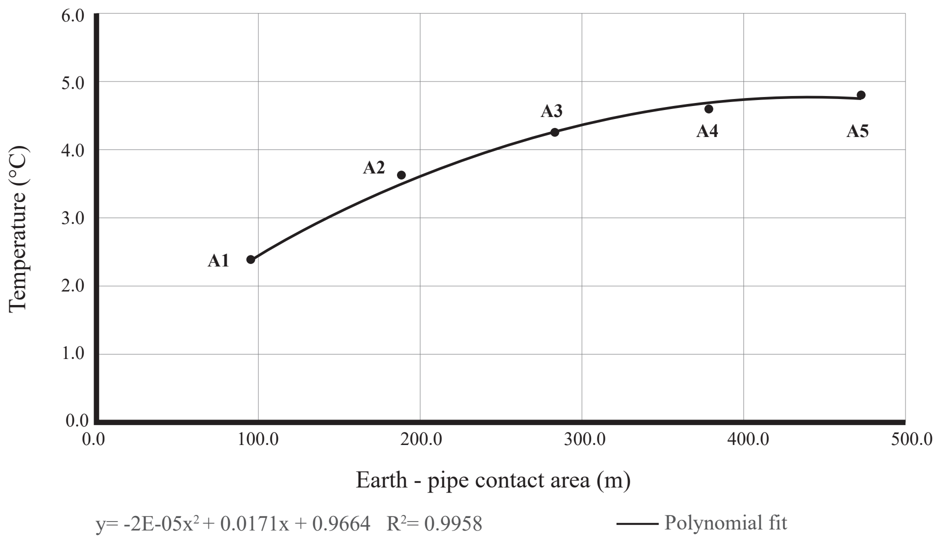


FIGURE 5.13 Maximum classroom temperature differences between the proposed EAHEs and the Base Case as a function of the pipe-ground contact area

detailed in the **Chapter 4**-Section 4.2.4 and the thermal performance of the Base Case school classroom was used as a reference point.

The classroom operative temperature (T_o) on a typical day of the hottest month (April) for each one of the proposed EAHE systems is presented in Figure 5.11. The estimation was made by averaging the hourly T_o of the 30 days of the month. Figure 5.12 shows the To differences during the typical day between the proposed EAHEs and the Base Case. Both graphs show that increasing the contact area between the pipe and the ground will lead to a better thermal performance, especially in the hottest hours of the day where the indoor temperature can be up to 4.8°C below the Base Case.

The pipe-ground contact area of each one of the evaluated EAHE systems were regressed against the maximum temperature differences using a polynomial fit. Figure 5.13 shows that the maximum cooling (4.6°C) was obtained when the pipe-ground contact area was around 425 m^2. There is no additional increment above this point.

Outside air volume: A similar procedure to the one used in the previous section was used to estimate the number of air changes per hour (ACH) at which the classroom will have the best thermal performance. The EAHE system was used as the only source of outside air, therefore, the natural ventilation on the model was set to the off-mode. Previous computer simulations presented in Appendix 5.2 show that the classroom's thermal performance is better when EAHE is used as the only source of ventilation. A plausible explanation for this is that the tube's outlet air temperature is lower than the one that enters through the windows.

Table 5.5 shows the characteristics of EAHE systems and the ACH tested. Again, the operative temperature (T_o) was used as a proxy the of classroom's thermal performance. Figure 5.14 and Figure 5.15 show the T_o on a typical day of the hottest month (April)

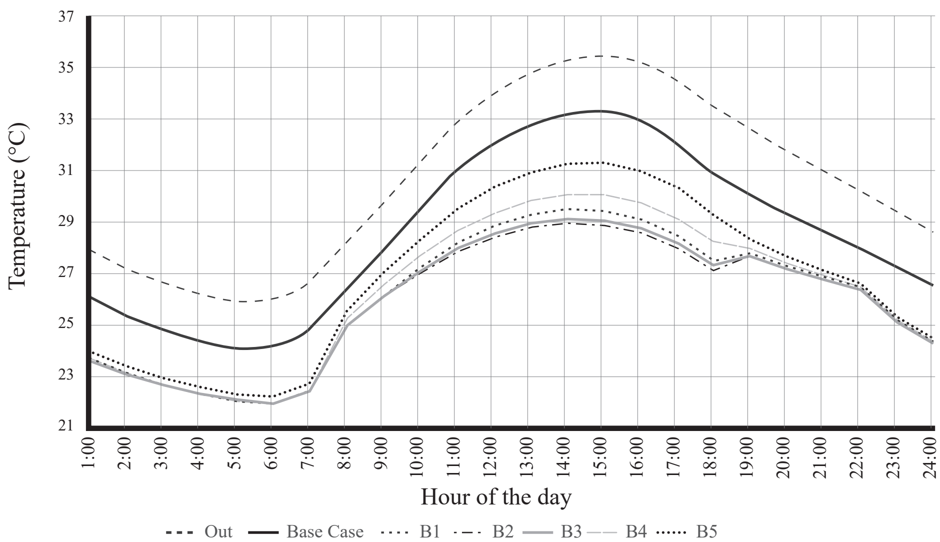


FIGURE 5.14 Indoor classroom's temperatures (T_o) on a typical day of the hottest month using different EAHE outside air volumes (ac/h). Estimated by averaging hourly temperatures of the 30 days of the month

TABLE 5.6 Characteristics of the evaluated EAHE system

Pipe-ground contact area (m^2)	Length of the pipe (m) [(1)]	Pipe depth under ground surface (m)	Required area (m^2) [(2)]	Outdoor air volume (ac/h)
282.7	600	1.0	1200	25

(1) The length was estimated according to a pipe radius of 7.5 cm
(2) The required area was estimated assuming that distance between pipes is one meter
The pipe's thermal conductivity is 0.5 W/m- K (polyethylene)
The operation schedule of the EAHE is from 7 a.m. to 6 p.m.
The EAHE is the classroom's only ventilation source. Natural ventilation in the Design Builder was set to the OFF mode
The characteristics of the soil are Heavy Saturated and Bare and Wet

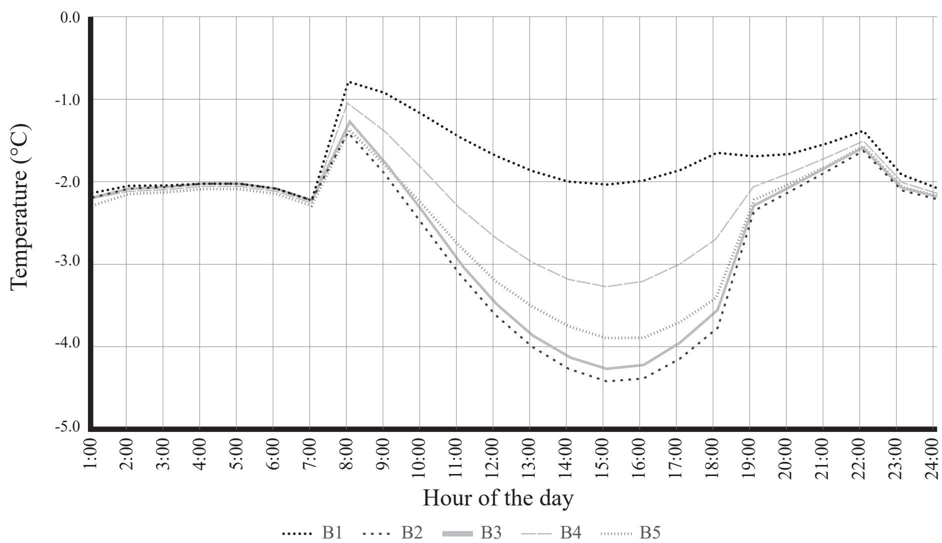


FIGURE 5.15 Indoor temperature differences during a typical day of the hottest month between the proposed EAHE outside air volumes (ac/h) and the reference case

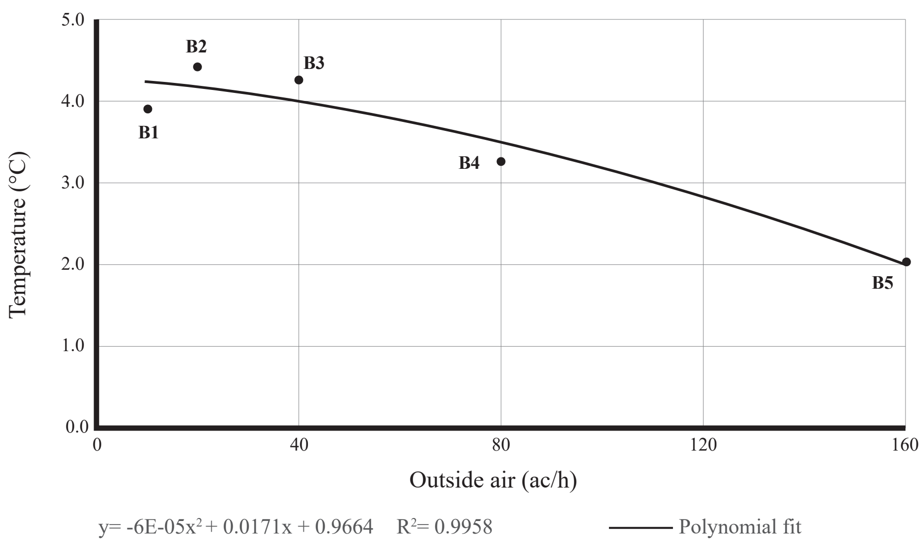


FIGURE 5.16 Maximum classroom temperature differences between the proposed EAHE systems and the Base Case as a function of the outside air volumes (ac/h)

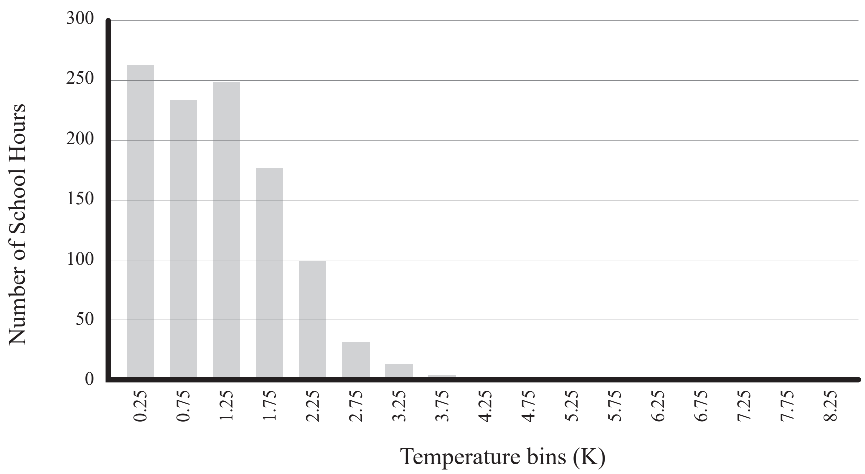
and the T_o differences during a typical day between the proposed EAHEs and the reference case. Both graphs show that the classroom's thermal conditions are better when the EAHE systems are in operation, no matter the ACH. However, when the air change rate is above 40 ac/h, the thermal differences decrease dramatically. A plausible explanation is that the air needs a certain amount of time in the tube to be cooled down. These results were corroborated by regressing the tested ACH against the maximum temperature differences (Figure 5.16).

Forty air changes per hour was the estimated outdoor air volume in the monitored classrooms. Therefore, this was the ACH chosen for further analysis. A maximum cooling potential of around 4°C would be expected.

Depth at which the pipes are buried: A procedure similar to the one used in the previous section was employed to estimate at which pipe depth the EAHE would have the maximum cooling potential. Table 5.5 shows the characteristics of EAHE systems and the depths tested.

According to the selected characteristics, soil and climatic conditions, the results of the simulations performed in Design Builder do not show, for the tested tube depths, a big difference in the thermal behavior of the class. The maximum difference between a tube buried at 0.5 m and another buried at 3 m was 0.44°C in the warmer hours of the day.

After optimizing the main four aspects that affect the efficiency of the EAHE system, a final dynamic simulation of the classroom's thermal environment was made for a whole year in the Design Builder software version v5.3.0.14. The EAHE system's characteristics are presented in Table 5.6. The model's main settings were not changed. The resulting operative temperature was used to estimate the H_e and to compare them with the Base Case.



School year hours over the $T_{o\text{-}max}$ (Exceedance Hours- EH): 1071 (52.0%)
ΔT school year peak: <4°C

FIGURE 5.17 Model 3: Exceeding degrees (ΔT). The number of degrees over the $T_{o\text{-}max}$ was estimated and binned into 0.5°C intervals for each hour

Figure 5.18 presents the fluctuation of the T_{o-max} and the upper classroom's temperature limit (T_{o-max}) through the school year and the corresponding indoor temperatures. From a total of 2060 school hours, 1071 were over the T_{o-max}, meaning that 52% of the time the classroom's temperature is above the reference temperature. Using an EAHE system could lead to a 31% reduction of the H_e. A maximum cooling potential of XXX°C was achieved.

The exceedance degrees (ΔT) are presented in Figure 5.17 and the Daily Weighted Exceedance (W_e) along the school year is presented in Figure 5.19.

5.3.2.4 Microclimate controls (S4)

The microclimate can be modified by appropriate landscaping techniques. Green areas, water surfaces and ground materials can be applied at an urban level (i.e. parks, playgrounds and streets) and at a building site level (i.e. courtyards, rooftop gardens, green walls and green roofs) to cool down the external air before it enters the building (Givoni 1991a; Geetha, Velraj 2012) .

Green areas can cool down the ambient air and surface temperatures through the process of shading and evapotranspiration (Jamei, Rajagopalan, Seyedmahmoudian, Jamei 2016). Trees and other plants can intercept the solar radiation before it reaches the building envelope and other external surfaces, preventing unwanted solar heat gain. The shading quality is determined by the placement, the height and geometry of the canopy, the foliage's characteristics, and the structure (Jamei, Rajagopalan, Seyedmahmoudian, Jamei 2016).

However, plants have also the capability to modify the daily temperature swings though the evaporation and transpiration of moisture through leaves (Huang, Akbari, Taha, Rosenfeld 1987). This phenomenon is called evapotranspiration (Jamei, Rajagopalan, Seyedmahmoudian, Jamei 2016; Kamal 2012). The solar energy absorbed causes an increase in latent heat and, therefore, cools the leaf and the temperature around it. This condition does not occur in impermeable urban surfaces, which immediately retain and absorb solar radiation (Jamei, Rajagopalan, Seyedmahmoudian, Jamei 2016). Therefore, from the point of view of energy conservation, a tree can be regarded as a natural "evaporative cooler" using up to 100 gallons of water a day (Kozlowski, Kramer 1960). As with shading, the evaporative cooling effect of the trees depends on the total height, the canopy's geometry and the foliage's characteristics. However, the humidity level and the soil moisture of the surrounding area are also important.

Field and computer simulation-based studies presented in Table 5.7 show that green and shaded areas tend to be colder than their paved surroundings and that there is a reduction in the air temperature when the percentage of trees or green areas increase. A single tree can already moderate the climate well, but the impact is limited (Wong, Kardinal Jusuf, Aung La Win, Kyaw Thu, Syatia Negara, Xuchao 2007). However, bigger greens areas like urban parks can have larger impacts, lowering air temperatures not only within them but also in the surroundings. Reported differences in air temperature can go up to 7°C and average reductions are around 1°C and 3°C at peak temperature hours. However, as shown by (Huang, Akbari, Taha, Rosenfeld 1987; Taha, Akbari, Rosenfeld, Huang 1988; Vailshery, Jaganmohan, Nagendra 2013), this difference changes through the day and tends

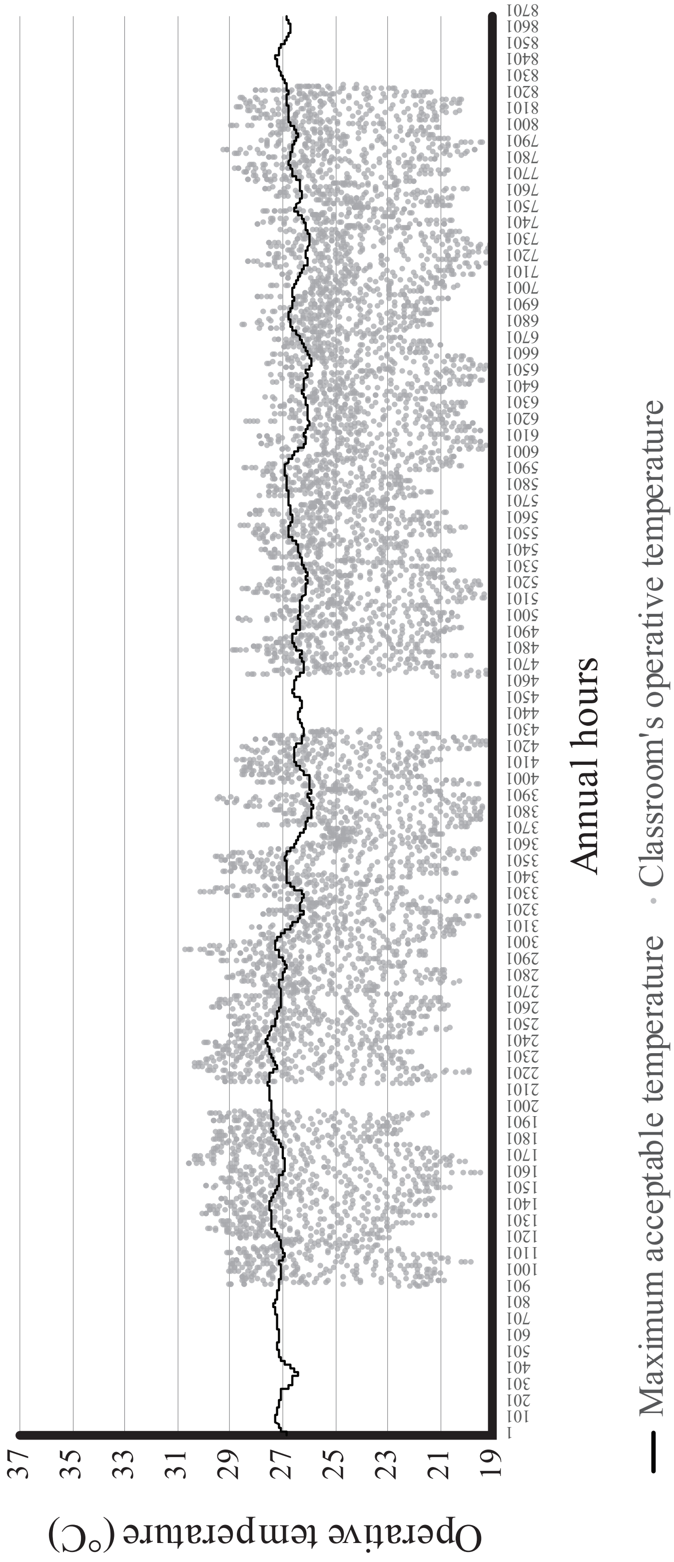


FIGURE 5.18 Model 3: Exceeding degrees (ΔT). The number of degrees over the $T_{o\text{-}max}$ was estimated and binned into 0.5°C intervals for each hour

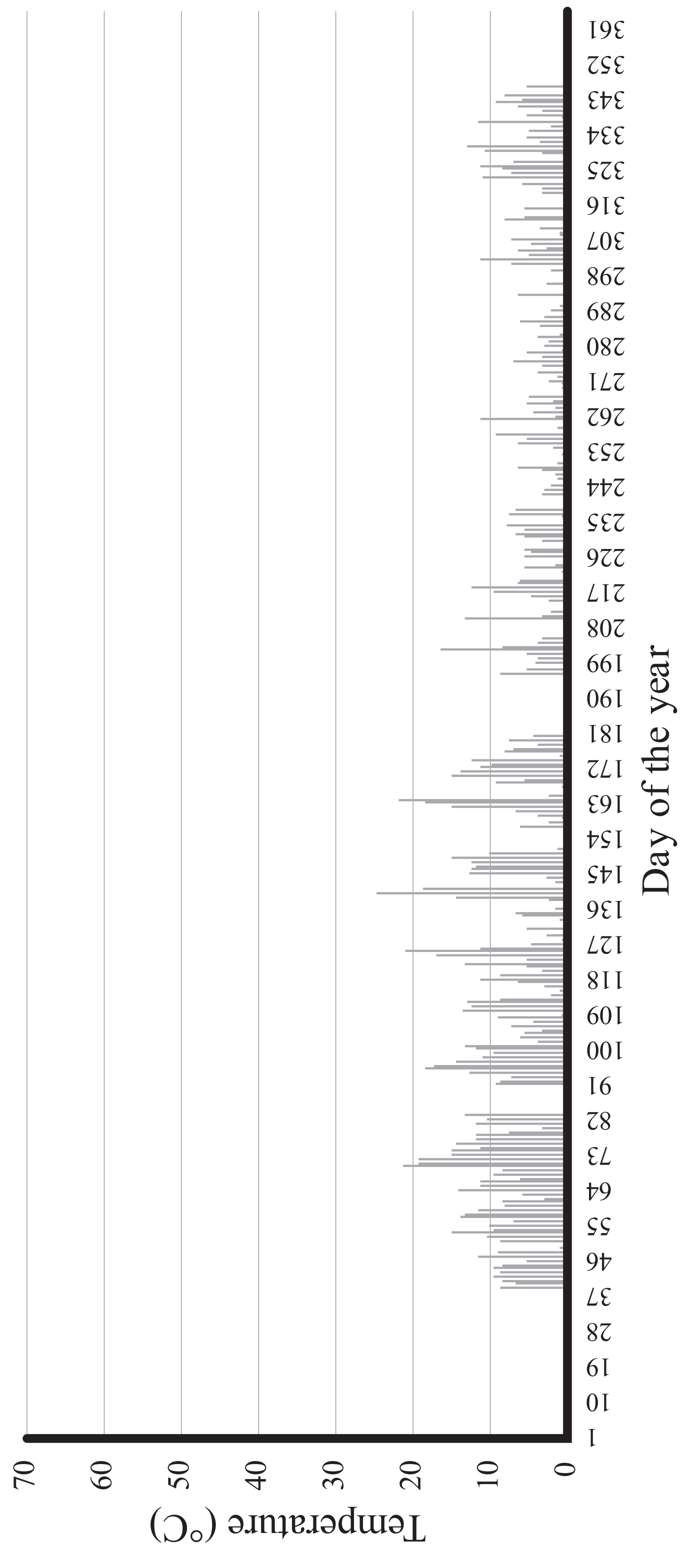


FIGURE 5.19 Model 3: Daily Weighted Exceedance (W_e). Estimated by adding all the exceeding degrees (ΔT) of a school day

TABLE 5.7 Summary of selected field and computer simulation studies examining the impact of green areas on ambient air temperatures

Study	Year	Location	Type	Temperature difference or reduction (°C)	
(McGinn, 1982)	1982	NA	Field study	2.0-3.0	Daytime peak differences between neighborhoods under mature tree canopies and newer areas with no trees, both located in the suburbs
(Saito, Ishihara, and Katayama 1990)	1991	Kumamoto City, Japan	Field study	3	Highest difference in summer between the inside and outside of a small green area (60 X 40m)
(Nichol 1996)	1996	Singapore	Field study	1.5–2	Mean daytime values between tree canopies and surrounding areas
(Ca, Asaeda, and Abu 1998)	1998	Tokyo, Japan	Field	2.0	Highest Ta difference on noon time grassland was more than 2.1°C lower than those measured above hard surfaces in commercial and parking areas
(Bass et al. 2015)	2002	Toronto, Canada	Simulation	0.6	Average Ta reduction when 5% of the total area of the city of Toronto was replaced with green roofs
(Givoni et al. 2003)	2003	Israel	Field	2.3	Highest difference between a kibbutz and its surroundings
				>1.5	Average difference between a kibbutz and its surroundings
(Nyuk Hien Wong and Yu 2005)	2005	Singapore, Singapore	Field	4.0	Highest Ta difference between urban and rural areas
(Y. Chen and Wong 2006)	2006	Singapore, Singapore	Field / Simulation	1.3	Highest average Ta difference between green areas and its surroundings
(Chang, Li, and Chang 2007)	2007	Taipei, Taiwan	Field study	0.8	Summer midday differences between parks and surroundings
				3.0	Peak noontime temperatures differences between parks and surroundings
(N. H. Wong et al. 2007)	2007	Singapore, Singapore	Simulation	3.3	Highest difference during daytime between a dense green area and away from the greenery areas
(Oliveira, Andrade, and Vaz 2011)	2011	Lisbon, Portugal	Field study	6.9	Highest difference during the hottest month of the year between shaded and sunny sites in a small garden space
				1.6	Median differences under the sun during the hottest month of the year between shaded and sunny sites in a small garden space
				0.7	Median differences under the shade during the hottest month of the year between shaded and sunny sites in a small garden space
(Ng et al. 2012)	2012	Hong Kong	Simulation	1.0	Average reduction when adding 33% more trees in a highly dense area in Hong Kong
(Shahidan et al. 2012)	2012	Putrajaya, Malaysia	Simulation	2.7	Average Ta reduction when increasing tree canopy density and modifying ground material
(Vailshery, Jaganmohan, and Nagendra 2013)	2013	Bangalore, India	Field study	5.6	Highest difference on summer sunny days between street segments with trees and with no trees
(Srivanit and Hokao 2013)	2013	Saga, Japan	Simulation	0.2	Average reduction at the hottest hour of the day in summer when increasing the number of the trees by 20%
				2.3	Maximum reduction at the hottest hour of the day in summer when increasing the number of the trees by 20%
(L. Chen and Ng 2013)	2013	Hong Kong	Simulation	0.45	Average Ta reduction when trees are planted in a courtyard
(Gromke et al. 2015)	2015	Arnhem, Netherlands	Simulation	1.6	Highest difference between street segments with trees and with no trees
				0.43	Average difference between street segments with trees and with no trees

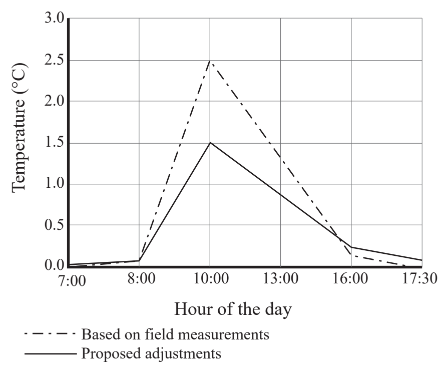
T_a: Ambient air temperature

to be negligible at dawn and dusk.

Field measurements were carried out in Costa Rica to validate these findings in a warm-humid environment. A small shaded green area and its paved surroundings were monitored between the 20th and the 27th of June 2018 during sunny days (Additional information about the measurement procedure can be found in the Appendix 5.3). Figure 5.20 shows the mean air temperatures registered in both locations through the day. The maximum mean temperature difference was 2.5°C and was registered at 10 a.m. Differences tend to be negligible, one hour after and one hour before dawn and dusk respectively. Results are similar to the ones reported by the studies presented in Table 5.7. However, the maximum difference was registered at 10 a.m. and not at midday or mid-afternoon.

Based on the published information and the field measurements performed, an adjustment (Equation 5.3) due to microclimate controls was introduced into the site's weather data file (**Chapter 4-** Section 4.3.3).

TABLE 5.8 Air temperature differences between a small shaded green area and its surroundings. Field measurements made in a warm humid in Costa Rica between June 20th-28th 2018 with a Kestrel 5500



Hour	Based on field measurements (°C)	Proposed adjustment (°C)
8:00	0.1	0.1
9:00	1.3	0.8
10:00	2.5	1.5
11:00	2.1	1.3
12:00	1.7	1.1
13:00	1.3	0.9
14:00	0.9	0.7
15:00	0.6	0.5
16:00	0.2	0.25
17:00	0	0.1

FIGURE 5.20 Mean registered air temperatures of a small shaded green area and its surroundings. Measurements performed in a hot-humid climate in Costa Rica between June 20th -28th with a Kestrel 5500

$$T_{out\text{-}mc} = T_{out} - T_{adj\text{-}mc} \qquad (5.3)$$

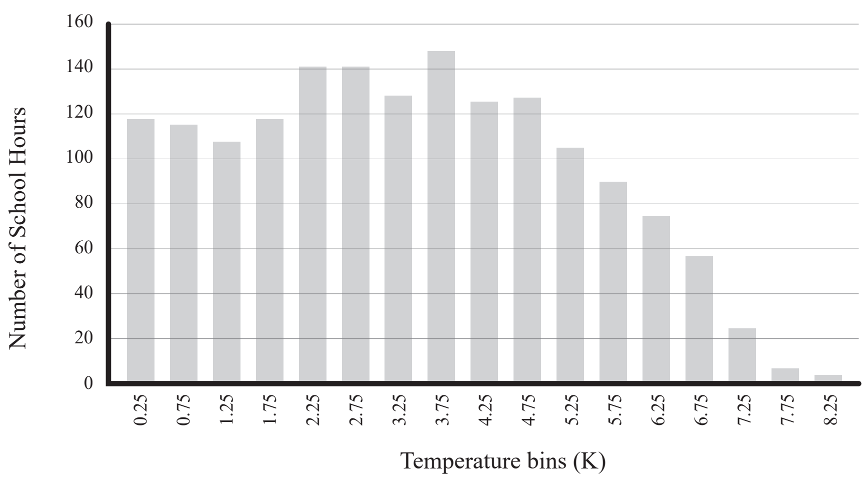
Where T_{out} is the outdoor dry bulb temperature and $T_{adj\text{-}mc}$ corresponds to the adjustment proposed to the day hours as reported in Table 5.8. The proposed correction to the outdoor dry bulb temperatures is slightly lower than the differences registered in the field study and the ones reported by (Huang, Akbari, Taha, Rosenfeld 1987; Taha, Akbari, Rosenfeld, Huang 1988; Vailshery, Jaganmohan, Nagendra 2013); however, it represents a conservative scenario based on the fact that some means of existing vegetation can be found in the existing school buildings.

Relative humidity and dew point were also adjusted. Considering that temperature and relative humidity are inversely related and both of them affect the dew point, these climatic elements were modified in the weather file. The relative humidity was adjusted inversely 3.96% for each degree, while the dew point was changed following the equation proposed by Lawrence (2005). For further details of both adjustments refer to Appendix 5.4.

With the modified weather file, the classroom's thermal conditions were simulated for a whole year in the Design Builder software, version v5.3.0.14. The temperature was used to estimate the He from the thermal outcomes.

Figure 5.22 presents the fluctuation of $T_{o\text{-}max}$ through the school year and the corresponding indoor temperatures. Zones with no data correspond to the holiday periods. From a total of 2060 school hours, 1636 were over the $T_{o\text{-}max}$. The classroom was over the maximum temperature limits for 79% of the school time.

Therefore, a decrease of 4% in the EH can be expected by using microclimate controls. A maximum cooling potential of 0.9°C was reached inside the classroom when compared to the Base Case.



School year hours over the $T_{o\text{-}max}$ (Exceedance Hours- EH): 1636 (79.4%)
ΔT school year peak: >8 °C

FIGURE 5.21 Model 4: Exceeding degrees (ΔT). For each hour the number of degrees over the $T_{o\text{-}max}$ was estimated and binned into 0.5°C intervals. Microclimate controls was applied as a passive cooling strategy

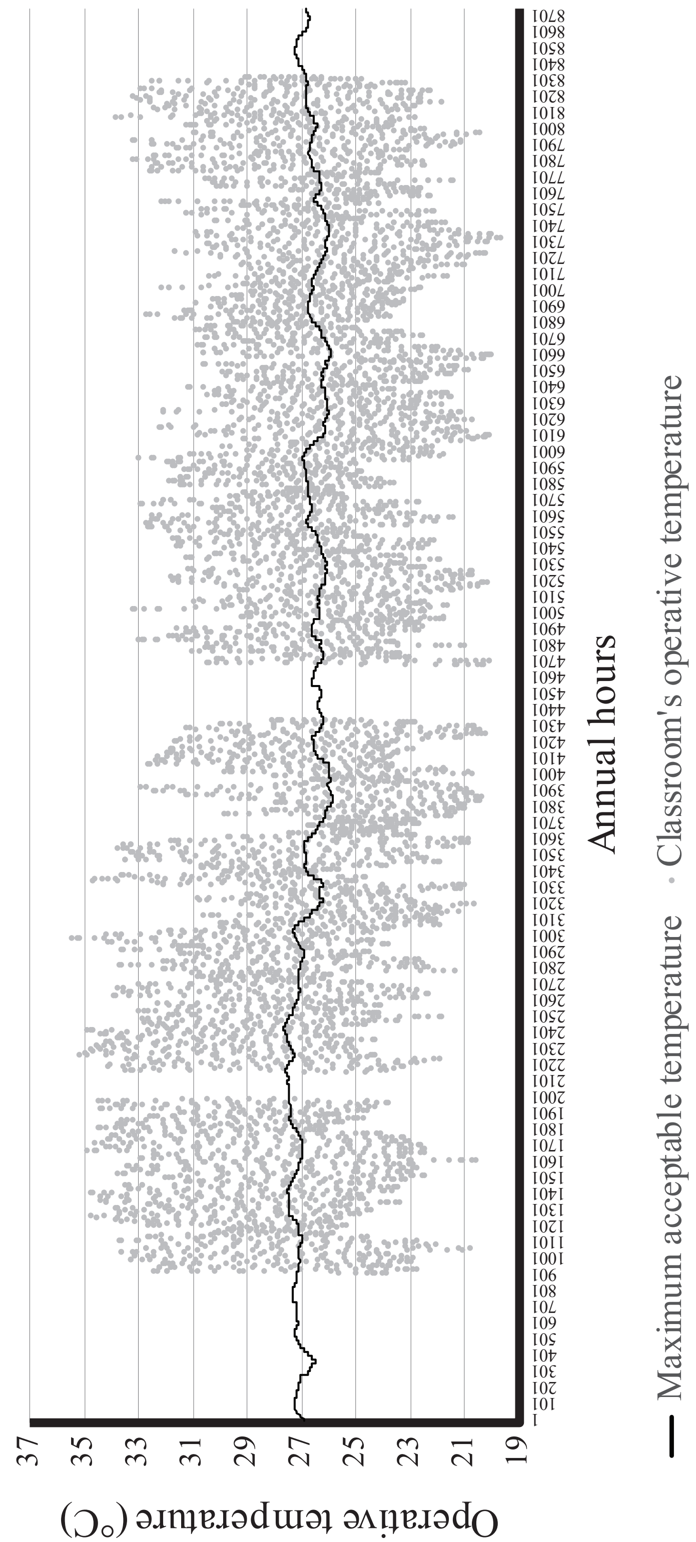


FIGURE 5.22 Model 4: Fluctuation of the operative temperature upper limit ($T_{o\text{-}max}$) through the school year and the corresponding classroom operative temperatures. Microclimate controls were applied as a passive cooling strategy

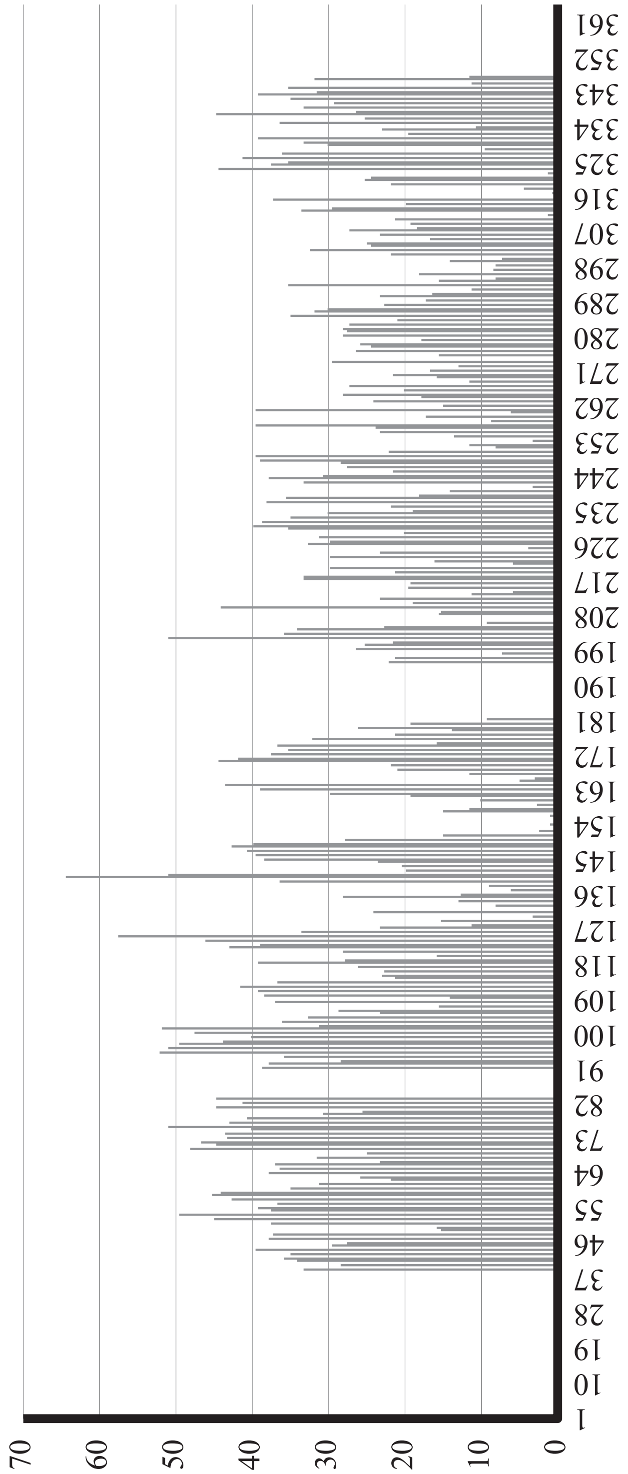


FIGURE 5.23 Model 4: Daily Weighted Exceedence (W_e). Estimated by adding all the exceeding degrees (ΔT) of a school day

TABLE 5.9 School classroom overheating indicators for the Base Case and proposed models where individual passive or low energy consuming cooling strategies were applied

Model	Strategie applied	EH (%)	Difference (°C) (1)	H_e (%)	Difference (°C) (1)	W_e (SD) (°C)	ΔT (°C)
Base case	None	83.4	-	73.9	-	31.6 (13.2)	>8.0
1	S1	61.6	21.8	49.1	24.8	16.3 (9.9)	<7.0
2	S2	74.8	8.6	62.5	11.4	21.4 (10.7)	<7.0
3	S3	52.0	31.4	28.0	45.9	7.1 (5.0)	<4.0
4	S4	79.4	4.0	68.1	5.8	27.0 (12.7)	>8.0

S1: Apparent cooling effect of air movement
S2: Roof thermal properties
S3: Ground cooling
S4: Microclimate controls
(1) Difference between the model's percentage of EH and H_e and the Base case. Higher difference percentage means higher improvement in the classrooms thermal conditions

TABLE 5.10 School classroom overheating indicators for the Base Case and proposed models where the four selected passive or low energy consuming cooling strategies were combined

Model	Strategie applied	EH (%)	Difference (°C) (1)	H_e (%)	Difference (°C) (1)	W_e (SD) (°C)	ΔT (°C)
Base case	None	83.4	-	73.9	-	31.6 (13.2)	>8.0
5	S1 + S2	46.0	37.4	30.6	43.3	9.5 (6.6)	<5.0
6	S1 + S3	5.2	78.2	0.7	73.2	1.5 (1.7)	<2.0
7	S1 + S4	54.2	29.2	40.8	33.1	13.5 (8.7)	<6.5
8	S2 + S3	9.0	74.4	0.1	72.8	1.2 (0.9)	<1.5
9	S2 + S4	46.7	36.7	24.3	49.6	6.0 (3.5)	<3.5
10	S3 + S4	47.3	36.1	23.4	50.5	6.3 (4.7)	<4.0
11	S1 + S2 + S3	0	83.4	0	73.9	-	-
12	S1 + S2 + S4	3.6	79.8	0.1	72.8	0.7 (0.8)	<1.5
13	S1 + S3 + S4	3.6	79.8	0.4	73.5	1.3 (1.5)	<1.5
14	S2 + S3 + S4	6.5	76.9	0	73.9	0.9 (0.6)	<1.5
15	S1 + S2 + S3 + S4	0	83.4	0	73.9	-	-

S1: Apparent cooling effect of air movement
S2: Roof thermal properties
S3: Ground cooling
S4: Microclimate controls
(1) Difference between the model's percentage of EH and H_e and the Base case. Higher difference percentage means higher improvement in the classrooms thermal conditions

A measure of the severity of the Exceedance Hours is presented in Figure 5.21. The exceeding degrees from the limiting maximum acceptable temperature (ΔT) are shown binned into 0.5°C intervals. ΔT is over 1°C 68% of the time, and the exceeding degrees can surpass 7°C, but only for a few hours in the school year (11).

The variation of the Daily Weighted Exceedance (W_e) through the school year is presented in Figure 5.23. The We mean was estimated to be 26.6°C (SD ± 13.1°C). However, peaks of 65°C were seen.

5.3.2.5 Summary

To cool down the classroom's indoor thermal conditions and reduce the number of school year EH, four passive or low energy consuming strategies with a high cooling potential in the warm humid climates were applied independently to the Case Study's school classroom. Table 5.9 shows a summary of the main overheating indicators for the simulated models including the Base Case (BC). All the models, compared with the BC, showed an improvement of the indoor thermal conditions, meaning that the strategies applied were able to dampen the indoor air temperatures. The percentage of EH during the school year decreased by between 4 and 32%. Other overheating indicators like the Hours of Exceedance (H_e), the exceeding degrees (ΔT), and the Daily Weighted Exceedance also showed an improvement. The maximum reduction in the EH was achieved with Models 1 and 3 where the air speed in the classroom was increased and an EAHE system was included.

TABLE 5.11 Pending

However, none of the models improve the thermal conditions of the classrooms enough to meet the criteria of the CIBSE TM52. The temperature inside the classroom is still above the maximum permitted in more than 50% of the school hours.

5.3.3 Estimation of the Exceedance Hours method (EH) and the CIBSE TM52 overheating indicators after applying different combinations of the selected cooling strategies

A multi-variable analysis was made, where all the interactions between the different cooling strategies were considered with the goal of estimating/knowing whether it is possible to reach a greater cooling potential through the combined application of the passive strategies. Eleven simulation models combining all possible interactions between the four strategies selected were developed and analyzed.

Table 5.10 shows the evaluated models and the results. The CIBSE TM52 criteria was met in at least 7 of the models.

The maximum cooling potential in degrees celsius that can be achieved with each of the models is presented in the Table 5.11. The maximum cooling potential corresponds to the maximum temperature difference between the analyzed model and the Base Case. Classrooms were cooled down by up to XXX°C

5.4. DISCUSSION

An elementary school building in the warm-humid climate of Costa Rica was chosen as a Case Study (SC). A previous study developed in Chapter 4 showed that despite the building's good orientation, architectural configuration and solar protection, the classrooms are at risk of overheating for 83% of the school hours.

Four passive or low energy consuming strategies with a high cooling potential were identified and applied individually and combined into CS. The results show that it is possible to achieve an optimal classroom thermal environment for learning in the tropics by combing 2 or more strategies. Seven of the eleven models meet the CIBSE TM52 requirements, which establishes that 3% is the maximum percentage of school hours that the classrooms temperature can be 1°C over the upper temperature limit (Table 5.10).

The combination of strategies shows positive synergies. The combination between ACEAM and ground cooling is the most effective (Model 6). Between them they provide an optimal thermal environment during 95% of the school year. If ground cooling is not used, the only possibility to fulfill the CIBSE's requirements in the CS school building through passive techniques is by combining the other 3 strategies (Model 12).

5.4.1 Apparent cooling effect of air movement (ACEAM)

Results show that the apparent cooling effect of air movement (ACEAM) (S1) is a highly effective cooling strategy. Increasing the air speed from an average of 0.3 m/s to 1.2 m/s would mean a reduction close to 25% in the He number. However, achieving this cooling effect relying only on the breeze, window opening, and cross-ventilation might not often be achievable. The building's density may affect good wind exposure or planning constraints may produce an inadequate cross ventilation (Szokolay 1997). Therefore, electric fans could be a good option to provide a constant and well distributed flow at an average air speed of 1.2 m/s during all the school hours.

Even if fans use energy, they do it at low rates and they are easy to use, low cost, and low maintenance devices. As a result, the ACEAM, due to the cost-effectiveness relationship, should be the first strategy to be implemented in the school classrooms. The use of fans will make the ACEAM a relatively simple cooling strategy to implement, turning it into a stable and easy option to control cooling sources. The modifications that must be done in the school buildings are minimal and they can be done on both old and new schools. However, it is still necessary to study the air velocities and flow patterns produced by fans to estimate the number of devices needed and their distribution in the classroom. Kimura et al. (1993) showed that fluctuating air movement of a sine wave nature made the subjects feel cooler than other fluctuation patterns did. Installation in ceilings, walls or on desktops should also be considered. Toftum (2004) showed that delegating individual control of the air velocity to occupants helps to increase their acceptance of electric fan cooling and that this can be easily created with desk fans.

Two main issues are still a topic of discussion for the scientific community. The first one is the appropriate level of air velocity. The ASHRAE's thermal adaptive comfort model admits no more than 1.2 m/s (ANSI/ASHRAE 2013), while according to Szokolay (2006) velocities up to 1.5 m/s can be considered. The second issue is the cooling effect of air movement. Unlike which is proposed by the ASHRAE model, many authors have shown higher cooling effects. Khedari (2000), for example, showed that increasing the air speed from 0.2 m/s to 1.5 m/s will produce a cooling effect of 4.5 K. While Szokolay (2006) proposed a mathematical model based on 12 studies from different climates where an air velocity of 1.5 m/s will produce an apparent cooling effect of 4.8 K.

Higher cooling effects will help to decrease the EH and He percentage even further For example, if Khedari's (2000) 4.5 K is used instead of the ASHRAE's 2.2 K, the air movement will produce an additional 30% reduction in the He number. Therefore, additional research including tropically acclimatized children is needed for these two topics.

However, as in all passive cooling strategies, the apparent cooling effect of air movement has some limitations that should also be analyzed before its implementation. The perception of air movement depends not only on the air velocity and other thermal environment parameters, but also on personal factors like activity level, overall thermal sensation and clothing (Toftum 2004). The pressure on the skin and the general disturbance induced by the air movement may cause discomfort in itself (Toftum 2004), and high air speeds may also cause more dust particles to be suspended, dry eyes, and could irritate the mucous.

Additionally, in urban zones with high outdoor pollution and noise, ventilation through window opening might complicate the teaching process and affect the pupils' health and performance.

5.4.2 Ground cooling

Ground cooling was the strategy with the greatest cooling potential. It is also a source of stable cooling and a mechanical system that once working, is easy to control and graduate. However, it is also the most difficult strategy to implement due to the technical challenges and the investment that must be made. EAHE systems are currently considered a very mature and quite efficient technology with many working examples worldwide (Santamouris, Kolokotsa 2013), but in an early development stage in the tropical climates.

To achieve a cooling potential as high as the one estimated in the studied/simulated models (Models 3, 6, 8, 10, 11 and 13-15), it is necessary to install a 15 cm diameter 600 m long polyethylene pipe, which according to preliminary calculations based on the existing bibliography would require at least 1200m^2 of land (considering all the pipes being buried at the same level). This amount of land is required due to the thermal interference between pipes that is affected by the distance between tubes (Liu, Yu, Liu, Qin, Zhou, Zhang 2017). To avoid this, Santamouris (2006) and Patel and Ramana (2016) recommend a distance of two meters between pipes, while Liu et. al (2017) proposed one meter.

Another technical challenge is the maintenance of the systems. In tropical climates this should be taken into consideration, due to the high level of humidity condensation that might appear in the underground pipes (Katili, Boukhanouf, Wilson 2015). The accumulation of dust and water together with the difficulties in cleaning the pipes are factors that might affect the quality of the air that enters the building.

An accurate analysis of the microclimatic conditions and the soil around the building are essential to estimate the ground cooling potential and to decide which technique should be applied to the building (Santamouris 2007). The cooling potential of the soil can be improved if it is covered, shaded or irrigated (Givoni 2007). Givoni (1991b) demonstrated through experiments in Israel and North Florida that it is possible to lower the earth surface temperature by about 8-10 K below the summer temperature.

Despite the thermal benefits that an EAHE could present, the dimension of the pipe system and other technical challenges mentioned above, require a detailed cost-benefit analysis before its implementation.

5.4.3 Roof insulation

The roof insulation is, together with ACEAM, the easiest strategy to implement. Even when it involves constructive changes in the building, it can be applied in new and old schools. However, this strategy only provides an 8.6% reduction of the EH. However, its construction is significant when combined with other strategies. For example, roof insulation, cooling ventilation and microclimate controls individually provide a reduction of 8.6%, 21.8% and 31.4% respectively. (Table 5.10). On the other hand, Model 12, which combines these three strategies, manages to reduce it by 79.8%, being one of the most effective combinations.

The thermal insulation is a cooling strategy that has the advantage that it can be applied by material or by design. Well ventilated attics, double roofs, or second floors, provide an excellent thermal insulation. In school buildings, classrooms can be located on the first storey, while complementary spaces like dining rooms, offices, and libraries would occupy second floors.

The insulation material and thickness employed in the evaluated models had the aim of estimating the strategy's maximum cooling potential and should not be considered a recommendation. Material and thickness selection should be made by a technical and cost-benefit analysis. Again, the high level of humidity condensation should also be considered, especially when using metal sheets for roofing.

5.4.4 Microclimate controls

The microclimatic controls are the least effective strategy of the 4 analyzed. The reduction in the number of Exceedance Hours (EH) is only 4%. However, just like with roof insulation, the contribution is significant when combined with other strategies.

Since microclimatic controls may require a certain amount of land for vegetation, this strategy can be combined with the ground cooling. In the studies, no mention is found of the relationship between the size of the green area and its cooling effect, so additional studies are needed to estimate whether this relationship exists directly and how much additional land would be necessary. In urban sites where the amount of land is a limitation, this strategy could be applied through pergolas, green roofs, and green walls, among other options.

5.4.5 Summary

Results show that an optimal thermal learning environment can be achieved in the Case Study's school building with only passive or low energy consumption cooling strategies, avoiding the use of mechanical cooling. However, the step that must be given to transform some of the cooling strategies into efficient/effective architectural and/or constructive solutions is not so simple, as they present huge technical and economic challenges.

Therefore, even when cost-benefit analysis is still necessary to make final decisions, a gradual use of the cooling strategies considering the climatic conditions of the site is proposed in Table 5.12. Warm-humid climates may differ from one place to another, even within small distances; therefore, cooling needs may also vary. The country town of Bebedero, where the school is located, is one of the warmest places in Costa Rica (Vargas-Soto 2016; San Juan, Hoses, Martini 2014) and the cooling needs might be higher than in other locations (Porras-Salazar, Pulido-Arcas, Piderit-Moreno 2018). Thus, through a gradual use, those strategies that are easy to implement are favored (i.e. cooling effect of ventilation and roof insulation), while the ones that present more technical and economic challenges are relegated for the extreme weather locations (i.e. microclimate controls and ground cooling).

Accordingly, it can be seen that even when ground cooling was the strategy with the highest cooling potential, due to the aforementioned technical challenges and the system's cost, it should only be considered for new schools located in very hot humid climates and after a thorough cost-benefit analysis. In the same vein, microclimate controls are proposed as a complementary strategy: Its effectiveness is not questioned, through landscaping techniques it is possible to reduce air temperature; however, the cooling potential varies according to many variables that are difficult to control.

This study presents the limitation that it does not consider the economic or space implications that the application of strategies could entail. Subsequent studies would have to focus on these estimations.

Even though the most effective strategies were identified, analyzed and the cooling potential estimated, a first draft about how and where to implement the studied strategies is also presented. This proposal needs validation through field and computer simulation studies; however, it is a first step towards developing standards and guidelines that can lead to learning thermal conditions in the tropics in a better way.

5.5. CONCLUSIONS

- An optimal thermal learning environment can be achieved in the Case Study's school building with passive or low energy consuming cooling strategies only. However, the step that must be given to transform some of the cooling strategies into efficient/effective architectural and/or constructive solutions is not so simple, presenting

TABLE 5.12 Recommended gradual use of the cooling strategies according to microclimate

Required reduction in the percentage of H_e to achieve the CIBSE criteria	Classification:		Suggested cooling techniques according to microclimate
	Site's temperature conditions	School type	
<10%	Moderate	A	Cooling requirements can be achieved with window opening ventilation or fans providing an average air speed of approximately 0.6 m/s can be used (S1)
10-25%		B	Cooling requirements can be achieved with ceiling of wall fans provinding an average air speed between 0.6 m/s and 1.2 m/s can be used (S1)
25-45%	Warm	C	Cooling requirements can be achieved with combination of the cooling effect of ventilation (S1) and roof insulation (S2)
45-70%	Hot	D	Cooling requirements can be achieved with a combination of the cooling effect of ventilation (S1), roof insulation (S2), and microclimate controls (S3)
>70%	Very hot	E	Cooling requirements can be achieved with mechanical cooling or a combination of ground (S3), ventilation cooling (S1) and roof insulation (S2)/ microclimate controls (S4)

Note: In all of these scenarios as in the studied base study, school buildings should be well oriented and solar gains controlled.

technical and economic challenges.

- There is a small number of cooling strategies that can be efficient in warm-humid climates. Due to the low day-night and yearly temperature swing, many of the strategies that perform quite well in other hot climates have limited effects in warm-humid regions.
- The ground cooling and the cooling effect of ventilation (ACEAM) were the strategies that presented the highest cooling potential, and therefore generated the highest decrease in the He percentage. Using the former alone will result in a reduction of 45.9%, while the second produces a 28% contraction.
- Even when ground cooling was the strategy with the highest cooling potential, it is also the most difficult strategy to implement due to the technical challenges and the investment that must be made. Careful technical and cost-benefit analysis should be made before its implementation.
- A gradual use of the cooling strategies considered the climatic conditions of the site was proposed due to the different warm-humid microclimates and to promote a sustainable use of the resources. However, cost-benefit analyses are needed to make final decisions.

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6. FINAL DISCUSSION, CONCLUSIONS, AND FUTURE WORK

6.1. FINAL DISCUSSION

How well children learn depends on a great number of factors. Some of them are external to the schools, while others are directly related to them, like the resources they have for teaching. Among these, the built environment is one of the most important. A revision of the literature of the main databases available demonstrated that there is enough evidence to suggest that the built environment affects the children's attendance, performance and health.

The thermal environment is considered the most important of the variables that characterize the quality of the indoor environment (Frontczak, Wargocki 2011). It is also a key factor in warm-humid climates, characterized by high humidity and temperatures. Therefore, although there are other factors within the educational setting that can have a major impact on the student's academic performance (i.e. socio-economic factors or the quality of the teachers), providing suitable environmental conditions in the classrooms is an architectural contribution, which would make the student's learning process easier as well as strengthening improvements made from other areas.

The relationship proposed in **Chapter 2**, created from a literature review, predicts that in temperate climates, the performance in psychological tests and school tasks were on average 10% higher when temperature was reduced from 26°C to 23°C. However, these findings cannot be extrapolated to tropical regions which are climatically and culturally different (Wargocki, Wyon 2007b). Therefore, an experiment with 37 tropically acclimatized pupils was developed in **Chapter 3**. Results show that children performed significantly better when the temperature was reduced from 30°C to 25°C, corroborating the findings of temperate climates and extending them to the tropics.

These results have several implications on the economic costs of high temperature classrooms, and their impact on how school buildings are designed and constructed. The experiment showed that a child under a normal temperature of 30°C should invest 25% more time to achieve the same levels of productivity in the grammatical reasoning school tasks than the same child at 25°C. If these results are extrapolated to a 200-day school year, it means that children under normal warm conditions will need to spend 50 days more, to achieve the same results than their reduced temperature counterparts. In an average class of 25 students, this represents 1250 school days. Considering that school buildings should provide students with an optimal learning environment, perhaps the economic costs of the extra time spent by pupils and teachers should be considered into building costs.

The shape of an empirical dose-response relationship between performance at school work and classroom temperature could not be defined in this research. Children's performance was evaluated at only two temperatures (25°C and 30°C), and it is not possible to predict the shape that the curve would have between these two points. Further studies should be developed in the future to estimate the temperature at which optimal performance will be achieved. However, the results from the experiment and recently published journal articles relating thermal sensation with school work and office work performance, show that adults and children perform better when their thermal sensation is between slightly cool (-1) and neutral (0) on the ASHRAE's seven-point scale. Thus, it is plausible that the optimum schoolwork performance in tropics will be achieved at this thermal sensation range, so it can be expected that temperatures above what is neutral to heat balance will have negative effects on the performance. Because the information available is still limited, this limit should be revised and updated as new results are published.

Using the neutral temperature as the maximum indoor temperature limit, the thermal conditions of lightweight construction classrooms that only have window openings were evaluated in **Chapter 4**. Are these traditional classrooms capable of providing an optimal thermal environment for learning? A widely used Costa Rican public school building prototype was employed as a Case Study. Eighteen architectural solutions looking towards adapting the building to the site's warm thermal conditions were previously detected. Results show that children spend 80% of their time in a thermal environment that is not suitable for learning. A step forward in passive building design was needed.

In **Chapter 5**, the existing literature was revised to identify passive or low energy consumption strategies with high cooling potential that had not been used in the design and construction of the Case Study's school building. Four strategies were found and individually or jointly evaluated: (1) The cooling effect of ventilation, (2) roof's thermal properties, (3) ground cooling, and (4) microclimate controls. Results show that the criteria to avoid overheating of the CIBSE TM52 for natural ventilated buildings can be achieved by combined these strategies (Nicol, Spires 2013).

However, even when an optimal thermal learning environment can be achieved only with passive and low energy consumption cooling strategies, transforming the strategies into effective architectural solutions could suppose high technical and economic challenges. For example, a cooling potential of up to 4°C can be achieved through ground cooling. But the EAHE system required needs at least 600 meters of buried polyethylene pipes that are

TABLE 6.1 Classification of schools located in different cities of Costa Rica according to the microclimate. The criteria presented in Table 5.12 was used

City	Geographic location	Meter above sea level (m)	H_e (%)	Classification:	
			<0.3 m/s	Site's temperature conditions	School type
San Jose	1°17′N 103°50′E	1140	25.5	Moderate	B
Alajuela	13°45′N 100°29′E	939	31.7	Warm	C
Cartago	10°28′N 66°54′E	1435	11.1	Moderate	B
Cañas	10°22’N 85°11’O	12	73.9	Veryhot	E

15 centimeters in diameter, spread over 1200 square meters of land for each classroom, which is not a simple task to complete. And due to the low number of EAHE systems installed in tropical climates, operation and maintenance costs are expected to be high. Therefore, a gradual use of the cooling strategies following the microclimate was proposed at the end of **Chapter 5**.

Given that the evaluation of the thermal conditions of naturally ventilated classrooms can be done a priori, using the simplified approach method to estimate the indoor temperatures (**Chapter 4**- Section 4.3.4), school classrooms located in different cities of Costa Rica were catalogued according to the criteria presented in the Table 5.12. The results are shown in Table 6.1. It can be seen that classrooms located in cities at higher altitudes have, in general, lower indoor temperatures and might require lower cooling loads (A and B types). However, while in San Jose and Cartago an air speed of 1.2 m/s would be sufficient to meet the CIBSE criteria (B), in Alajuela it would be necessary to include the roof insulation (C). Using this method, a further classroom classification can be performed for an entire region or country, making it easy for architects, designers and school authorities to identify the cooling needs of each site and the possible ways to provide it. While examples are given in Table 6.1, this is a pending task that should be addressed in future work.

It may be surprising that for type E classrooms, the use of mechanical cooling was considered. However, this alternative is recommended for specific sites where the climatic conditions make it difficult to provide an optimal environment for learning solely through the use of passive strategies. This decision was based on the fact that passive design cooling has its limitations and that, in the same way as active heating systems are required in the

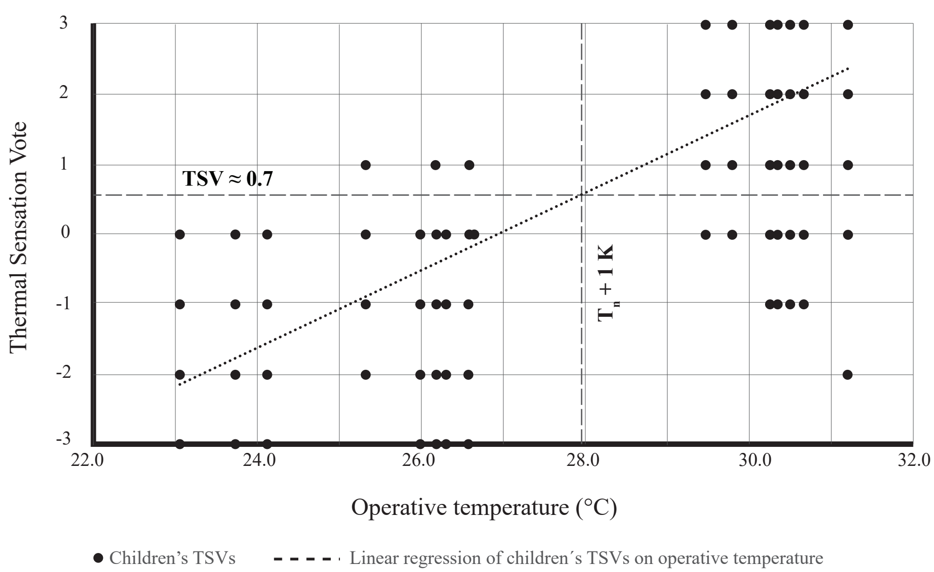

FIGURE 6.1 Expected thermal sensation at T_n + 1 K. Estimation based on the surveys made on Chapter 3.

temperate regions, in some tropical zones, active cooling would be necessary. Thus, the gradual use of strategies promotes a responsible use of resources, including energy, but without compromising the good academic performance of the pupils.

Nevertheless, someone may wonder: (1) why not increase the maximum percentage of H_e permitted or (2) why not give children more time to finish their schoolwork, instead of using active cooling on type E classrooms. These two questions that emerged in conversations held with teachers, school authorities, and other researchers throughout this investigation will be addressed below.

Increasing the H_e percentage: According to the literature (Jiang, Wang, Liu, Xu, Liu 2018; Lan, Wargocki, Lian 2011), the optimal temperature for learning is lower than the neutral temperature. Therefore, a small decrease in performance might be expected already at the proposed $T_{o\text{-}max}$. If a higher percentage of He is permitted, the pupils' performance would decrease even more. A dose-response relationship is needed to estimate how the percentage of H_e will affect children's schoolwork performance, and as it has been said before, it was not estimated in this study. However, it should be considered that Hours of Exceedance (H_e) are the percentage of hours where indoor temperature is 1 K over the $T_{o\text{-}max}$, or over the neutral temperature (T_n), in this case. According to Figure 6.1, T_n + 1 K corresponds to a Thermal Sensation Vote (TSV) of +0.85, which is the same TSV used to establish the upper 80% acceptability limit in the ASHRAE's adaptive thermal comfort model (ACM). Therefore, increasing the percentage of H_e will affect not only the pupils' performance but also will be accepting temperatures beyond the comfort limits.

Using the ASHRAE's adaptive thermal comfort model's upper 80% acceptability limit does not look like the best option. An estimation of the annual mean upper temperature limit using equation 6.1 (ANSI/ASHRAE 2013), shows that it will be 30.2°C (SD 0.5), which is over the temperature at which the surveyed children from Bededero-Canas performed worst at the school tasks (30.2°C).

$$\text{Upper 80\% acceptability limit} = 0.31\, t_{(pma)\,out} + 21.3°C \quad (6.1)$$

A plausible explanation of the poor performance at temperatures within the comfort limits established by the ACM, is that in the field, pupils seemed to be more sensitive to temperature changes than what is predicted by the model. A narrow span of 3.2°C was registered instead of the predicted 7°C. de Dear et al. (2015) had already shown that children attending schools with low temperature dynamics, like the ones located in the tropics, tend to be more sensitive to temperature changes. Appendix 5.5 shows the comfort models proposed by many different studies performed in the tropics with adults and children (Kwok 1998; Kameni, Tchinda, Orosa 2014; Wong, Khoo 2003; Karyono 2008). The temperature spam was calculated for each one of the models. Results show that it took between 3 K and 5.5 K of operative temperature change to see a shift of 1.7 thermal sensation units, confirming that tropically acclimatized subjects have a higher thermal sensitivity.

Therefore, in conclusion the way that H_e are estimated, already provides a sufficient thermal adaptation margin that should not be extended.

Giving more time to children: When giving more time to children to perform the schoolwork tasks, it is important to understand that the negative effects of normal warm temperatures on the speed at which children performed the tasks seen in the experiment, were because raised classroom temperature constituted a barrier to cognition. The high temperature conditions make the learning process more difficult and, therefore, have much more far-reaching effects outside the test situation. Reduced working speed in experimental exposures has been shown to predict the effect of raised classroom temperatures on learning over long periods as assessed by the results of end-of-year examinations (Park 2016).

The two issues addressed in the previous sections were derived from the perception that mechanical cooling is costly and eco-unfriendly. Something that might be true today. Mechanical systems like air conditioning are energy intensive and during their operation demand large amounts of electricity that is expensive to produce even with non-renewable sources, so the majority of the population cannot afford it, even when there is a perceived need among dwellers (Lundgren, Kjellstrom 2013).

However, considering the development of cleaner and more efficient technologies in recent years, having a renewable environmentally friendly and low-cost energy source seems to be a matter of time. For example, the efficiency of photovoltaic cells has increased, while costs have dropped exponentially. According to the NREL efficiency chart, some solar cell prototypes have reached an efficiency of up to 45% under laboratory conditions (NREL 2018), meaning that they can convert almost 50% of the sun's incoming energy into electricity. On the other hand, the price of silicon PV cells per watt has decreased from 75 dollars to 30 cents in the last 40 years (Bloomberg New Energy Finance & pv.energytrend.com).

Tropical schools have favorable conditions for electricity generation in situ by using photovoltaic cells. Schools are one or two storey buildings where the roof represents a large portion of the envelope and they are located in the region of the Earth that receives the highest incoming solar radiation, with most cities receiving and annual insolation of 4 to 6 $kWh/m^2/day$. This is while the greatest demand for air conditioning occurs during times of high heat and solar radiation and peak photovoltaic power output (Lundgren, Kjellstrom 2013). Therefore, it should not be a surprise that in the near future school buildings, including their air conditioners, are going to be powered by photovoltaic cells. In addition, air conditioning systems are increasingly efficient and have begun to replace the use of hydrofluorocarbons (HFCs) with substitute chemicals like hydrofluoroolefins (HFOs) that are more environmental friendly.

Nevertheless, the central point of this discussion is not about promoting or not mechanical cooling in school buildings, it is about educating children. If the high classroom temperatures affect the cognitive processes and there are no effective solutions with passive strategies, mechanical cooling should be used. Of course, in the most efficient way, but it should be used. In this case, designing a school in a sustainable way should mean that the conditions that make the learning process more difficult for children are going to be avoided (Wargocki, Wyon 2013), because educating children should be always more important than saving energy.

6.2. CONCLUSIONS

About the hypothesis:

There is strong evidence that children's schoolwork performance in warm-humid climates will improve if normal occurring classroom temperatures are reduced. Results from the experiment performed in **Chapter 3** show that tropically acclimatized pupils improved their performance in logical reasoning and reading and comprehension tasks when normal classroom temperatures were reduced from 30°C to 25°C. Therefore, the first null hypothesis has been rejected.

Regarding the second hypothesis, results from **Chapter 5** show that a thermally optimal classroom environment in warm-humid climates can be achieved with passive or low energy consuming strategies alone. Different combinations of cooling strategies were explored in a Case Study's school building located in the tropics and at least 7 of the models predict that the classroom's thermal conditions will be optimal for learning. Thus, the second null hypothesis has also been rejected.

About the research objectives:

A relationship between learning outcomes and thermal environment in elementary school classrooms was developed in **Chapter 2**. Data from 18 studies were used. The results predict that performance in psychological tests and school tasks were on average 10% higher when temperature was reduced from 26°C to 22°C. Results suggest that the thermal environment in temperate climates affects the academic performance of children. However, none of these studies were performed in tropical climates.

A study to analyze the effects of classroom temperature on tropically acclimatized children's thermal perception and school performance was developed in **Chapter 3**. Results show that children performed the language and logical-thinking tasks significantly better in terms of speed at the lower temperature, while the less able pupils performed better on all tasks at the lower temperature. According to the results of the experiment and what has been published recently on the topic, temperatures above what is neutral for heat balance should be avoided in tropical school classrooms. Therefore, a maximum temperature limit ($T_{o\text{-}max}$) equal to the neutral temperature was proposed for tropical classrooms.

The thermal conditions of traditional lightweight construction classrooms that only have window openings in the tropics were evaluated in **Chapter 4**. The purpose was to know if they were able to provide pupils with an optimal thermal environment for learning according to the proposed temperature limit. One classroom of a school building located in the warm-humid climate of Costa Rica was chosen as a Case Study. The classroom was selected due to its location, building condition and age and that is was constructed using a widely employed architectural prototype and a construction system. Results show that the indoor temperatures were over the upper temperature limit more than 80% of school time. During school hours, temperatures are on average 3°C over $T_{o\text{-}max}$, however, peaks differences of up to 8°C are common during warmer days. Therefore, children spend 80% of their time in a thermal environment that is not suitable for teaching.

To improve the thermal conditions of current classrooms, in **Chapter 5** four design strategies with a high cooling potential in warm-humid tropics were identified and evaluated, individually or jointly, in the Case Studys' school building: (1) The cooling effect of ventilation, (2) roof's thermal properties and shading, (3) ground cooling, and (4) microclimate controls. The results show that the CIBSE TM52 criteria to avoid overheating for natural ventilated buildings was achieved by seven of the evaluated models. However, transforming the strategies into effective solutions does not seem to be so easy, something that was discussed in **Chapter 6**.

In conclusion, the objectives of this thesis have been achieved. Given the influence that building design and construction have on indoor thermal conditions, educational architecture must consider the classroom's thermal conditions in order to create optimal teaching environments where pupils can feel and perform better. In order to meet the challenges faced by humanity regarding global warming, mechanical cooling loads should be reduced to a minimum, but if necessary, they should be considered as an alternative.

6.3. FUTURE WORK

Even though the thesis findings have fulfilled the research objectives, as this research was developed, new questions and issues emerged that, although due to time constraints, could not be addressed here, were recognized as having the potential to be addressed as future research work. These issues will be listed below. The order in which they are presented is not related to their level of importance or urgency, but how they emerged throughout the thesis.

- The results from the experiment performed in **Chapter 3** require verification in other schools and with other pupils. These studies should also examine whether long-term exposure to reduced classroom temperatures in tropical climates would provide any measurable benefit for other learning outcomes, including end-of-year examination results and national tests.

- Further studies should be performed to develop the shape of the dose-response relationship and to estimate the optimal temperature for learning in the tropics which was not determined in this work.

- Further research should study why the effects of temperature on numerical tasks were not seen in the experiment run in **Chapter 3**. This was because children performed very poorly under both thermal conditions and this has the effect of reducing environmental sensitivity or because there is no effect at all of temperature on tropically acclimatized pupils.

- New Case Studies should be conducted to evaluate the thermal performance of the traditional lightweight construction classrooms in the tropics. These studies should consider other building types and microclimates.

- The simplified approach method to estimate the classroom's indoor conditions should be validated with further field and computational simulation studies. Special focus should be given on how to adjust the outdoor air temperatures to make them similar to real indoor temperatures.

- Additional research should be performed to estimate the correct cooling effect of air movement and whether the air speed in classrooms can be increased above 1.2 m/s. Studies should focus on tropically acclimatized pupils.
- Additional research should be conducted to estimate the cooling effect of green areas on the tropic's air temperature, and influence on indoor temperature.
- Cost-benefit analysis should be performed for each of the passive or low energy consumption strategies before their implementation.
- An estimation of the costs of upgrading the thermal conditions in schools by regions or countries should be performed. For example, Wargocki and Wyon (2013) estimated that the total cost of improving indoor environmental conditions in Danish schools would be approximately $1 per pupil per day.

6.4. CONTRIBUTIONS OF THE THESIS

Journal publications:

Indoor Air Journal, 2018: Reducing classroom temperature in a tropical climate improved the thermal comfort and the performance of elementary school pupils.

Authors: Jose Ali Porras-Salazar, David P. Wyon, Beatriz Piderit-Moreno, Sergio Contreras-Espinoza, and Pawel Wargocki

Conferences:

(1) Healthy Buildings Europe. Lublin- Poland, 2017 | Extended abstract and podium presentation: Classroom carbon dioxide concentration and learning in elementary schools.

Authors: Pawel Wagocki and Jose Ali Porras-Salazar.

(2) 38th AIVC conference. Nottingham- UK, 2017n | Conference paper and podium presentation: Quantitative relationships between classroom CO2 concentration and learning in elementary schools.

Authors: Pawel Wargocki, Jose Ali Porras-Salazar and William P. Bahnfleth.

(3) 15th Conference of the International Society of Indoor Air Quality & Climate (ISIAQ). Philadelphia- USA, 2018 | Extended abstract and podium presentation: Reducing Classroom Temperatures in a Tropical Climate Improved the Performance of Elementary School Pupils.

Authors: Jose Ali Porras-Salazar, Pawel Wagocki, and Beatriz Piderit-Moreno

(4) III Congreso Interdisciplinario de Investigación en Arquitectura, Diseño, Ciudad

y Territorio. Santiago- Chile, 2018 | Conference paper and podium presentation: ¿Proporcionan las aulas escolares en el clima cálido- húmedo, un ambiente térmico óptimo para el aprendizaje?

Authors: Jose Ali Porras-Salazar, Jesus Pulido-Arcas, and Beatriz Piderit-Moreno

(5) XXVII Conferencia Latinoamericana de Escuelas y Facultades de Arquitectura (CLEFA). Concepcion- Chile, 2018 | Conference paper and podium presentation: Estudio de la eficiencia de un sistema de tubos enterrados con intercambiadores tierra-aire para la reducción de la carga de refrigeración en edificios escolares situados en climas tropicales: caso de estudio en Costa Rica

Authors: Jose Ali Porras-Salazar, Jesus Pulido-Arcas, Beatriz Piderit-Moreno, and Alexis Perez-Fargallo.

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Appendix

APPENDIX 3.1. Estimation of the classroom's cooling load using ASHRAE's Cooling Load Temperature Differences (CLTD) method. Summary of calculations

Cooling load source	Peak cooling loads by load source. An U-Value of 3.3 was used for the roof (W)	Load source contribution to total peak cooling load (%)	Peak cooling loads by load source. An U-Value of 2.0 was used for the roof (W)	Load source contribution to total peak cooling load (%)
A. Sensible Cooling Load				
Roof and Exposed Walls	6122.0		3805.5	
Roof	5897.9	39.1%	3581.4	28.1%
North wall	224.1	1.5%	224.1	1.8%
Fenestration Areas	2298.3		2298.3	
South windows	38.6	0.3%	38.6	0.3%
North windows	55.6	0.4%	55.6	0.4%
East wall	940.6	6.2%	940.6	7.4%
West wall	940.6	6.2%	940.6	7.4%
South wall	323.0	2.1%	323.0	2.5%
Internal Sources	1504.6		1504.6	
People	1128.8	7.5%	1128.8	8.8%
Flourescent Lights	375.8	2.5%	375.8	2.9%
Power Equipment & Appliances	0.0		0.0	
	0.0	0.0%	0.0	0.0%
Outside Air	1679.0		1679.0	
Infiltration	0,0	0,0%	0,0	0,0%
Ventilation	1679.0	11.1%	1679.0	13.2%
SUBTOTAL	11603.9	77.0%	9287.3	72.8%
B. Latent Cooling Load				
People	843.8	5.6%	843.8	6.6%
Infiltration	0.0	0.0%	0.0	0,.%
Ventilation	2625.0	17.4%	2625.0	20.6%
SUBTOTAL	3468.8	23.0%	3468.8	27.2%
TOTAL	**15072.6**	**100.0%**	**12756.1**	**100.0%**

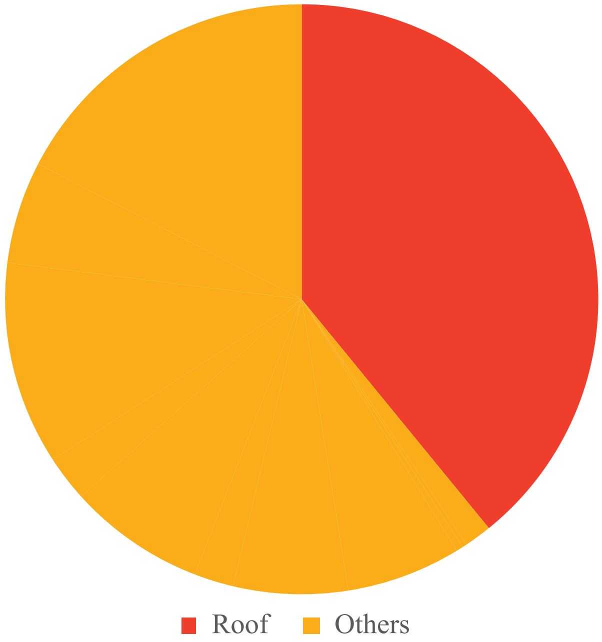


FIGURE A.3.1. Load source contribution to classroom's total peak cooling load (%). U-Value of the roof: 3.3

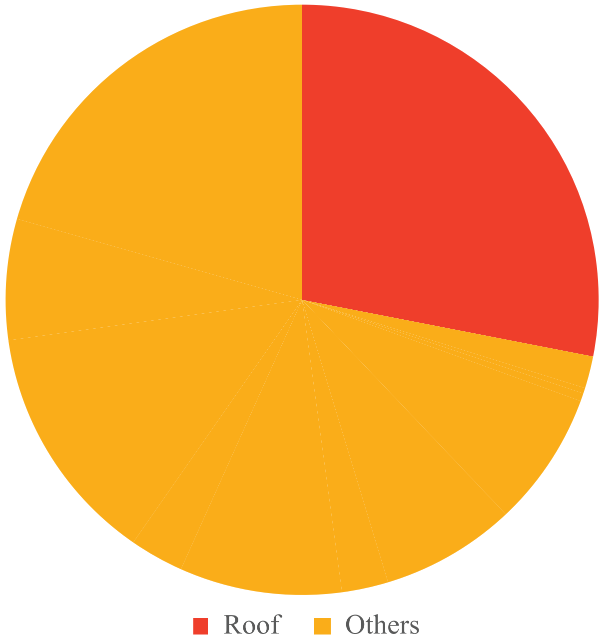


FIGURE A3.2. Load source contribution to classroom's total peak cooling load (%). U-Value of the roof: 2.0

APPENDIX 3.2. Thermal comfort survey questionnaire translated to English

1. At this moment, how does the classroom feel? Tick one of the following options:

Very cold	Cold	A bit cold	OK	A bit hot	Hot	Very hot
☐	☐	☐	☐	☐	☐	☐

2. Tick the box of the phrase you agree with:

- I wish the room was **much colder** ☐
- I wish the room was **colder** ☐
- I wish the room was a **bit colder** ☐
- I don't want any change ☐
- I wish the room was a **bit warmer** ☐
- I wish the room was **hotter** ☐
- I wish the room was **much hotter** ☐

3. At this moment, is the room temperature OK?

YES ☐ **NO** ☐

4. At this moment, are you wearing additional garments besides your regular uniform?

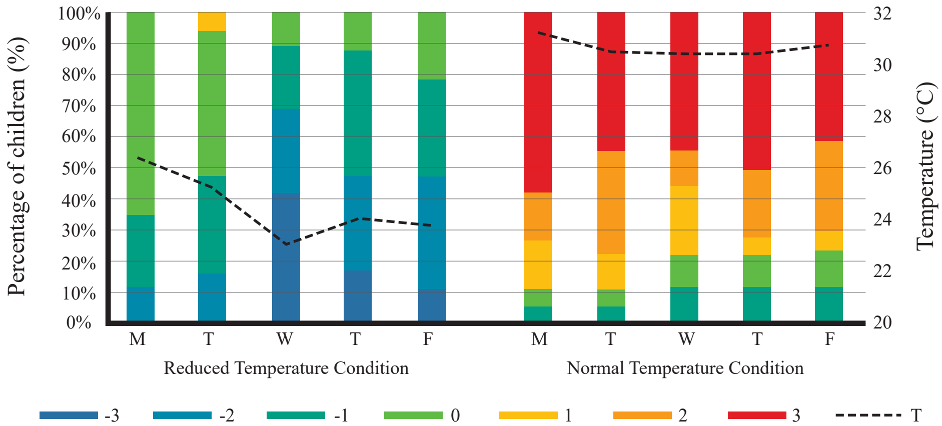
YES ☐ **NO** ☐

If you answered YES, tick on one or more of the following options:

☐ Sweater or vest ☐ Underwear t-shirt ☐ Short pants under the skirt

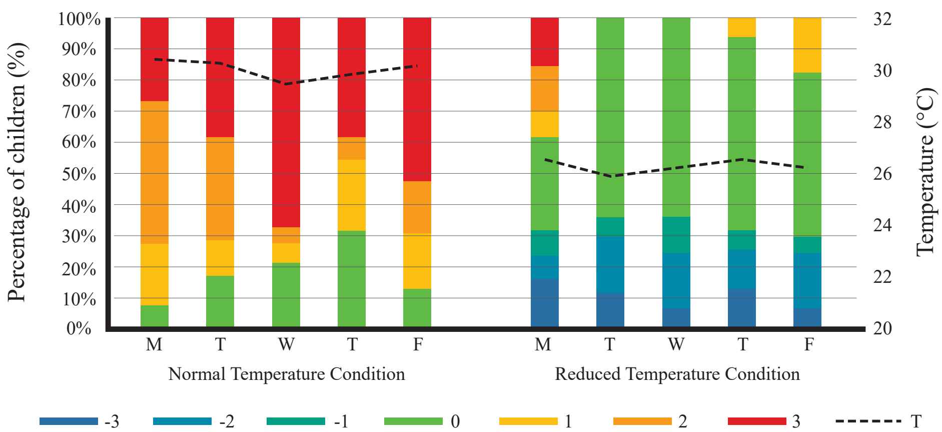
5. What were you doing on your last break? Tick the option that fits better with what you were doing:

☐ Running-Playing ☐ Seating-Resting



(a) Classroom 1

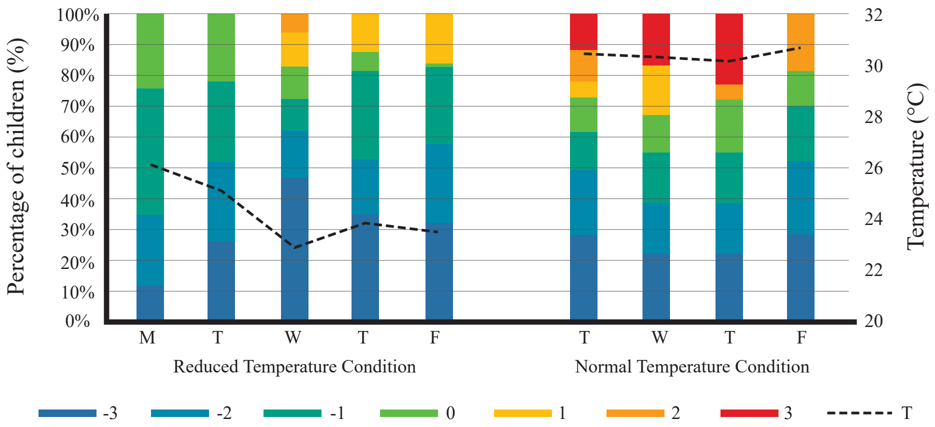
(1) Seven point scale: +3 Hot, +2 Warm, +1 Slightly warm, 0 Neutral, -1 Slightly cool, +2 Cool, +3 Cold.
Results are presented in the same order as the children were exposed to normal and reduced temperatures



(b) Classroom 2

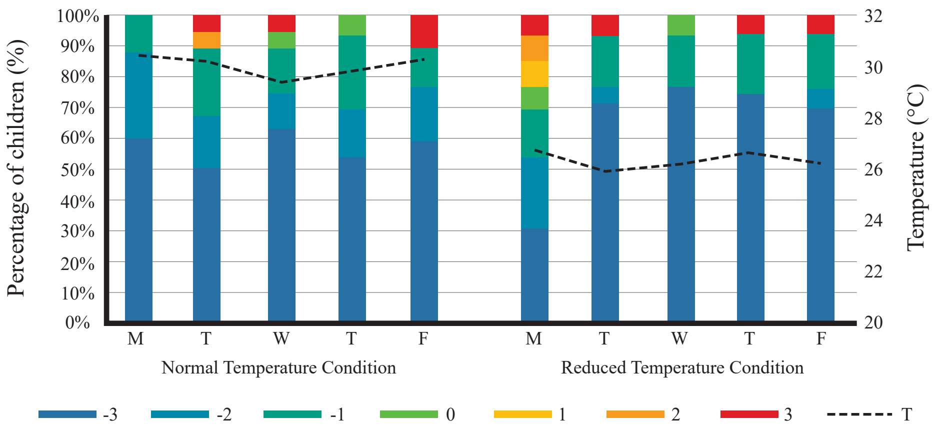
(1) Seven point scale: +3 Hot, +2 Warm, +1 Slightly warm, 0 Neutral, -1 Slightly cool, +2 Cool, +3 Cold.
Results are presented in the same order as the children were exposed to normal and reduced temperatures

APPENDIX 3.3. A. Summary of thermal sensation votes of children under normal and reduced classroom temperature conditions. (a) Classroom 1 and (b) Classroom 2



(a) Classroom 1

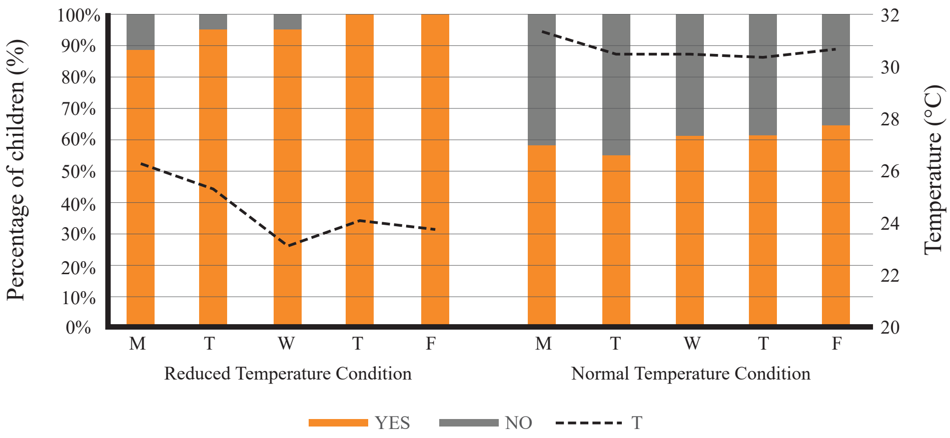
(1) Seven point scale: +3 Much hotter, +2 Hotter, +1 A bit warmer, 0 No change, -1 A bit colder, +2 Colder, +3 Much colder. Results are presented in the same order as the children were exposed to normal and reduced temperatures



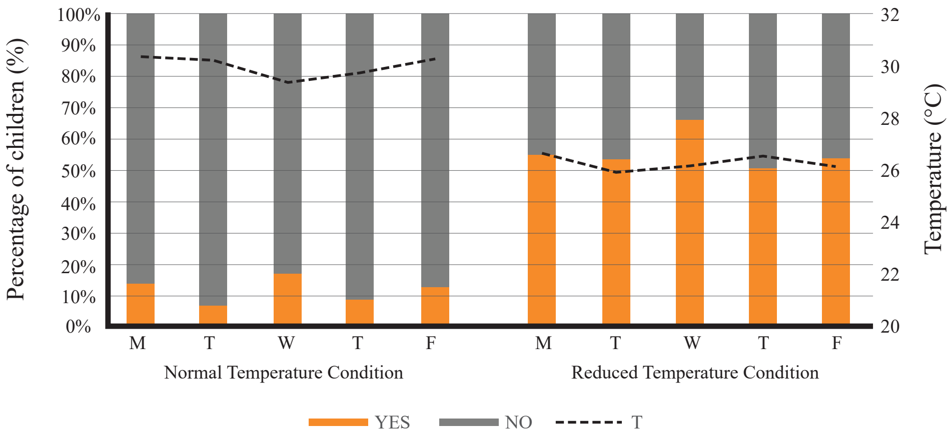
(b) Classroom 2

(1) Seven point scale: +3 Much hotter, +2 Hotter, +1 A bit warmer, 0 No change, -1 A bit colder, +2 Colder, +3 Much colder. Results are presented in the same order as the children were exposed to normal and reduced temperatures

APPENDIX 3.3.B. Summary of the thermal preference votes of children under normal and reduced classroom temperature conditions. (a) Classroom 1 and (b) Classroom 2



(a) Classroom 1



(b) Classroom 2

APPENDIX 3.3.C. Summary of the thermal cceptability votes of children. (1) Yes: temperature in the room is OK. No: temperature in the room is not OK. (a) Classroom 1 and (b) Classroom 2

APPENDIX 3.4. ANOVA and multivariate analysis for the Reading and Comprehension tests outcomes

TABLE 3.4.A.1 Final model of mixed ANOVA analysis for the Reading and Comprehension tests outcomes. The analysis was made in the software R using the package lmerTest. Results from Tuesday's and Thursday's Reading and Comprehension tests were analyzed together. The day of the week (d) factor was included in the anlysis to differentiate in which day the test was performed.

Test	Performance Metric	Final model	p-value for c
Reading and Comprehension	Attempted units per min	$Y = a + c + d + P + \epsilon$	0.007
	Percentage of correct answers	$Y = g + P + \epsilon$	0.231

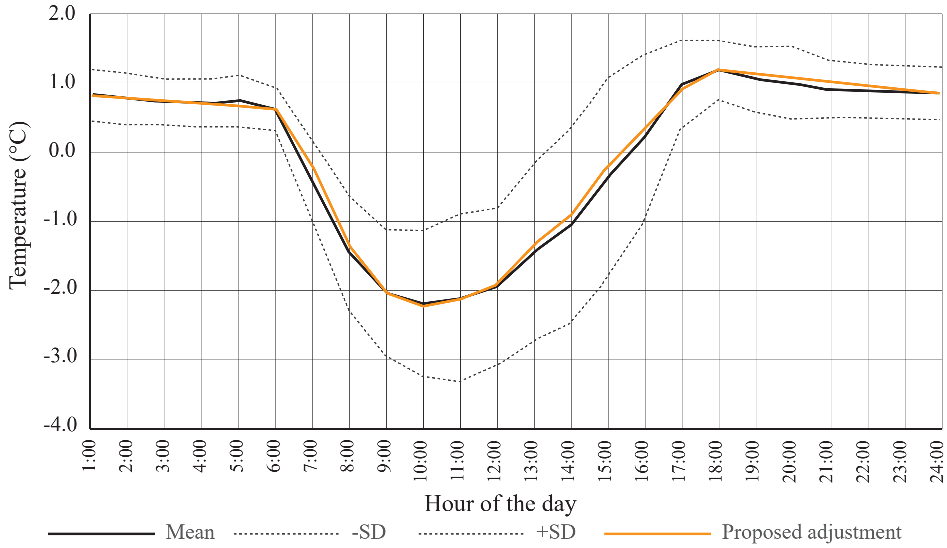
For final model, Y corresponds to measures of performance, c, g, a, d, P correspond to condition (normal or reduced temperatures), gender, class, day of the week (Tuesday or Thursday) and pupil identification accordingly. Capital letters represent random factors while small letters represent fixed factors. It was assumed that the residuals on both of the conditions were normally distributed.

TABLE 3.4.A.2 Multivariate analysis for the Reading and Comprehension tests outcomes. The analysis was made in the software R using the package nlme.

Test	Day of the week when the test was applied	Performance Metric	Final model	p-value for the interaction between test outcomes and condition (Y:c)
Reading and Comprehension	Tuesday	Attempted units per min	$Ytus = g + a + c + P + \epsilon$	0.024
		Percentage of correct answers	$Ytua = g + a + c + P + \epsilon$	0.463
	Thursday	Attempted units per min	$Yths = g + a + c + P + \epsilon$	0.054
		Percentage of correct answers	$Ytha = g + a + c + P + \epsilon$	0.108

For final model, Y corresponds to measures of performance. c, g, a, P correspond to condition (normal or reduced temperatures), gender, class, and pupil identification accordingly. Capital letters represent random factors while small letters represent fixed factors. It was assumed that the residuals on both of the conditions were normally distributed.

APPENDIX 4.1. Air temperature difference betwee outdoor and indoor conditions. Estimated by averaging 30- minute interval temperature records from 2016 September 9th to 2016 December 9th

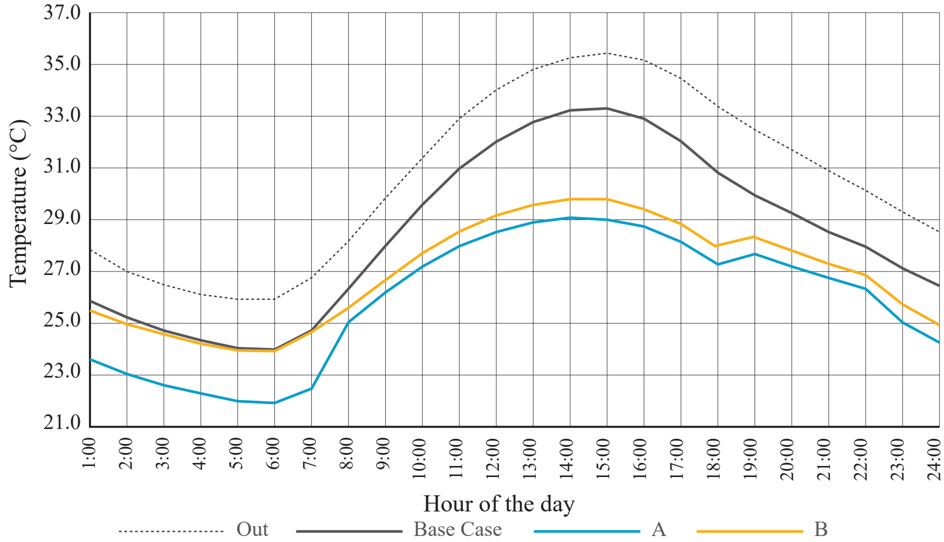


APPENDIX 5.1. Estimation of classroom's average air speed. Simplified method.

Equation		
Average air speed =	$\frac{(ACH)}{(Opening\ area)}$	$\frac{(Classroom's\ air\ volume)}{3600}$
Parameters (1)		
Classroom air volume	159,2	m^3
Glazing area	11,0	m^2
Percentage of glazing area that opens	50%	
Opening area	5,5	m^2
Air changes per hour	40,0	ac/h
Volume of air passing through the window per second	1,8	m^3/s
Average air speed	0,322	m/s

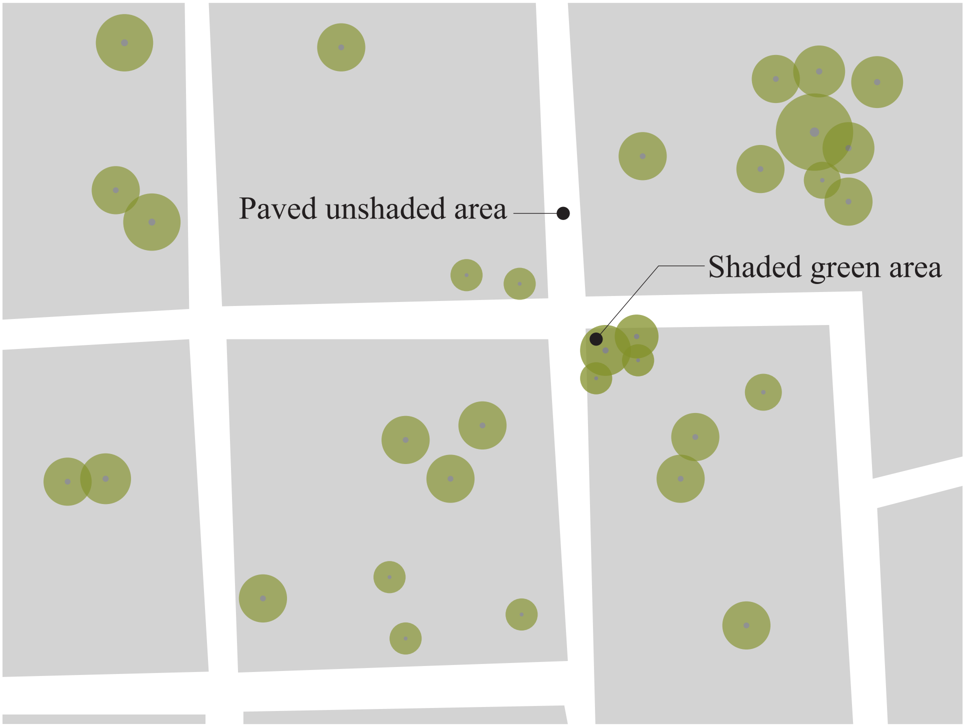
'(1) All parameters correspond to the settings used in the Base Case model

APPENDIX 5.2. Comparision of the indoor (T_o) classroom´s temperatures ina typical day of the hottest month when usingthe EAHE system as teh only source of natural ventilation (A) and when combined with window opening (B). estimated by averaging hourly temperatures.



APPENDIX 5.3. Field measurements of air temperatures in a small shaded green area and its surroundings. Measurements performed in a warm humid climate in Costa Rica between June 20th-28th 2018 with a (KESTREL METER 4000 WEATHER METER)

	Shaded green area				
Date	Hour				
	8:00	10:00	13:00	16:00	17:30
20-Jun-18			32	32.2	
21-Jun-18		29.9	33.6	30.6	
22-Jun-18		33.9	30.3	28.5	
26-Jun-18		32.6	32.5	27.7	
27-Jun-18		34.2	30.8	29.8	
28-Jun-18	28.1	30.4	31.2		28.4
Average	28.1	32.2	31.7	29.8	28.4
	Paved unshaded area				
Date	Hour				
	8:00	10:00	13:00	16:00	17:30
20-Jun-18			37.5	31.8	
21-Jun-18		36.8	35.2	31.4	
22-Jun-18		35.8	30.8	28.4	
26-Jun-18		33.1	32.5	27.8	
27-Jun-18		36.4	30.9	30.2	28.4
28-Jun-18	28.2	31.5	31.4		
Average	28.2	34.7	33.1	29.9	28.4

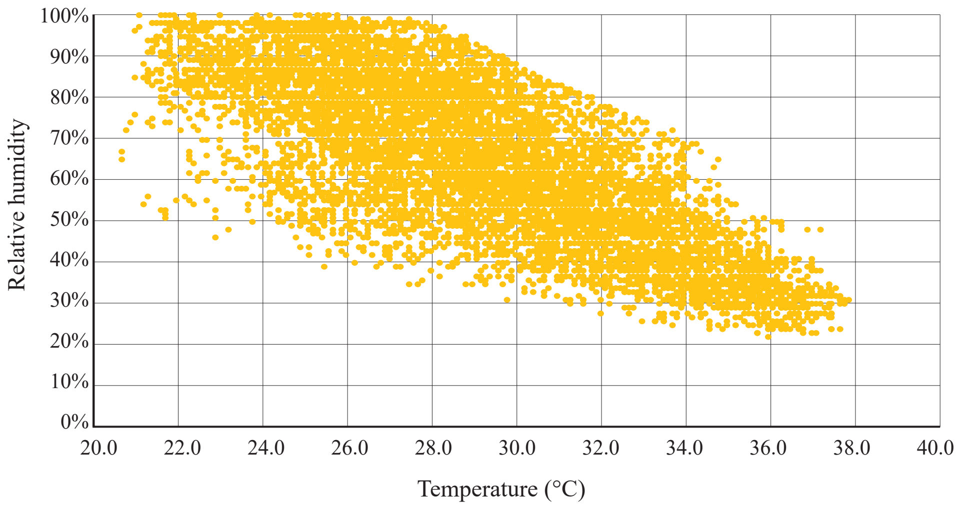


APPENDIX 5.4.

Range of observed temperatures in the TMY (°C)	Estimation of the relative humidity (%) (1)	Estimation of the dew point (°C) (2)
20,3	100%	0,5
21,0	97%	1,2
22,0	93%	2,2
23,0	89%	3,2
24,0	85%	4,2
25,0	81%	5,2
26,0	78%	6,2
27,0	74%	7,1
28,0	70%	8,1
29,0	66%	9,1
30,0	62%	10,1
31,0	58%	11,1
32,0	54%	12,1
33,0	50%	13,1
34,0	46%	14,1
35,0	42%	15,1
36,0	38%	16,1
37,0	34%	17,1
38,0	30%	18,1

‘(1) The relative humidity was estimated using the relationship presented in Figure A.5.4 (y = -3.9569x + 180.39)

‘(2) The dew point was estimated according to the equation proposed by Lawrence, Mark G. (2005): Td = T - ((100 - RH)/5, where Td is the dew point, T the temperature, and RH the relative humidity



y = -3,9569x + 180,39 R^2 = 0,5597

APPENDIX 5.2. Relationship between relative humidity and temperature. Hourly weather data was retrieved from the Case Study’s TMY

APPENDIX 5.5.

Sutdy	Year	City/Country	Type of study	Number of subjects		Neutral temperature (°C) (1)	Lower 80% acceptability limit (°C) (1)	Upper 80% acceptability limit (°C) (1)	Span (°C) (2)	Thermal sensitivity (TSV/°C) (3)(4)
De Dear et. al	1987	Singapore	Field study	583	Adults	28,6	27,1	30,1	3,0	0,57
Busch	1990	Thailand	Field study	391	Adults	26,1	22,9	29,3	6,4	0,27
Karyono	1993	Jakarta/ Indonesia	Field study	97	Adults	26,6	23,9	29,3	5,4	0,31
Kwok	1998	Hawaii/USA	Field study	2181	Children	26,6	23,8	29,4	5,6	0,30
Wong & Khoo	2003	Singapore	Field study	506	Children	28,8	27	30,6	3,6	0,47
Kameni et al.	2014	Duoala/ Cameroon	Field study		Adults	24,9	22,5	27,3	4,8	0,35
Kameni et al.	2014	Yaounde/ Cameroon	Field study		Adults	24,2	22,2	26,2	4	0,43
Present study		Bebedero-Canas/Costa Rica	Field intervention study	343	Children	26,9	25,3	28,5	3,2	0,53
ASHRAE 55		USA- Standard			Adults				7,0	0,24
EN 15251		European-Standard			Adults				8,0	0,25

(1) Operative temperatures except for Kamani et al. that uses air temperature

(2) Difference in Celcius degrees between the Upper 80% and Lower 80% acceptability limits

(3) Thermal sensivity as thermal sensation units per degree

(4) Thermal sensivity for each study was estimated dividing 0.85 TSV which corresponds