Low-invasive measures for improving the summer indoor climate in school buildings

zur Erlangung des akademischen Grades einer

Doktor-Ingenieurin (Dr. –Ing.)

von der KIT-Fakultät für Architektur
des Karlsruher Instituts für Technologie (KIT)

genehmigte

Dissertation

von

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Tag der mündlichen Prüfung: 30.10.2019
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Dedication

To my mother Maria Montano, my father Horacio Camacho, my brother Andres Camacho Montano and my sister in law Adriana Unigarro Sanchez.

Acknowledgments

Firstly, I would like to thank Professor Andreas Wagner for his supervision and support throughout the phases of this work. To Professor Malcolm Cook for his supervision and support of my career for about eight years. To both of them for their work in the publication “Avoiding overheating in existing school buildings through optimized passive measures”.

I would like to thank the Federal German Government of the Baden Württemberg State, the Karlsruhe Institute of Technology and the Karlsruhe House of Young Scientists for the LGF-Scholarship, which allowed me to conduct this research project.

To Mr. Thomas Gillich, Mrs. Anne Sick, and all the HGW team for their support during this study.

To Professor Alexander Summerfield for his support in the work of the publication “Clearing the air on EU guidance projects for school buildings”, and to Professor Dejan Mumovic and Mrs. Heike Erhorn-Kluttig for their inputs in this work as well.

I would like to thank all my family but specially my mother Maria Montano, my father Horacio Camacho, my brother Andres Camacho Montano, my sister in law Adriana Unigarro Sanchez and my cousin Javier Mongua for their enormous support during all my life. To my relatives: Alba, Luis, Helver, Claudia, Felipe and Gabriela. I always carry in my heart your teachings and the happy moments we have had.

Thanks to the people who with their supervision helped me to become a better engineer, and because of their great heart, they also became personal friends: Dr. Angelica Ospina, Cristina Gamboa, Miguel Orejuela, Pilar Medina, Dr. Maria Spyrou, and Emmily Sjölander.

Thanks to my lifelong friends: Carolina Barreto, Maria Paula Lopez, and Maria Fernanda Rueda.

Thank you to the members of the Building Science Group (fbta) for their support and valuable inputs at the presentations in contexts of the *brown bag lunch*. A special thank you to my lovely colleagues Farah AlAtrash, Reza Safi, Sandra Mende and Romina Risetto.

Declaration

I certify that the work in this thesis entitled "Low-invasive measures for improving the summer indoor climate in school buildings” has not previously been submitted for a degree in this or any other university. I also certify that the thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the thesis itself have been appropriately acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis and the regulations of the Karlsruhe Institute of Technology (KIT) about good scientific practices have been obeyed.

Karlsruhe, June 2019.

Sandra Carolina Camacho Montano

Kurzfassung

Der Wunsch, Gesellschaften mit nachhaltigen Entwicklungen zu verwirklichen, hat eine rationelle Ressourcenanwendung und die Erstellung von Klimaschutz- und Anpassungsplänen erfordert. Zu diesem Zweck wurden mehrere Projekte auf der ganzen Welt finanziert, um die daraus gewonnenen Erkenntnisse in Richtlinien einfließen zu lassen. Innerhalb des Bausektors haben sich mehrere Richtlinien herausgebildet, mit Empfehlungen für die Sanierungsprojekte. Sie sind jedoch häufig zu allgemein oder zu spezifisch (basierend auf Fallstudien). Daher finden Architekten schwer umfassende Studien, denen sie folgen können. Im Zusammenhang mit Schulgebäuden wurden einige deutliche Lücken gefunden. Erstens konzentrieren sich die Richtlinien für Sanierungen in der Regel auf die Reduzierung des Heizwärmebedarfs, da dieser den größten Anteil des Energieverbrauchs darstellt, aber der Anstieg der Außentemperaturen zeigt jedoch, dass die Gefahr einer Überhitzung im Sommer zunimmt. Zweitens vernachlässigen einige vorhandene Richtlinien in der Regel den Einfluss verschiedener Gebäudetypologien unter aktuellen und zukünftigen Summer Klimabedingungen, und drittens wurden keine angemessenen Komfortbereiche in Abhängigkeit verschiedener Altersgruppen festgelegt.

Diese Studie berücksichtigt diese Faktoren und liefert spezifische Leitlinien für geeignete Maßnahmen zur Verbesserung des thermischen Raumkomforts in Klassenzimmern in der Stadt Karlsruhe. Zu diesem Zweck wurde die Auswirkung passiver Maßnahmen durch Simulationen der Energiebilanz und thermische Leistung von Gebäuden analysiert. Zu diesem Zweck wurden die Auswirkungen passiver Maßnahmen anhand von Simulationen der Gebäudeleistung analysiert, die für den Monat Juli des Testreferenzjahres 2010 durchgeführt wurden, um die aktuellen Bedingungen zu ermitteln, und anhand des Sommerreferenzjahres 2035, um das zukünftige Szenario zu analysieren und anzunehmen, dass die Schulen den ganzen Tag genutzt werden. Die Simulationen der Basisszenarien erläutern, dass die Anzahl der Überhitzungsstunden unter den gegenwärtigen Bedingungen bei den Gebäuden in schwerer Bauweise etwa 18% der Belegungszeit beträgt, bei den Gebäuden in mittelschwerer Bauweise 22%, und bei den Gebäuden in leichter Bauweise 25%. Bis 2035 könnte der Prozentsatz der Überhitzung dieser Gebäude auf ungefähr 27%, 31% und 37% ansteigen, was einem Anstieg der Überhitzung von ungefähr 10% bedeutet. Die Anzahl der Überhitzungsstunden wurde gemäß der Norm EN15251 berechnet.

Die Bewertung der Maßnahmen erfolgte durch Sensitivitätsanalysen und einem mehrstufigen Optimierungsprozess, der die Anzahl der unbehaglichen Stunden und die Investitionskosten minimierte. Der Optimierungsprozess schlug vor, dass mit einer geeigneten Kombination von Maßnahmen die Anzahl der unbehaglichen Stunden während der Belegungszeit im Jahr 2035 auf rund 6% in den Gebäuden in schwerer Bauweise, 8% in den Gebäuden in mittelschwerer Bauweise und 12% in den Gebäuden in leichter Bauweise reduziert werden könnte. Durch die Verwendung neuer Fenster mit mindestens zwei vertikalen Öffnungen und Deckenventilatoren konnte die Anzahl der unbehaglichen Stunden in den Gebäuden schwerer und mittelschwerer Bauweise vermieden werden. In den Gebäuden leichter Bauweise könnten sie auf rund 4% der Belegungszeit reduziert werden.

Schließlich wurden parametrische Analysen zur Überprüfung der Ergebnisse und Berücksichtung der Auswirkungen der Maßnahmen durchgeführt. Aufgrund der Gemeinsamkeiten zwischen den am besten geeigneten Lösungen für die verschiedenen Klassifizierungen der Gebäude wurden Empfehlungen abgegeben, bei denen die Umsetzbarkeit und die Wirtschaftlichkeit im Vordergrund standen. Es wurde vorgeschlagen, dass die Gebäude in schwerer Bauweise ihre Masse stärker ausnutzen sollten, um eine Überhitzung durch mechanische Belüftung zu verhindern. Wenn eine gute Lüftungsstrategie in diesen Gebäuden nicht umgesetzt werden kann, wären weitere Maßnahmen erforderlich, wie z. B. Fenster mit Sonnenschutz oder Außenverschattung. Eine weitere Alternative zu kontinuierlicher Belüftung stellen Deckenventilatoren dar, um den thermischen Komfort zu erhöhen.

Gebäude in mittelschwerer Bauweise können weiterhin eine verbesserte Lüftungsstrategie nutzen, um eine Überhitzung zu reduzieren und die Luftqualität zu verbessern. Es wären jedoch zusätzliche Maßnahmen erforderlich, um den thermischen Komfort einzuhalten. In diesen Fällen sollte, je nachdem, wie die Fenster nachgerüstet werden könnten, eine weitere Maßnahme wie Deckenventilatoren oder Außenverschattung nach ihrer Wirtschaftlichkeit in Betracht gezogen werden. Gebäude in leichter Bauweise benötigen jedoch mehr Sonnenschutz, um eine Überhitzung zu vermeiden. Es wird daher empfohlen, zusätzliche elektrochrome Verglasungen einzubauen oder zwei weitere passive Maßnahmen zu kombinieren.

Flussdiagramme mit diesen Empfehlungen wurden erstellt, um die Entwickler anzuleiten. Solche Richtlinien könnten für Städte mit ähnlichen Klimabedingungen in Mittel- oder Nordeuropa geeignet sein, da viele Gebäude möglicherweise sehr ähnliche Konstruktionseigenschaften aufweisen. Es wird jedoch empfohlen, dass nach Möglichkeit jeder Fall einzeln durch Simulationen der Gebäudeleistung untersucht wird, da bestimmte Aspekte die Gebäudeleistung weiter beeinflussen können, wie z. B. die Gebäudeumgebung.

Abstract

The wish to achieve societies with sustainable developments has called for the rational use of resources and the creation of mitigation and adaptation plans to climate change. To this end, several projects around the world have been funded to investigate, test and report on results and lessons learned. Within the building sector, several guidelines have emerged to guide refurbishment projects. However, they are often too general or too specific (based on case studies) and designers struggle to find comprehensive studies to follow. In the context of school buildings, some clear gaps have been found. First, the guidelines on refurbishments are usually focused on reducing the heating demand, since it represents the major energy consumption, but, the rise in outdoor temperatures shows that the risk of overheating during the summer is increasing. Second, they some of them neglect the performance of different building construction types in the summer under the current and future climate conditions, and third, they have not been able to establish appropriate comfort ranges depending on the age groups.

This study integrates these factors and provides specific guidance on the most appropriate set of measures to improve indoor thermal comfort in classrooms in the city of Karlsruhe, Germany. For this purpose, the effect of passive measures was analysed through building performance simulations undertaken for the month of July of the Test Reference Year of 2010, to establish the current conditions, and the Design Summer Year of 2035 to analyse the future scenario, and assuming that the schools are used during the whole day The simulations of the base-case scenarios suggested that the number of discomfort hours due to overheating under the current conditions are around 18% of the occupied time in the heavyweight buildings, 22% in the medium weight buildings and 25% in the lightweight buildings. By 2035, the percentage of overheating could rise to approximately 27%, 31%, and 37% respectively, which means a rise in overheating of about 10%. The number of discomfort hours due to overheating was calculated following the standard EN15251.

The evaluation of the measures was undertaken through sensitivity analyses and a multi-objective optimization process minimizing the number of discomfort hours and the investment costs. The optimization process suggested that with an appropriate combination of measures, the number of discomfort hours during the occupied time in the year 2035 could be reduced to around 6% in the heavyweight buildings, 8% in the medium weight buildings and 12% in the lightweight buildings. Furthermore, using new opening arrangements, with at least two vertical openings, and adding ceiling fans, the number of discomfort hours could be avoided in the heavyweight and medium weight buildings. In the lightweight buildings, they could be reduced to around 4% of the occupied time.

Finally, parametric analyses were undertaken to scrutinize the results and consider the side effects of the measures. With the similarities found between the most appropriate solutions for the different classifications of the buildings, recommendations were made prioritizing the most feasible measures in terms of costs and practicability. It was suggested that the heavyweight buildings should take advantage of their mass to prevent overheating by means of continuous ventilation. If a good ventilation strategy cannot be implemented, it would be necessary to take other measures, such as windows with sun protection or external shading. However, as continuous ventilation might not always be feasible, due to safety or the proximity to noisy locations, ceiling fans would be recommended to increase thermal comfort.

The buildings with light partitions can still take advantage of an improved ventilation strategy to reduce overheating and improve the air quality, but an additional measure would be required to achieve thermal comfort. In these cases, depending on how the windows could be upgraded, a further measure such as ceiling fans or external shading should be evaluated according to the costs. The lightweight buildings, however, require more sun protection to prevent overheating. Therefore, it would be recommended to install electrochromic glazing or combine two other passive measures.

Flowcharts with these recommendations were created to guide the developers. Such roadmaps might be suitable for cities with similar climate conditions in the middle or the north of Europe, since many buildings might have very similar construction characteristics. It´s recommended however that when possible, each case is study individually through building performance simulations, as there might be specific aspects affecting further the building performance, such as the building surroundings.

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Author’s Biographical Sketch

I am a Civil Engineer graduated from *Los Andes University* in Bogota, Colombia. I graduated with distinction from the Master of Science Low Carbon Building Design and Modelling at Loughborough University in the United Kingdom. I did my Master research project under the supervision of Professor Malcolm Cook. Because of this research project, I received the award of Outstanding Work by the Energy Institute. I was also one of the finalists of the CIBSE - ASHRAE Graduate of the year.

I have professional experience in Colombia, Germany, and in the UK, where I have worked as part of multidisciplinary teams and partners including private and public organisations, higher education institutions, private companies, and research councils. I was the Technical Manager of the Colombian Green Building Council, where I represented the country at the LEED® International Roundtable. I worked as a Project Engineer in the Energy and Environmental Team at Tesco PLC in the United Kingdom, and I worked as an intern at Wolf Bavaria GmbH in Germany.

Table of Contents

1 Introduction

The concept of sustainability is perhaps found at the earliest instance in the manuscript *The Limits to Growth* published by Meadows et al. in 1972. This is a study of the earth's carrying capacity in relation to the population exponential growth (when the global population was half what it is now) and the uncontrolled exploitation of resources. They said, "*The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his individual human potential. It is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future*". These principles arose in response to the energy crisis of the decade of the seventies, where, for the first time, the industrialized world faced a shortage of their main energy source: petroleum. This situation led the humankind to rethink many of the processes that are carried out to sustain current societies. From this analysis, many initiatives calling for efficiency, the rational use of resources, and responsibility with the environment began to emerge. The construction sector naturally was not alien to this movement, on the contrary, every time more studies began to show the great potential of buildings and civil constructions to create more sustainable societies. However, the concepts of rational and efficient architecture date back from much earlier.

Ancient civilizations such as the Mesopotamians (2100 B.C.) built temples analysing the sun path and testing materials to create comfortable indoor environments. Later, the Romans and the Greeks (around 100 A.C.) built houses and temples looking for optimum solutions with shading but good daylight. Such concepts were overrated during the industrialization and later periods with the introduction of electricity and mechanical systems. However, sustainability has brought these good practices back and poses new challenges to the building sector, as integral solutions with economic feasibility and social and environmental responsibility are now required.

The call for the rational use of resources together from the reports on climate change has resulted in the emergence of various global, national and local initiatives that seek to establish reasonable goals, as well as the path to achieve them. To this end, several projects have been funded to investigate, test and report on results and lessons learned. However, the development of guidelines based on this process is a very difficult task as they should be specific so that they can be followed and applied, but at the same time general enough so that they can be implemented in different contexts. For the building sector, in terms of sustainability, perhaps the most complete set of guidelines are found in the green building certification schemes. However, they are not applicable to all locations and specific conditions. That is why the municipalities have chosen to create their own climate change mitigation and adaptation plans.

Within the construction sector, the greatest potential for efficiency lies in the existing stock, since the buildings lifespans are around 40 years and even more. Therefore, one of the priorities of each city that seeks to be more sustainable is to find the most appropriate solutions to renovate buildings, considering that the implemented measures must be cost-efficient, long lasting and with significant effects on the energy efficiency and people´s welfare. In addition, it should be considered that temperatures will continue rising in the following decades, and places previously considered with mild climates may now have risks of overheating.

The specific building use poses further requirements. Additional to the codes regarding structural safety, fire protection, energy efficiency, etc., buildings such as schools should be designed (or refurbished) considering the occupant high densities, and the need for high indoor environmental quality as required in learning spaces. Moreover, subjects as children are considered sensitive as they are in growing process and are more susceptible to the impact of surroundings features. Therefore special attention should be paid to aspects such as air quality, lighting levels, thermal comfort ranges, acoustics and noise levels, external views, furniture arrangement, indoor colours, etc., tailored specifically to enhance children´s learning process.

City authorities and designers are aware of the significance of refurbishing school buildings in a sustainable way considering the factors previously mentioned, but they struggle to find studies that combine them. A comprehensive tool that describes the effect of different measures on the indoor climate at current and future weather conditions, as well as the potential investment costs still missing. Such guidelines are key to support decisions that will have an effect on the city for the next decades.

1.1 Justification

The research project "Low-invasive measures for improving the indoor climate in school buildings" has the aim of finding recommendations to serve city's authorities as guidelines to choose more appropriate refurbish measures for the schools' buildings to reduce the risk of overheating considering side effects such as costs and energy consumptions. To this end, an integral investigation has been conducted considering the prognoses on future climate conditions, the characteristics and specific performances of different building construction types, the effect of various passive measures and the costs of such options.

This investigation was carried out under the supervision of Professor Andreas Wagner, Head of the Building Science Group and Vice-dean of the Architecture Department of the Karlsruhe Institute of Technology, and the support of the Office of Construction and Building Industry of the City of Karlsruhe (*HGW – Amt für Hochbau und Gebäudewirtschaft*). The HGW provided information, access to the school buildings and supported the supervision process as well.

To be able to give recommendations with a certain degree of confidence, it is required that the study is undertaken with rigorously following scientific methods. Therefore, the investigation included an extended phase of analysis of the existing building stock of the city and the characterization of the different building construction types. This analysis allowed selecting an appropriate sample to study further through Dynamic Thermal Simulation (DTS). Subsequently, the current and future climate of the city was studied, and onsite measures were recorded in various classrooms to obtain an overview of the indoor conditions during hot days. The next stages focused on the modelling of the chosen buildings and the analysis of passive measures to reduce the risk of overheating. The evaluation was carried out using several methods including local and global sensitivity analyses, parametric analyses and optimization processes.

1.2 Research Objectives

The general objectives of the project are briefly described as follows:

- Undertake a rigorous literature review along with the analysis of existing buildings in the city in order to identify typical designs of the buildings, specific construction details, and performance trends regarding energy consumption and indoor environmental quality.
- Identify that progress has been made so far in order to create guidelines for renovating schools and identify current gaps.
- Undertake climate analysis to identify the relevant characteristics that should be considered to improve indoor thermal comfort and energy efficiency. This includes the analysis of changes in recent years, as well as the prognoses of future conditions as an effect of climate change.
- Develop models of existing buildings to investigate their performance under base-case scenarios and analyze improvement measures through Dynamic Thermal Simulations (DTS). This includes the calibration of the models and the evaluation of the individual and global effects of different low-invasive measures.
- Determine to what extent the indoor conditions of school buildings can be improved, taking into account comprehensively the potential for reducing overheating of the measures, their costs and the increase in future temperatures.
- Identify differences or similarities between the different building construction types
- and propose refurbishment alternatives for each case
- Identify possible secondary effects (positive and negative) of the potential renovation measures.

1.3 Hypothesis

Although it is considered that Karlsruhe has a mild climate, the city is one of the hottest in Germany and has experienced an increase in the number of hot days (with daily temperatures above 30°C) during the summer. Therefore, it is believed that there is already a condition of overheating in classrooms.

It is also believed that low invasive measures can greatly reduce overheating, if not avoid it. Hence, school buildings could be refurbished avoiding air conditioning or mechanical systems and consequently avoiding a significant increase in energy consumption as well.

It is expected that indoor temperatures are higher in the buildings constructed in the mid-20th Century than in the buildings of the 19th Century because the latter tend to have higher thermal mass and possibly lower window-to-wall ratios.

1.4 Thesis structure

This thesis is organized in 11 chapters. The current chapter presents a brief introduction to the investigated problem and states the pursued objectives of this thesis.

Chapter 2 explores the current state of the art including the global, national and local guidelines to improve the performance of buildings and promote sustainability throughout the building life cycle. It also describes programs developed around the world to promote high-performance schools and gives a summary of the studies on indoor environmental quality in classrooms and refurbishment options.

Chapter 3 characterizes the current and future climate conditions in Germany and Karlsruhe and highlights differences between temperatures recorded at the city centre, the suburbs, as well as the information found in the local weather files.

Chapter 4 describes the stock building analysis and reviews the details of typical building construction types at different periods. It also shows the process that was carried out to select the buildings to study with the dynamic thermal simulations and their specific characteristics.

Chapter 5 explains what the inputs are required to carry out the simulations, what their sources were, and how the models were calibrated to be a reliable representation of the real conditions of the buildings. Chapter 6 describes more specifically the passive measures selected to be evaluated through the simulations.

Chapter 7 comprises the analyses to establish the overheating situation of classrooms under current and future weather conditions, and subsequently, the sensitivity analysis and optimization processes that were carried out to evaluate, under different perspectives, the effect of the measures in the reduction of overheating.

Chapter 8 shows a deeper study of the effects of the measures through parametric analyses. In this chapter, it is explained how overheating could be significantly reduced through passive measures, and discusses potential side effects.

Chapter 9 delves into the combined effects of the measures and proposes modernization alternatives for the different construction types.

The thesis ends with the description of other passive measures that have not been extensively studied or evaluated in this study but may have a boom in the coming years and may also be potential solutions.

2 Background

2.1 Generalities

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body responsible for assessing scientific knowledge related to climate change. It was established in 1988 by the United Nations Environment Program (UN-Environment) and the World Meteorological Organization (WMO) to provide policymakers with periodic scientific assessments of climate change, its implications, and potential future risks, and to propose adaptation and mitigation strategies. It has 195 Member States.

This panel published in October 2018 one of its most iconic report, known as the “1.5 Report” because it claims that the global temperature rise must be kept below 1.5°C by the end of this century to avoid the worst impacts. Limiting global warming to 1.5°C would reduce the irreversible negative effects on ecosystems, human health and wellbeing, and would facilitate the achievement of the United Nations Sustainable Development Goals. However, scientists and governments of many countries have agreed that this new threshold poses unprecedented challenges (IPCC, 2018).

Many countries have committed to plans to reduce emissions, such as the agreement of the COP21 (Conference of the Parties, delivered in Paris in 2015); one of the most iconic conferences due to its outputs and the participation of 197 negotiating parties. In it, and for the first time, it was agreed that the commitments to contribute to climate change should be universal and legally binding, fair and differentiated, and sustainable and dynamic (France Diplomatie, 2019). Furthermore, several countries have actively worked on the development of their own vulnerability reports, together with mitigation and adaptation plans, since it is known now that some effects of the climate change are already irreversible.

The building sector plays an important role in contributing to these goals. According to the IPCC, in 2010, buildings accounted for 32% of total global final energy use, 19% of energy-related greenhouse gas emissions (including electricity-related), and approximately one-third of black carbon emissions. Moreover, it is a transverse sector, as it has implications on others, such as energy, public health, and the economy and general development of a society. Therefore, the potential of this sector for achieving sustainable communities is greater than merely the reduction of emissions for the buildings´ operation. It is anticipated that the energy use and related emissions of the sector would double or potentially even triple by the mid-century due to the increased access in the coming years for billions of people in developing countries to adequate housing, electricity, and improved cooking facilities (IPCC, 2014).

Although the global scope for reducing carbon emissions is quite challenging, the technological solutions for the building sector exist and are well-demonstrated through many zero-energy building cases around the world. However, the IPCC recognizes that they may not always be the most cost- and environmentally effective solutions. Therefore, in order to increase the sustainability of the sector, national and local governments need to support the development of efficient and economically viable projects, both small-scale and large-scale. In terms of small-scale projects, the new high-performance buildings are the sustainable applications with the highest growth, because their profitability is proven and can be exploited by the owners within a few years after the investment. The financing instruments for the sector have also allowed mechanisms such as leasing to become economically attractive for stakeholders.

High-performance buildings are not only energy efficient but also built to consider sustainability throughout the life cycle. Thus, the design of these buildings considers aspects such as operating costs and investment payback periods, sustainability of materials, including certificates for recycling and closed or regenerative life cycles (i.e. cradle-to-cradle[1]), waste management, water and ecosystems conservation, and, naturally, aspects related to the health and well-being of the occupants, including the indoor environment quality and conducting periodic user-satisfaction surveys, among others. Given the number of aspects to be considered and the number of people involved, the development of these types of projects has improved through the integrative process and awarding sustainability certificates such as LEED® and BREAM®, which represent supporting labels for the various stakeholders.

However, the strongest need for sustainable cities falls on the existing buildings, where, unfortunately, the costs are higher and less attractive, due to higher payback periods. In this regard, the IPCC calls for urgent, ambitious and immediate measures. Due to the long lifespans of buildings, the plans put in place will have an impact for decades, which will affect not only the energy consumption and the carbon emissions but also the health and wellbeing of societies. The response to this call can be observed in the various studies of vulnerability, mitigation and adaptation to climate change in several nations and cities, together with specific policies and action plans that include mandatory measures but also financing mechanisms that promote retrofitting projects in the forthcoming years.

In Germany, the energy consumption related to the construction sector is around 42%, where 14% corresponds to non-residential buildings. The energy consumption in non-residential buildings has fluctuated around the 1100 PJ since the 1970s; however, a new peak was reached in 2010, with an energy consumption of 1344 PJ (Sustainable Buildings Centre, 2014). The sector was classified with a medium to high vulnerability because it is simultaneously affected by four factors: temperature, heat, weather extreme events and sea-level rise (Umweltbundesamt, 2015). To improve the sustainability and the efficiency of the sector, the country has established mandatory regulations and voluntary guidelines. One of the main regulations is the German Energy Saving Ordinance (EnEV), with purposes such as reducing 60% of the energy consumption of the sector by 2050 in comparison to 2010, and the increase of the climate-neutral inventory of existing buildings during the same period (DENA 2019). Climate neutrality implies the establishment of a baseline for greenhouse emissions, their reduction, and the compensation for those which are unavoidable through UN certified emission reductions (CERs) (United Nations, 2019).

The EnEV defines structural and heating system standards for buildings and specifies the energy efficiency for new and existing buildings. EnEV is based on the Energy Saving Act (EnEG), and it

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[1] Cradle-to-cradle is a concept where products and systems are designed to reabsorb obsolete materials back into the system and then use them again.

is supported by other standards and laws, such as the Renewable Energies Heat Act (EEWärmeG) (DENA 2019). According to the German Environment Agency (UBA), it is possible to reduce primary energy consumption in the building stock by as much as 80% through comprehensive building renovation and the increased use of renewable energy in buildings (Umweltbundesamt, 2016).

To achieve these goals, the German Federal Government set out the Energy Efficiency Strategy for Buildings in 2014. This strategy brings together the three aspects of power, heat, and energy efficiency to form a clear policy framework for the energy transition in the buildings sector, and addresses first approaches to technical, energy-efficient solutions, as well as economic aids that provide funding for such projects. A software-based tool for the energy-efficient retrofitting of buildings, in turn, supports the strategy. This tool can be used by energy advisors on efficiency in buildings to give owners a clear overview of potential modernisation work considering energy conservation and the use of renewables. It also provides an estimate of the relevant investment costs and of the savings that could be achieved in terms of heating costs and carbon emissions. The tool, however, is focused on residential applications[2] (BMWI, 2019).

In addition to these national initiatives, local and use-specific studies and guidelines have been developed. The next section explores some of these.

2.2 Sustainable Energy Action Plan of Karlsruhe

One of the first plans developed in Karlsruhe to establish a roadmap to achieve the commitments on climate change was the Sustainable Energy Action Plan (SEAP). The SEAP is a key document showing how the Covenant of Mayors (CoM) signatories would reach its commitments by 2020. It used the results of the Baseline Emission Inventory to identify the priority fields of action and opportunities for reaching the local authority's greenhouse gas emissions reductions target. The plans explicitly imply the active involvement of public authorities who cover a multifunctional role as regulators, as building owners, tenants and developers and, lastly, as boosters for market suppliers of energy efficient products and services. This initiative shows how municipalities can significantly influence energy management and sustainable development. (Covenant of Mayors, 2010).

The SEAP of Karlsruhe was approved in 2009, with a CO_2 emission reduction target of 27% by 2020, in comparison with 2007. The document consists of 80 measures divided into six fields of action: (i) General, (ii) Urban Planning and Land Transport, (iii) Energy Efficiency, (iv) Renewable Energies, (v) Transport, (vi) Information, Counselling and Participation (City of Karlsruhe, 2010). The main measures that address public building energy consumption are briefly described as follows:

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[2] The tool can be found at: http://www.sanierungskonfigurator.de/start.php.

- Measure 4: Monitoring extension. Under this measure, which belongs to the general action, the Office of Construction and Building Industry (HGW) was set up. According to the SEAP fourth Progress Report, published in 2017, the urban energy-monitoring programme comprises about 350 buildings, including all 90 schools, where the consumption is recorded on a monthly basis in the city´s database. Around 30 schools and 20 public offices belong to a special *Savings Project* (EinSparProjekt), which seeks a reduction of 15% in energy and water consumption. The HGW provides tailored training to managers and the authorities of these buildings and keeps close track of their progress, delivering a monthly report (City or Karlsruhe, 2017b).

This last report, in 2017, showed that in 2013 the annual average energy savings were about 2% (over the year before), but for 2014 and 2015 the annual savings rose to 4%. Overall, the heating energy consumption has been reduced by 35% (in comparison to 1990) and the CO_2 emissions by around 50%.

The electricity consumption has shown another trend; the period between 1993 and 2010 experienced an increase of around 1% per year. The savings started in 2014 with annual reductions of approximately 3.5%. Overall, the savings have been around 3% (in comparison to 1993). The CO_2 emissions went down in the same period by 13%, due to the increasing share of renewable energies in electricity generation.

- Measure 13: Higher energy standards of urban new buildings. This measure belongs to the Urban Planning and Land Transport field. The latest report states that several new buildings and extensions of existing buildings have been completed, largely planned according to the Passivhaus standard. The HGW has reported that the goal is to plan new public buildings in Karlsruhe with specifications close to this standard, which aims for a maximum heating requirement of 15 kWh/m^2a and a maximum primary energy requirement of 120 kWh / m^2a. However, the planning processes have shown that their cost-effectiveness is not adequately represented in the life cycle, and therefore, the Passivhaus standard can often not be fully achieved, especially for buildings with low volumes (City of Karlsruhe, 2017b).

- Measure 22: Energy optimization of municipal buildings: part of the action field for Energy Efficiency. This measure aims to find energy-saving measures for existing buildings based on the energy reports from the HGW. During 2009 and 2010, 41 remedial measures were completed, which led to improvements in energy-use terms, including 31 in the heating sector, 8 for power efficiency and 2 measures to reduce water consumption. Some examples of the measures taken are roof and facade renovations, window replacement, and lighting refurbishment of schools.

The HGW also created a plan for integrated energy analyses of five schools, including a programme for climate protection. Another 16 buildings, belonging to the volunteer fire departments in Karlsruhe, have been also the focus of research on energy improvement opportunities with low investment. It is expected that these studies will allow the creation of an action plan with the key points for energy savings for fire departments.

- Measure 25: Guidelines for energy standards in municipal buildings. The Municipal Council created and adopted the *Guidelines on energy efficiency and sustainable buildings* (LENB in German) in November 2009. It consists of two parts: Part 1 - Guiding principles and general requirements and Part 2 - Specific requirements for building structures and technical equipment, as well as a set of guidelines for sustainable building management.

The LENB Part 1 sets up the framework for the refurbishment and new-build plans to proceed in accordance with the national and European efficiency and climate change goals. It states that the economic and rational use of energy has the highest priority for buildings. It is expected to reduce pollutant emissions by both energy reduction as well as conversion to renewable sources. It has a chapter for measures for new and existing buildings. The measures are divided into requirements for locations and the urban environment, and spatial and usage requirements. In terms of refurbishment measures, the first goal was to create an inventory of the building stock, and the performance and renovation needs of these buildings.

For all the buildings, the old components relevant to energy use should be replaced, meeting the latest energy standards and considering commissioning procedures. The vulnerability of buildings (technical and physical) should be systematically and continuously identified. Within these requirements, there are some guidelines for the building envelope and the technical equipment, so that they start moving closer to the Passive House characteristics, as far as it is technically and economically feasible. The aim is to preserve the character and especially the facade features as much as possible, with the accurate thermal protection (internal and/or external) to act according to the current winter and summer characteristics, including measures to avoid structural damage. It is also stated that rooms with high internal heat loads should be arranged, as far as possible, on the north façade or in naturally-ventilated basement rooms.

Regarding the indoor environment, the LENB Part 1 highlights the importance of the definition of room temperatures for indoor thermal comfort as well as for energy efficiency. However, it does not give any specific ranges of guidance on how to establish them. It also states that setting the requirements for summer heat protection requires combined solutions of construction measures and technical systems, considering the optimization of the life cycle costs. The summer heat protection must be proven by calculations, and appropriate structural measures must be taken to meet the requirements of room acoustics and take into account the thermal storage capacity of the components. Buildings should operate without air conditioning, and it also recommends testing solutions such as automatic windows. This type of technology is currently being tested at the Max-Planck Gymnasium. Night ventilation is recommended through ventilation flaps with effective burglary and insect protection to avoid overheating during the summer.

The LENB Part 2 is more specific. In terms of sun protection, it gives the following recommendations:

- External protection devices should have the following minimum lifespans: 25 years for movable sun protection made of aluminium or plastic, 15 years for awnings, and 60 years for fixed solar protection made of light metal.

    - Sun protection systems are preferably to be installed outside. All sunny windows receive a ventilated, external sunscreen (reduction factor Fc ≤ 0.25 according to DIN 4108-2) designed for wind speeds of at least 13 m/s. The sun protection must be adjustable, so that artificial light can be dispensed with, even with full protection.
    - The transmission factor for sun protection should not exceed b <0.2, according to VDI 2078.

This transmission factor (also called b-factor) corresponds to the ratio of the g-value (Total Energy Transmittance) of the respective glazing and the g-value of glass pane without coating (Fensterfersand, 2019). Therefore, it is recommended that rooms that experience direct solar radiation for several hours are equipped with glazing with low b-factors to guarantee good shading.

    - Horizontal louvres are preferable because they enable more daylight to enter.
    - Sun protection systems that operate automatically should have a manual override option without a key switch.

- Measure 57, part of the 6th action field, was created in 2009 by the Karlsruhe Energy and Climate Protection Agency - KEK. The KEK is composed of five teams who work on building energy efficiency, renewable energies, and environmental management systems. The KEK also offers seminars and training on climate protection and energy efficiency.

This section presents a brief overview of the policies that are coming into force to mitigate and adapt to climate change, both globally and locally. The following sections will focus on school buildings.

2.3 Schools in Germany

Europe has over 64 million students and almost 4.5 million teachers (European Commission, 2014). In Germany, there are 11 million school students with almost 800000 teachers located in approximately 52000 schools. One-third of these schools were built prior to 1945, one-tenth date from 1945 to 1965 and the rest were mostly built in the early 1990s. The schools built after the Second World War are mostly precast concrete skeletons, which do not comply with the European and national standards of energy efficiency, and therefore consume a lot of energy. (Statistisches Bundesamt Deutschland, 2016).

In 1950, there were about 41300 schools in the old Federal Republic. Many of these schools were still rural and therefore some of them were closed in the late 1950s and early 1960s in the context of a school-re-planning movement. New procurement and manufacturing processes enabled faster, larger and less expensive constructions. From 1970 to 1990 approximately 2500 larger schools were constructed. These schools were more specialized; therefore, in contrast with the older schools, they had functional rooms. The reunification of the two Germanys in 1989 then resulted in in a larger school building stock, 52307 in 1993 (Wüstenrot Stiftung, 2004).

The modernization and renovation of schools in the Federal Republic have increased dramatically in the last 30 years due to the increase in student numbers and the need for more spaces. According to the Wüstenrot Foundation (2004), the 1970s buildings present major problems because they require the restoration of electrical, plumbing and heating equipment, adjustments to safety and disabled facilities, and a great deal of modernization in terms of functional, hygienic, energy-related and ecological aspects.

In terms of energy consumption, the recorded data from school buildings around the country shows a very wide range, from 32 kWh/m^{2}a to as much as around 400 kWh/m^{2}a (Karsten et al., 2016; HGW, 2016). The data comparison shows no significant difference between new and renovated projects (Karsten et al., 2016). However, the consumption has decreased over time: the energy consumption in the seventies averaged around 380 kWh/m^{2}a and in the early nineties averaged about 210 kWh/m^{2}a.

One of the most important programmes in terms of development and refurbishment to produce highly efficient school buildings in Germany is the so-called *EnEff:Schule*. The following section will explain and discuss this and similar programmes around the world

2.4 High-Performance Schools

Looking specifically at school buildings, several aspects come together. On one hand, there are the requirements of the building itself, where it must provide security, functionality and nowadays also efficiency during its life cycle, and on the other hand, the specific challenges of schools where the ultimate goal is to achieve optimal learning spaces. From this premise, the concept of high-performance schools is born. In high-performance schools, the efficiency is a prerequisite, but it also considers the wellbeing of all occupants, the quality of the learning processes, and the awareness and engagement of pupils and school students together with sustainability. This principle has two objectives, first, by providing students with energy conservation and an environmental protection context, students' consciousness of sustainable development will be greatly enhanced, and secondly, energy and water savings campaigns would have better outcomes as the main occupants would actively participate in them (Zhao et al., 2015).

However, bringing all those aspects together is not an easy nor economical task. Therefore, in order to guide stakeholders, various initiatives around the world have reported on successful pilot projects and published guidelines based on the outcomes and lessons learned. Depending on the context, it is expected that some aspects will be prioritized over others. Various authors agree that a balance should be sought, but there is no quantified evidence of the trade-offs. Tiberiu and Vlad (2012), for instance, state that in school building design, efforts should be made in order to ensure the construction of quality learning environments. Students' comfort and performance should be a priority in school design, but a detailed analysis of the energy consumption and cost effectiveness of the building are also mandatory, and therefore the starting point to make decisions. Causone et al. (2015) suggest that, for the European context, energy consumption should be the focus of the refurbishment process, because old buildings are severe energy wasters, providing low energy environmental quality and represent a large fraction of the European building stock. Rospi et al. (2017) emphasise that comfort levels should be a priority because students and teachers spend much time in school buildings, and their wellness and productive capacity are primarily affected by thermal comfort and indoor air quality. However, they highlight the effect of the age difference in buildings: in the Mediterranean city of Madera, for example, the buildings constructed prior to 1991 are highly energy inefficient and therefore this aspect should be the main concern.

The next section will explore some of the most relevant initiatives that have gathered studies of individual projects to produce more general guidelines.

2.4.1 Green schools

One of the first integrative programs for green schools was The Centre for Green Schools launched in 2010 by the United States Green Building Council (USGBC), as an initiative to encompass the concepts of green buildings and enhance the learning processes by actively integrating teachers, students, staff, and parents. To this end, the Centre promotes the methods and the use of the LEED® for schools rating system, varied training programs tailored to different stakeholders and various activities such as the Green Apple Day of Service and the annual Green Schools Conference & Expo (The Center for Green Schools, 2019).

The LEED® Rating System recognizes the unique nature of school buildings and addresses issues such as classroom acoustics, children’s health, and a school’s relationship to its community. The system states that children breathe more air in proportion to their bodies than adults do, and their developing bodies are more susceptible to the effects of environmental toxins. Therefore, the indoor spaces must be carefully designed to minimize pollutants and maximize support for health and well-being. The system gives guidance on specific strategies for unique space types, from classrooms to gymnasiums, cafeterias to laboratories (USGBC, 2019).

The LEED® Rating System provides guidelines for new-builds as well as for existing schools. Saving water and energy is a prerequisite, which can be achieved through different paths depending on the project. For instance, refurbishment projects should demonstrate energy efficiency performance that is 25% better than the median energy performance of similar buildings by benchmarking against the national source of energy data. For new-builds, a whole-building energy simulation is recommended, or following a prescriptive path showing 50% improvement using the ASHRAE Advanced Energy Design Guide 90.1 2010. To save water the guide recommends highly efficient equipment for both refurbishments and new constructions.

The Green Schools programme places great emphasis on air quality, to enhance learning performance, but also to reduce the risk of Sick Building Syndrome, where some illnesses, can be directly related to the building itself. The typical example is when several children get a cold during the same period, which is explained as being due to lack of proper ventilation in classrooms. Therefore, the Green Classroom Professional has been created, which is a certified training programme tailored to teachers and school authorities to promote sustainable environments without influencing the building design. Although the training also covers topics related to efficiency, several guidelines direct attention to air quality. For this purpose, it seeks to raise awareness about how air comes into a classroom and leaves it, so that people can avoid blocking the vents with furniture, books, or other objects; whether the classroom receives heated air, cooled air, or both; which devices can be controlled from inside the classroom; and why CO_2 levels should be monitored. Additionally, it provides guidelines on the cleaning products that should be used or avoided, the type of pollutants that are common inside school buildings and why they should be periodically monitored. The program tries to include parents as well, giving them some recommendations, such as reducing engine idling close to the school premises and accompanying the monitoring process of the school.

2.4.2 Energy efficient schools

In Germany, the Federal Ministry for Economic Affairs and Energy has conducted the research project Energy-efficient schools (EnEff:Schule), which is part of the energy-optimized construction framework and research program - EnOB. The aim of this project is to test refurbishment strategies in various school pilot projects and report on the performance achieved. Initially, seven school buildings and six main aspects were considered: building envelope, heating, ventilation, sun protection, cooling, lighting, and regulations. To enable a cross-analysis a research team was formed with experts from the Fraunhofer Institute for Building Physics (IBP), the Institute for Resource Efficiency, and Energy Strategies (IREES) and the University of Munich (HM) (Fraunhofer-Institut für Bauphysik, 2013).

By means of demonstration projects, the Programme has shown which different innovative ways drastically reduce final and primary energy demand for heating, domestic hot water heating, ventilation, cooling, lighting, and school operations. The demonstration projects have run on different energy levels, including 3-litre schools, PassivHaus schools and plus energy schools. A 3-litre school is a low-energy building which has an annual primary heating energy demand of less than 30 kWh/m^2a (energy content of 3 litres of fuel oil). This consumption considers the heat losses of the system and the required driving energy for pumps and fans, as well as the fuel type. This does not include the energy required for water heating, for lighting and for the school teaching and work aids.

Plus energy schools produce more primary energy over the year than they need for heating, ventilation, domestic hot water, lighting and the necessary auxiliary energy. In order to achieve this ambitious goal, the losses due to transmission and ventilation must be drastically reduced in a first step. This is achieved by high thermal protection of the envelope, the extensive elimination of thermal bridges and by efficient ventilation. In the second step, the energy demand is covered by onsite renewable energies, usually, photovoltaic modules connected to the grid for balancing the consumption. The energy assessment of the schools is carried out in accordance with the calculation method specified in DIN V 18599.

Most of the innovative techniques reported by the programme relate to the energy efficiency in terms of heating, as it is source of the higher energy consumption in school buildings. For summer protection and cooling, it only gives the reduction factor (FC) of various types of movable and fixed internal or external shading devices. However, it gives some examples of innovative facades that can be used to reduce overheating as well, if designed properly. These include, for instance, atria, conservatories, and double facades. In a glass double façade (GDF) the solar energy creates an intermediate climate in the air space between an inner and an outer glass facade, which has a higher temperature level compared to the outside air. In this way, heat losses are reduced and, thus, the corresponding heating energy requirements. Such elements should be carefully designed and simulated, as problems can arise during summer if the heated air in the façade gap cannot be dissipated quickly enough. The structural complexity of glass double façades still leads to controversial discussions. The schools with the most innovative refurbishment measures to reduce overheating are briefly described as follows:

2.4.2.1 Olbersdorf School

The Olbersdorf School, located in Olbersdorf, Sachsen in Germany, was built in 1928. The building is a four-storey masonry construction with pitched roof. With the renovation, in 2008, the 3-liter house standard was achieved. In the Olbersdorf school, the following measures against summer overheating were implemented:

- Electrochromic glazing
- PCMs in the attic
- Capillary tube in areas subject to particularly high thermal loads.

Simulations of the ITG Institute (Institute for Technical Building Equipment Dresden Research and Application GmbH) quantified the summer conditions expected for the different technologies. Contrary to what was previously expected, the PCMs had significantly low effects, as shown in Figure 1, while the electrochromic windows had a higher performance (Bolsius et al., 2013).

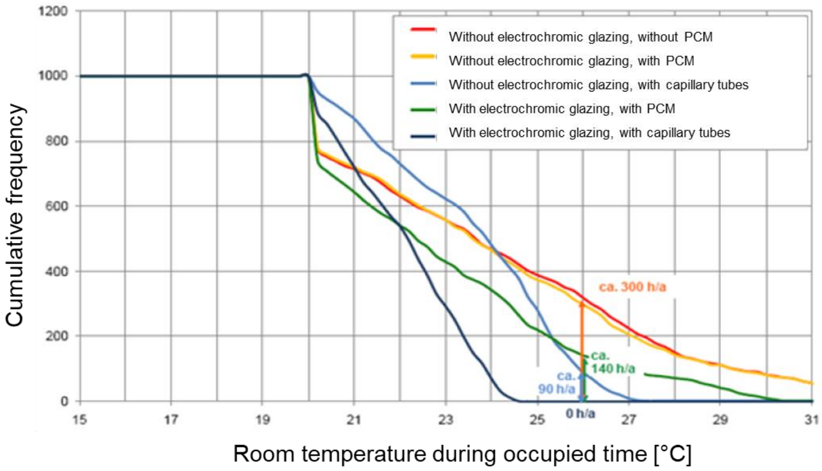

Figure 1: Comparison of the effect of measures to reduced overheating, implemented at Olbersdorf

School. Source: Bolsius et al., 2013

2.4.2.2 Max-Steenbeck-Gymnasium Cottbus

This school was built as a lightweight building in 1973 and was refurbished in 2012 to meet the Passivhaus standard. To prevent the risk of overheating, this school combined automatic windows devices and PCMs at ceilings. In contrast to the Olbersdorf School, the PCMs achieve a significant effect. As it can be seen in Figure 2, the indoor temperatures at the rooms with PCMs do not exceed 28°C. (Häusler, Neupetsch, 2015).

In this case, study it can be seen how the PCMs effectively rise the thermal mass of a lightweight building, and with the appropriate ventilation strategy, i.e. during the night, when the outdoor temperatures are low, the rooms can release the accumulated heat and create comfortable environments for the following day.

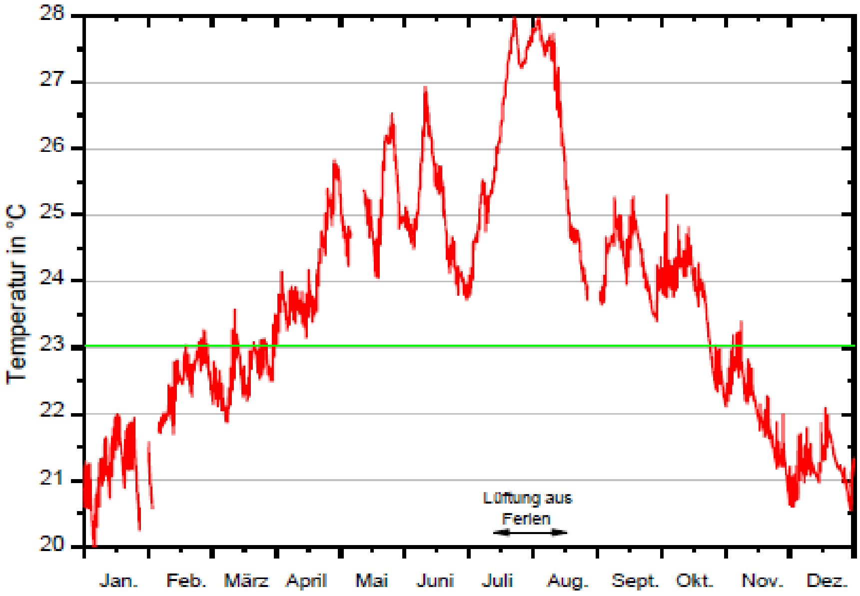

Figure 2: Indoor temperaturses at room with PCMs - Max-Steenbeck-Gymnasium Cottbus
Source: Häusler, Neupetsch (2015).

2.4.2.3 Science College Overbach in Jülich

Since 1918, the Congregation of the Oblates of St. Francis de Sales in Jülich Barmen maintains a monastery and a school. The School offers in addition to regular school lessons seminar to adults and therefore the premises are usually occupied during the whole day. The two buildings were refurbished to meet the *Passivhaus* standard. The school implemented an innovative “energy balance” that considered that the computer workstations were better allocated at the basements to provide more comfortable environments and reduce the energy loads. As a concentric structure, the building was constructed around a forum, from which the classrooms are arranged in a circle.

The windows were replaced with triple electrochromic glazing (Ug value: 0,5W / m²K). Depending on the switching state, the glass changes its colour from transparent to blue and thus makes it possible to control the light and heat input into the building (light transmittance TL: 13 - 46%, g-value 10 - 32%). Each window front can be controlled both manually and via the building management system. The specialized rooms receive daylight from two sides, which in conjunction with the electrochromic glazing ensures a sufficient supply of natural light during the day. In addition, there is an artificial lighting, which is designed to save energy and with daylight-dependent control. Two seminar rooms on the ground floor are equipped with special fluorescent lamps that reflect the daylight and seasonal colour temperatures of the corresponding light. Here, students can explore the effects of light colour on learning behaviour (Baunetz, 2018).

2.4.3 Teenergy Schools

Teenergy schools is a European project, which gathers eight international partners operating in four Mediterranean countries: Italy, Greece, Spain, and Cyprus. The purpose of the project was to gather data to improve benchmarks and improve the energy efficiency of school buildings under the three typical Mediterranean climates: coast, mountain, and plain. The project created an internet-based platform to gather energy consumption data. However, published data about the levels of consumption or savings were not found.

With the gathered information, the project classified refurbishment measures into three groups: Intervention A, as the first approach to improve energy efficiency with low costs but also low effects; Intervention B with medium cost and medium effect; and Intervention C, with high costs but also high impact on the overall buildings' performance (Trombadore et al., 2011). These were the measures for each group:

- Intervention A: lights with LED and movement sensors, and remote regulation of heating system with thermostats.
- Intervention B: insulation of external walls, ventilated and insulated roofs, replacement of windows, replacement of the heating system.
- Intervention C: shading devices, natural ventilation, PV panels, solar panels for hot water, underfloor heating systems.

2.4.4 Eco-schools

Eco-Schools was born in 1992 as an international environmental education programme, environmental management system and award scheme that promotes and acknowledges long-term, whole school action for the environment. Unlike a one-off project, it is a long-term programme that introduces participants (students, teachers, parents and the wider community) to the concept of an environmental management system. (Zhao et al., 2015). The initiative was launched in 1994 in Denmark, Germany, Greece and the United Kingdom, with the support of the European Commission.

In contrast to the previous two programmes, Eco-schools focus more on the educational programme directed to sustainable development rather than the building design and efficiency. In that sense, it promotes the active participation and involvement of students, teachers, parents, and school authorities. However, the programme requires an action plan based on the environmental actions undertaken by the schools, including energy efficiency (Eco-schools, 2014)

2.5 Sustainability guidelines

2.5.1 Worldwide guidelines

The previous section has shown the long road that has been followed to establish several codes and guidelines that the design and operation of buildings have to follow to ensure spaces that are safe, efficient and responsive to the present and future challenges of societies and climate change. Building design and management are very complex tasks that comprise different aspects to consider, as well as the roles of several stakeholders at different time periods. Therefore, the guidelines are spread over different aspects and when designers seek to follow them, they struggle to find specific answers in just one place. This might seem totally counter-productive but the reason behind this is that specificity requires such division. On one hand, the planning of new buildings differs greatly from the planning of a small or large refurbishment project. On the other hand, looking into the structural safety of a building involves different types of knowledge and actors than when looking into its energy efficiency. Moreover, although this is understood, at some point it is required that building authorities and designers can find guidelines that provide them, as far as possible, the combination of tools that allows them making decisions in terms of sustainability goals and investments. To tackle this challenge, the integrative design approach was developed and is now a requirement in the use of building certification systems such as LEED®.

The aim of the integrative design approach is to promote cost-effective and high-performance projects through an early analysis of the interrelationships among systems. To this end, early exploratory sessions, also called design charrettes, are undertaken with the participation of, as far as possible, all the actors involved. Figure 3 shows a list of the experts who should participate in such charrettes. In these meetings a moderator is chosen, usually someone with building management experience who has the overview of all the aspects involved in the construction projects. The moderator develops sessions where, through groups combining the appropriate stakeholders, the users' requirements are brought together with sustainability goals and the budget constraints. Due to the number of persons participating and the aspects to consider, the moderator has to have the ability to keep the sessions at a general level: however, the details of the projects are discussed and developed. By encouraging the participation of actors from several fields, repetitive processes are avoided, since, as the goals are established, the technical or budgetary restrictions that they may have are also discovered at the same time. In the traditional design process, usually relatively specific proposals about a project are rotated between the different disciplines and then each group reviews these and sends its comments to the next group. This process not only consumes more time but also demands constant budget changes.


- Owner's capital budget manager
- Architect or building designer
- Mechanical engineer
- Structural engineer
- Energy modeler
- Equipment planner
- Acoustical consultant
- Telecommunications designer
- Controls designer
- Food Service Consultant
- Infection Control Staff
- Building science or performance testing agents
- Green building or sustainable design consultant
- Facility green teams
- Physician and nursing teams
- Facility managers
- Environmental services staff
- Functional and space programmers
- Commissioning agent
- Community representatives
- Civil engineer
- Landscape architect
- Ecologist
- Land planner
- Construction manager or general contractor
- Life cycle cost analyst; construction cost estimator
- Lighting designer
- Other disciplines appropriate to the specific project type

Figure 3: List of participants in an Integrated Project Team (USGBC, 2018).

The certified green building market has had an exponential growth in recent years (WorldGBC, 2018). Despite the fact that certification systems have received strong criticism due to the costs of the certifications and the gaps between the design and the performance during the operation, it can be assured that these systems have provided comprehensive guidelines that have covered the different aspects that surround the sustainability of buildings. Figure 4 shows the categories that a building should cover in order to be considered sustainable according to the US Green Building Council and its green building certification system, LEED®. These categories have minimum requirements and reward the extra actions that are taken to achieve better performance.

Figure 4: LEED® Credit Categories (USGBC, 2018)

The ultimate purpose of the exploratory meetings, whether carried out following the charrette style or not, is to develop a simple road map of the measures that could be implemented to achieve sustainable goals. These goals and somewhat more specific measures are the starting point for the designers to develop their models and start the subsequent simulations to study the feasibility and effects of combined solutions. Although the analysis of new buildings and refurbishments are quite different, the general aspects of sustainability remain the same; therefore, such road maps should consider at least the following aspects (USGBC, 2018):

- Site conditions: assessment of surrounding impacts: potential sources of contamination or noise, nearby buildings that could affect the project or be affected by it, assessment of shading, lighting, landscaping, and hardscape.
- Orientation, envelope and thermal mass: explore the effects of the orientation of the building into the HVAC (Heating, Ventilation and Air Conditioning) loads and how the thermal mass and the building design can be potentially improved to reduce them. Pre-assessment of energy consumption, lighting, and renewable energy opportunities.
- Basic Indoor Environmental Quality (IEQ):
    - Indoor Air Quality (IAQ): determine minimum requirements for fresh air depending on the occupancy characteristics. For classrooms, the recommended minimum fresh air is 8 l/sp.
    - Lighting levels: assess interior surface reflectance values and lighting levels in occupied spaces. For classrooms, the recommended minimum level is 300 lux, although for certain activities 500 lux should be achieved.
    - Thermal comfort ranges: determine the acceptable thermal comfort range according to the occupancy characteristics. The appropriate comfort levels would be discussed in section 2.5.
- Energy and water savings: explore the range goal for savings as well as the benchmark, timelines, controlling systems and commissioning processes.
- Plug and process load requirements: assess reducing plug and process loads through programmatic solutions (e.g. equipment and purchasing policies, layout options).
- Programmatic and operational parameters: assess multifunctioning spaces, operating schedules, space allotment per person, and anticipated operations and maintenance.

In additional to these aspects, there are three further factors that should be considered, especially in buildings such as schools. These are mentioned in the LEED® guidelines and have also been addressed by various recent studies:

- Specific requirements according to the use: additional to minimum IAQ requirements, acoustics, external views, and minimum areas of open spaces should also be evaluated.

For instance, in terms of achieving high-quality indoor acoustics, School of the Future highlights reverberation time as a key parameter, owing to its direct correlation with speech intelligibility. This variable can be quantified for classrooms according to the German Standard DIN 18041. However, for assembly halls or gymnasiums, and for the impact of ventilation and mechanical systems on acoustics, it is recommended that experts evaluate these specific cases (Mørck et al., 2015).

Yang et al. (2013) also found that improving artificial lighting has almost no impact on pupils and students' satisfaction and cognitive performance but improving acoustics improved overall learning performance. They suggest that student perceptions are affected by internal environmental sounds such as HVAC fans or student conversations, as well as by external sources such as the sound of traffic. Poor classroom acoustics can contribute to a negative learning environment for students, as excessive noise causes distraction and annoyance, therefore background noises should be eliminated as much as possible.

- The learning environment can also be improved by indoor design. For instance, Barrett et al. (2017) discussed the concept of completeness in cognitive performance, under the framework of the Holistic Evidence and Design (HEAD). This UK study suggests three design principles that affect the learning performance of pupils: Naturalness, Individualization, and Level of stimulation. Within these principles, there are 30 factors that should be considered in order to enhance learning spaces. As an example, the study´s results show that both reading and writing performance are particularly affected by the Level of Stimulation parameters: complexity (visual diversity) and colours. And in terms of maths progress, the Individualization of the classroom plays a very important role. In addition, Flexibility ("as a measure of how well designed the classroom space is for the particular age of the pupils"), should entail different designs for younger and older pupils, where for the younger group, more intimate spaces are favourable whilst for the older group, larger and squarer rooms are more encouraging.

Sharing these concepts, several schools around the world now promote the roundtable classroom designs, where, instead of organizing tables and chair in rows, they are arranged as a circle. This arrangement has two purposes: first, to promote the participation of all the students, and second to stimulate equality between pupils; in roundtables there is no sense that someone is more or less "important" than other members of the group. Parsons (2016), for instance, reported on experimental testing of various adaptations of the traditional classroom, roundtable style classrooms, technology light classrooms, and technology rich classrooms, to identify which types of active learning classrooms are most effective for which environments. While in the early stages one big circle might be more adequate, as it gives a sense of security that promotes participation, at the latest years, even at university levels, various smaller circles might be more appropriate environments, as they promote teamwork.

- Commissioning and monitoring. It was mentioned that one of the criticisms of LEED® and other rating systems is that, in some cases, a great gap between the actual and predicted performance was found. It was pointed out that certification systems are focused on the design stage but there were no follow up requirements during operation, which had resulted in cases with high consumption (Barth, 2018). To remedy part of this issue, buildings and districts working on obtaining the LEED® certification are now tracking sustainability metrics. Once ready to pursue certification, they submit the data on how the buildings have performed. From there, the GBCI (the organization that administers project certifications for several green building designations, including LEED®) verifies that the building is operating as intended and that there are policies in place to ensure that such performance continues.

The commissioning process also helps to ensure that the systems will operate according to the design specifications. This process implies then that a commissioning authority (usually a third-party agent) verifies that the project's energy-related systems are installed, calibrated and perform as intended. The energy-related systems that should be included into the commissioning process activities include: heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems (mechanical and passive) and associated controls, lighting and daylighting control, domestic hot water systems, and renewable energy systems.

2.5.2 European guidelines

At European level, two projects stand out for their studies carried out in several countries and the sets of guidelines that were published as a result of their findings. One of them is SINPHONIE - Schools Indoor Pollution and Health: Observatory Network in Europe, which established a scientific and technical network across the European Union (EU) with the long-term objective of improving the standard of air quality in schools and kindergartens. At the same time, the project aimed to support future policy development by formulating guidelines, recommendations and risk-management options for better IAQ and associated health outcomes in schools. SINPHONIE was initiated and funded by the European Parliament, ran from 2010 to 2012, and studied 114 schools in 21 EU member states, as well as Albania, Bosnia, and Herzegovina, Norway, and Serbia (SINPHONIE, 2016).

SINPHONIE has a strong epidemiological perspective and an extensive assessment programme highlighting health impacts due to aspects of poor IAQ. It therefore addresses indoor environmental quality of schools in terms of the physical, chemical and microbiological stressors that impact and potentially affect human health. The studied and recommended values for such stressors can be found in their guidelines for healthy environments within European schools (SINPHONIE, 2014). Some of their most important recommendations are summarized as follows:

- Classrooms should be equipped with CO_2 alarms so that teachers can take appropriate actions and avoid unhealthy levels
- Follow the guidelines from the World Health Organization (WHO) in terms of Volatile organic compounds (VOCs), in order to avoid both short-term irritations and long-term health consequences for both adults and children. One of the most common VOCs found in classrooms is formaldehyde, a gas released from wood-based materials and component of paints, glues, and textiles. The WHO (2010) recommend that formaldehyde concentrations should not exceed an average of 0.1 mg m–3 exposure over 30 min. This naturally would imply that school premises are tested, which should be done at least once a year, if traces are found, or every three years, to identify potential hazard pollutants.

- Beside CO_2 and VOCs, there are numerous other pollutants that affect the IAQ in school buildings. SINPHONIE investigated an extensive range of physical, chemical and microbiological stressors from different sources that can negatively affect IAQ. The outcomes revealed by SINPHONIE highlight important patterns of interrelations between these factors, exposure, sources/causes and health impacts on students. Therefore, it proposes first to use indicators that can identify which symptoms experienced by the students are linked to IAQ problems, e.g. if the symptoms are widespread within a class or school or if they disappear when the occupants leave the building at the end of a school season. It then offers a set of indicators, tools, and protocols for monitoring IAQ and evaluating health in a school environment. Camacho-Montano et al. (2017) summarized the sources and recommendations of such stressors.

The second project is School of the Future – Towards Zero Emissions with High-Performance Indoor Environment, which was funded under the 7th Framework Programme of the EU and ran from 2011 to 2016. Its main objectives were the design, realization, evaluation and communication of good examples of future high-performance buildings through the energy-efficient renovation of four school buildings in Denmark, Germany, Italy and Norway, based on the contributions from 13 partners with experts in different fields (Erhorn-Kluttig, 2016; School of the Future, n.d.). School of the Future presents a broad design-oriented approach based on best practice in the four European countries. The specific recommendations are spread among their four guidelines. Their main outcomes are briefly summarized as follows:

- Improved Indoor Environmental Quality (Steiger et al., 2014): In terms of thermal comfort the guide recommends indoor temperature ranges for each season: 20–24°C for winter and 24–26°C for summer. It advises on careful design of natural and mechanical ventilation, including passive cooling systems, to avoid draught risk and reduce energy consumption, and the use of shading devices when possible, controlled by indoor temperature and total solar radiation on the facades (> 150–300 W/m^2). Night ventilation is also encouraged to reduce overheating.

In terms of indoor air quality, it recommends to limit the CO_2 concentration levels during occupied times in ranges from 1000 ppm to 1500 ppm and advises on the use of certified low emission construction products to limit VOCs to levels that minimize the associated health risks, following the German Federal Environmental Agency for recommended VOC levels.

In terms of lighting conditions, it recommends following the Standard follows 12464-1, considering the specific requirements for each space and addressing all the main design requirements together: the optimum lighting levels and light distribution, including glare limitation and colour-rendering index.

The acoustic design of the entire school building should be customized by space (standard classrooms, music rooms, sports facilities, social areas, etc.) in order to achieve optimum working and learning conditions. It promotes the use of the German Standard DIN 4109 for noise-protection requirements against various kinds of acoustic disturbances, both out- and indoors and advises especial attention in naturally ventilated and mixed-mode buildings, since noise through open windows and vents may lead the occupants to override the building's operational settings. It also draws attention to the concept of flanking transmission, where the sound passes over a partition, which can result in small areas with unacceptable levels of noise. In terms of achieving high-quality indoor acoustics, School of the Future highlights reverberation time as a key parameter, owing to its direct correlation with speech intelligibility. This variable can be quantified for classrooms according to the German Standard DIN 18041. However, for assembly halls or gymnasiums, and for the impact of ventilation and mechanical systems on acoustics, it is recommended that experts evaluate these specific cases (Camacho Montano, 2017).

- Retrofit of Building Construction Elements (Mørck et al., 2015): The guideline starts with advice about the insulation of the building envelope as the main strategy to improve energy efficiency. It cites examples of successful cases where the insulation at walls and roofs and the replacement of windows have led to significant reductions in energy consumption. It also shows the effects of double skin facades and shading devices. It also gives the results of some of the studied cases through the Net Present Value, simple payback time, reduced CO_2-emissions and energy savings, but it clearly states that, as the climate, costs of the measures and the energy prices vary from country to country, it is very difficult to draw general conclusions.

It highlights that for any building renovation project, a holistic point of view should be taken and recommends that one of the first activities in any renovation project is to identify the measures that are strictly necessary or mandatory, and then, according to the budget constraints, evaluate the subsequent improvement solutions.

- Retrofit of Building Services Systems (Zinzi and Thomsen, 2015): The guide describes five technologies: condensing boilers, heat pumps, ventilation systems, lighting, and photovoltaic systems. It recommends replacing traditional gas boilers by energy efficient condensing gas boilers in areas where natural gas is available. District heating, however, is presented as a better alternative. In terms of heat pumps, it warns about the high initial investment and high electricity cost of heat pumps. It also states that mechanical ventilation systems are suitable to achieve the desired indoor air quality, because they provide filtered fresh air continuously, discharge exhaust air and contaminants, and help to save energy by recovering heat from exhaust air and by using energy-efficient ventilation equipment. The energy efficiency of ventilation systems depends on the heat recovery rate of heat exchangers and the electrical demand of the fans. The electrical efficiency of the ventilation system should be planned very carefully; otherwise, the primary energy demand for ventilators could be higher than the primary energy savings of heat recovery.

The guide claims that electric lighting is one of the major energy consumers and particularly in school buildings, where it strongly affects visual performance and visual comfort by aiming to maintain adequate, appropriate illumination while controlling reflectance and glare. Therefore, it recommends highly efficient lights such as LEDs with automated controls, such as dimming and presence sensors. Depending on the space, task lighting units might be more efficient than traditional room lights.

Finally, the guide shows examples of the PV applications around the four studied countries with PV seen as self-consumption (in grid-connected or isolated places), highly architectural integrated PV and large-scale PV installations (up to 250 MW) also connected to existing grids. It suggests that PV prices have dropped significantly, making the application more affordable each time, but individual feasibility studies are required to determine the cost benefits.

- Solution Sets for Zero Emission/Energy-Surplus Schools (Erhorn-Kluttig and Erhorn, 2016): The guide shows various successful case studies of zero energy or even plus energy buildings, from both new-build and refurbishment projects. It presents renovation measures that can be combined to achieve the highest level of the energy performance of school buildings, with renewable energy generated directly at the building, which can be solar thermal or solar electrical energy, wind energy from micro wind turbines, heat pumps, etc. Renewable energy can also be obtained from outside the building property, such as biomass, biofuel and biogas, and renewable energy from outside the building property with no connection to the building, beside the national grid.

2.6 Indoor environmental quality in school buildings

The previous chapter have shown the various initiatives that have arisen up to now in response to the new requirements in energy efficiency. While these programmes have tried to be more specific by focusing on schools, there are still aspects that remain outside the guidelines. On one hand, the guides have not yet shown evidence that the pilot projects have been refurbished taking into account the prognoses on the future climate. On the other hand, the main focus remains on the building performance during the winter period and little has been said about the risks of overheating, the specific measures that can be taken to avoid it, and the effects of comfort on the students´ cognitive performance. In addition, none of the programmes seen so far have taken into account the different buildings’ construction types. Several studies, however, have covered these issues individually. This section seeks to cover most of them.

Montazami et al. (2015), for instance, pointed out that climate change may result in an increased risk of overheating and therefore the new building guidelines should reflect the outcomes of the future prognoses. They compared the old overheating guidelines for school buildings in the UK with the guidelines published in 2013. For the study, they analysed data from 140 classrooms in 18 naturally ventilated primary schools in London, UK, which were then compared with records of occupants’ thermal comfort responses to indoor temperature. They suggested that the old guidelines were too lenient, thereby allowing some overheating to occur. The guideline from 2013 was more stringent but needed further development to reflect occupants’ perceptions more accurately.

Chatzidiakou et al. (2014) studied cognitive performance and suggested that there are significant benefits if design targets are set for the low end of the comfort range, i.e. 20–22°C in winter and 22–24°C in summer, since children have a higher metabolic rate per kg body weight, and they are usually more active. Wargocki and Wyon (2013) also showed that the performance in maths and language skills was significantly lower at 27 and 30°C in comparison with performance at 20°C; this negative effect could be as great as 30%. Furthermore, the increased outside air supply improves concentration, logical thinking, and speed of performing a task in children. Liu et al. (2016) found that overall learning performance of school students in Northwestern China is highest when indoor temperature is 1 °C lower than comfort temperature, while Haddad et al. (2019) suggested that indoor temperature in primary schools should be kept a few degrees lower than in office buildings, to improve thermal comfort. Yun et al. (2014) studied the difference in thermal sensation between girls and boys and found that girls were slightly more sensitive to higher temperatures than boys.

De Giuli et al. (2012) studied seven primary schools in the Northeast of Italy and found that students are twice as sensitive to change in temperature in summer than in winter. Huang et al. (2015) studied certified green buildings to determine the effectiveness of the strategies adopted to prevent overheating by quantifying the in-room thermal comfort via long-term in-situ monitoring of temperatures. They concluded that an increase of indoor air velocity with the installation of ceiling fans has a large potential in the reduction of heating perception. The passive measures of the buildings reduced overheating in classrooms by up to 18% and the dissatisfaction by up to 22%. Reducing overheating can increase the average learning performance by 1.3%.

Singh et al. (2019) gathered the outcomes of several studies about thermal comfort in classrooms over the last 50 years and concluded that, despite the number of studies linking Indoor Environmental Quality (IEQ) with cognitive performance, a considerable gap in the basic information and understanding of the optimum learning conditions for specific cases still remains. They set out unanswered questions, for instance:

- What are the thermal comfort preferences of students in primary school, secondary school and university classrooms?
- Do these preferences differ within naturally ventilated and air-conditioned buildings?
- Is there a difference in students’ performance depending on climate and the classroom conditioning type (naturally ventilated, mixed mode or air-conditioned)?
- How can the test procedure be standardized to judge the performance of students (because different students may perform better in different tasks depending upon their interest and motivation)?

Although these questions remain open, some studies have found significant differences between students’ age groups. Nicol and Humphreys (2002) introduced the adaptive approach, under the assumption that “if a change produces discomfort, people react in a way which tends to restore their comfort” . However, with children and in classrooms the approach has some limitations. In secondary schools, where students are in the age group of around 12 to 18 years, they are in a position to express their thermal sensation feeling and most likely act upon it. In primary schools, the conditions of the classrooms depended strongly on teachers’ preferences, which, on one hand, has been shown to be counter-productive for acceptable indoor air quality, and, on the other hand, does not consider the suitable conditions for children´s learning environments. Therefore, a building management system would be advisable to provide good indoor environmental quality (De Giuli et al., 2012).

Teli et al. (2012) specifically looked into the situation in primary schools and found that both the models under steady state conditions, such as the Predicted Mean Vote (PMV), and the adaptive models, underestimate thermal sensation for children. Their study suggests that children prefer a much lower temperatures than other age groups. Yun et al. (2014) arrived at the same conclusion. They studied classrooms in a naturally-ventilated kindergarten in Korea and conducted surveys three times a day for 119 children (aged 4 to 6). They suggested that children were more sensitive to changes in their metabolism than adults, and their preferred temperature was lower than that predicted by the PMV model and the Standard EN 15251. Nam et al. (2015) pointed out that clothing of kindergarten children is also dependent on the thermal sensation of adults. In the case of children, the changes in metabolic rates were larger than those of adults, with values from 0.84 to 4.08 met, because some classes were implemented in sitting positions in indoor environments and other classes involved large amounts of activities, such as gymnastics, sports activities, and recreation.

Teli et al. (2014) are among the few researchers that have reported on the difference between building construction types. They measured the indoor conditions and gathered nearly 3000 responses of thermal comfort questionnaires comparing a medium-weight versus a light-weight school building. They found that the buildings had an average difference in air temperature of 2.7 °C during occupied hours in the period of investigation (June and July 2012), with the medium-weight building being cooler than the light-weight building. However, the questionnaires seemed to suggest that the different construction type and the cooler overall thermal environment in the medium-weight school building had little impact on the pupils' overall thermal sensitivity. They also suggest that children were more sensitive to higher temperatures than adults and consequently that current thermal comfort standards were not appropriate for the assessment of their thermal environment. They claim that current thermal comfort criteria lead to an underestimation of pupils' thermal sensation during summer.

Other studies have looked into the other variables of Indoor Environmental Quality. For instance, Chatzidiakou, et al. (2014) also showed the statistics of northern hemisphere countries, where asthma-related hospital admissions among children peak in September and coincide closely with their return to the school environment. This is a clear effect of the Sick Building Syndrome, which is more common in educational buildings rather than offices, because children are more prone to catch an illness, and their occupancy densities are even three or four times higher. The high densities naturally represent a challenge in terms of indoor air quality. As it was mentioned, the indoor conditions are highly dependent on the teachers’ preferences, but beyond the thermal discomfort, CO_2 levels represent a major problem, since it is very difficult to perceive that their levels are rising above the adequate levels. Although intermediate levels of CO_2 do not directly represent a hazard to human health, their almost immediate effect is that the occupants begin to feel tired. Various studies have found that these levels could be very high: even more than 4000ppm. Al-Rashidi et al. (2012) compared the CO_2 concentration levels of air-conditioned and naturally-ventilated classrooms occupied by children from six to ten years old. They found that air-conditioned classrooms have on average around 700 ppm while the CO_2 levels of naturally ventilated rooms were around 1600 ppm, with maximum levels of around 2000 ppm during classes. They suggested that the natural ventilation strategy of such schools should be evaluated to improve the learning environments. Theodosiou et al. (2008), in Greece, found CO_2 concentrations of around 3000ppm in representative nursery classrooms, when occupied. They also showed that the overall performance of their investigated buildings was affected by problematic building envelopes, improper control of heating and lighting systems, and the absence of proper legislative measures.

Lee et al. (2012) studied classrooms and lecture halls in China and, through measured data and surveys, investigated the relationships between several IEQ factors and self-reported learning performance (in calculating, reading, understanding and typing). They suggested that thermal comfort, indoor air quality, and visual environment are the most relevant factors for the occupants and that there is a good correlation between learning performance and the number of complaints due to unsatisfactory IEQ.

Yang et al. (2013) pointed out that specific classroom attributes and their impacts on student satisfaction and performance have been investigated independently, but not through holistic approaches, with their individual and cumulative impacts on student perceptions of their learning environments. They suggest that student perceptions rely heavily on spatial attributes, specifically visibility and furniture, and ambient attributes, specifically air quality and temperature, which are highly impacted by the design, management, and maintenance of classrooms.

2.7 Background lessons

This chapter has given an overview of the challenges that school buildings have to face to deliver integrated sustainable environments. As some authors have also highlighted, several key questions that allow the most appropriate conditions for specific applications to be identified, remain unanswered. It was shown that several individual studies have tackled specific aspects, but few of them have sought more holistic approaches. The guidelines, as part of large European or worldwide projects, have gathered some of these studies and successful pilot projects in order to give recommendations based on the main results and lessons learned. However, this has been shown to be a very difficult task, and it has been found that it is more common to find that each programme has reported on their own projects, rather than taking in the outcomes of similar programs or studies. This has resulted in gaps in the guidelines; hence, professionals engaged in the design of new or retrofit of existing school buildings currently struggle in finding the paths to follow.

Germany, and specifically the city of Karlsruhe, has guidelines to make buildings more efficient. The Karlsruhe Sustainable Energy Action Plan has proven to be a constructive initiative that has moved several sectors of the city towards sustainability. Regarding schools, great progress has been made in comparison with other European cities; Karlsruhe among a few, has a baseline of energy consumption and continues to monitor its buildings. The *EinSparProjekt* Program has shown positive results and has managed to engage several stakeholders in the development of more sustainable educational environments. However, the Guidelines on Energy Efficiency and Sustainable Buildings (LENB) are general and lack specific guidelines for refurbishing buildings and considering the future effects of climate change, especially during the summer, and the different building construction types of the city. This study thus seeks to provide recommendations that cover such gaps.

3 Climate characterization

3.1 Climate in Karlsruhe

Karlsruhe is the second largest city of the state of Baden-Württemberg, with a population of 305 616 habitants by December 2018 (City of Karlsruhe, 2019b). The city is located at an altitude between 100 (on the eastern shore of the Rhine River) and 322 m.a.s.l. (in the suburb of Wettersbach). Its geographical coordinates are 49°00′N and 8°24′E; the 49th parallel runs through the city centre. According to the Köppen Climate Classification, the city is under a "Cfb" zone, which corresponds to a Marine West Coast Climate (Climatemps, 2017). A mild climate prevails in Karlsruhe most part of the year because of the low height above sea level and its sheltered position between hills. The distribution of temperatures and number of sun hours by month in the city are shown in Figure 5, where it can be also observed that during a significant part of the year, Karlsruhe has temperatures between cold and comfortable. Through the influence of wedges of the Azores High, there are often hot summers with average temperatures around 20°C and high humidity in the lowlands. The winters are relatively mild, snowless and rainy with average temperatures around 3°C. Due to the basin location, there are temperature inversions where the warm air layers slide over colder air layers in the valley, hindering the exchange of air, and therefore promoting as well the concentration of pollutants in the air (Stadtwiki Karlsruhe, 2016). It is one of the sunniest and warmest cities in Germany, with a maximum temperature of 40.2°C recorded in the summer of 2003. That year also holds the record for the strongest heat wave in Europe, where the city experienced 53 hot days (days with temperatures over 30°C, of which 12 days recorded temperatures over 35°C) (City of Karlsruhe, 2014).

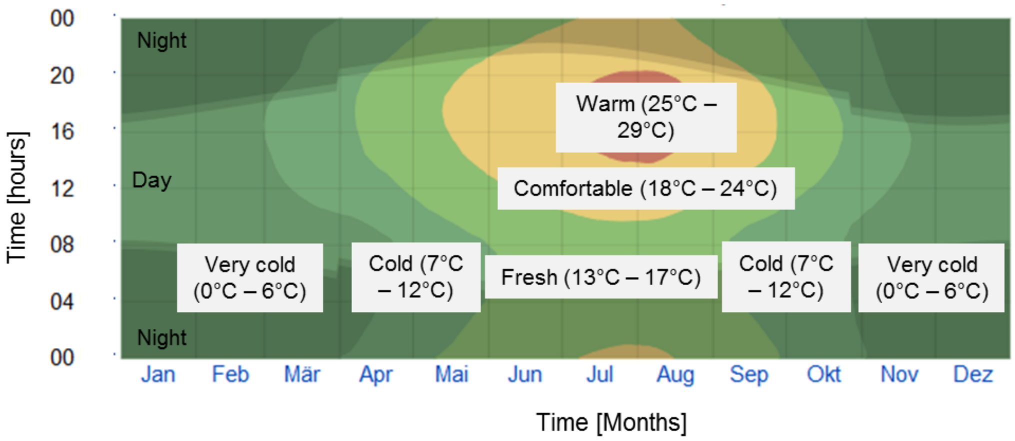

Figure 5: Graphical representation of temperatures, sun hours and thermal sensations throughout the year in Karlsruhe.

Source: Weather Spark (2019)

The average temperature for the year in Karlsruhe is 10°C. The warm season lasts three months from June to September, with an average daily high above 22°C. The hottest day usually lies in August, when the average high temperature is 26°C and the average low is 15°C. The cold season lasts almost four months, from November to March, with the average daily high below 9°C (Weather Spark, 2019). The average temperatures throughout the year in Karlsruhe are illustrated in Figure 6.

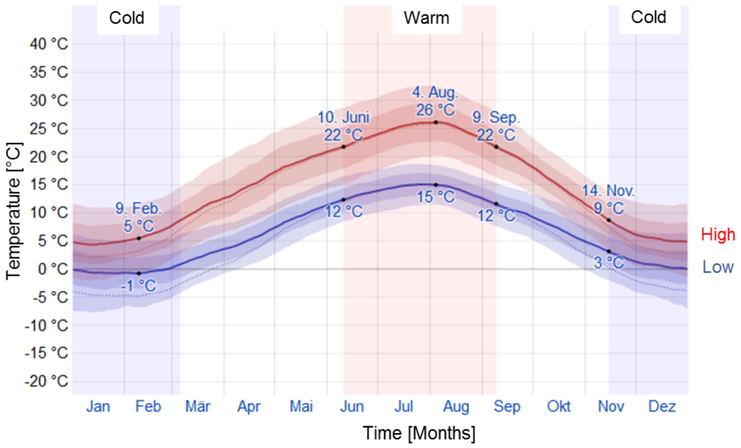

Figure 6: Average high and low temperatures in Karlsruhe.

The daily average maximum (red line) and minimum (blue line) with percentile bands of 25 to 75% and 10 to 90%. The narrow, dashed lines represent the corresponding perceived average temperatures.
Source: Weather Spark (2019)

Karlsruhe is considered a dry city, as illustrated in Figure 7. Unlike the temperature, which usually varies widely between day and night, the dew point usually changes more slowly. Therefore, while the temperature may fall at night, a dry day is usually followed by a dry night, and vice versa (Weather Spark, 2019).

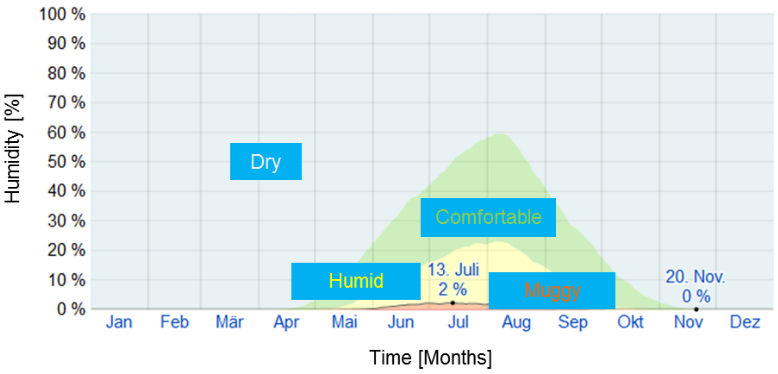

Figure 7: Humidity and comfort levels in the city of Karlsruhe.
Source: Weather Spark (2019)

In terms of precipitation, the yearly average is 757 mm. The month with the highest precipitation on average is August, with 79 mm, and the month with the least precipitation on average is February with 43 mm. The average number of rainy days is 80, with the highest occurrence in December with an average of 8 days and the lowest occurrence in February with an average of 5 days (Weatherbase, 2016).

The average hourly wind speed in Karlsruhe shows little seasonal variation during the year. The windier part of the year lasts approximately five months from November to April, with average wind speeds exceeding 14 km/h. The quieter time of the year lasts seven months and the average hourly wind speed drops to approximately 11 km/h. The prevailing wind direction comes from the west. (Weather Spark, 2019). The wind speeds and directions are displayed in Figure 8 and Figure 9.

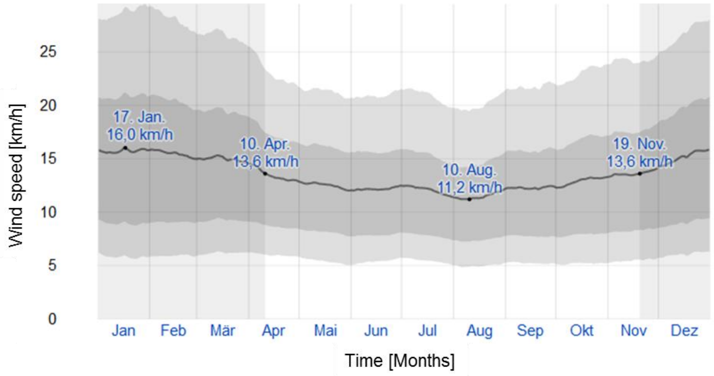

Figure 8: Wind speed in Karlsruhe throughout the year.
Source: Weather Spark (2019)

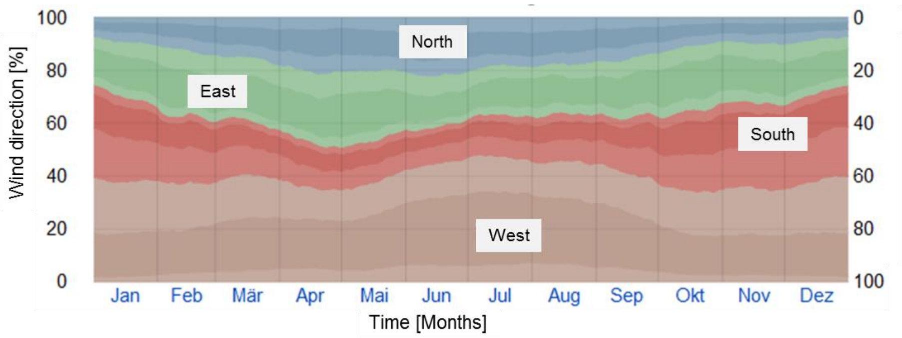

Figure 9: Wind direction in Karlsruhe throughout the year.
Source: Weather Spark (2019)

3.2 Climate change in Germany

According to *Germanwatch*, the average annual temperature in Germany in the 19th Century was about 8.2°C and the total rainfall was around 750 mm per year. Due to its stability, and also because of these relatively low temperature and precipitation conditions, the climate in Germany formed a solid basis for the basic supply of the population, human activities in general, and thus for a secure life. However, climate scientists predict changes in the Earth's climate for the coming century, which, as already suggested by climate change signals, will also affect Germany (Schwarz et al., 2007). The rising temperatures, more humid winters and the increase of more frequent extreme weather events, are already affecting the society in Germany. Their impacts are becoming noticeable in many sectors, including energy supply, agriculture, and healthcare. Depending on the future scenario of different increase rates of greenhouse gas emissions, temperatures in Germany, especially in the south and south-east regions, could rise until the end of the century by more than 4°C, in comparison with the past 50 years. This rise in temperature will come together with less snow and more precipitation in winter, but less rainfall in the summer, conditions that could endanger many economic and social sectors in the country (Umwelt Bundesamt, 2015),

To analyse the scenarios of future climate change and the corresponding strategies for adaptation, the German Federal Environment Agency has divided the country into six climate zones, classified as warm, dry, cool, low-mountain, foreland-mountain, and mountain, as illustrated in Figure 10.

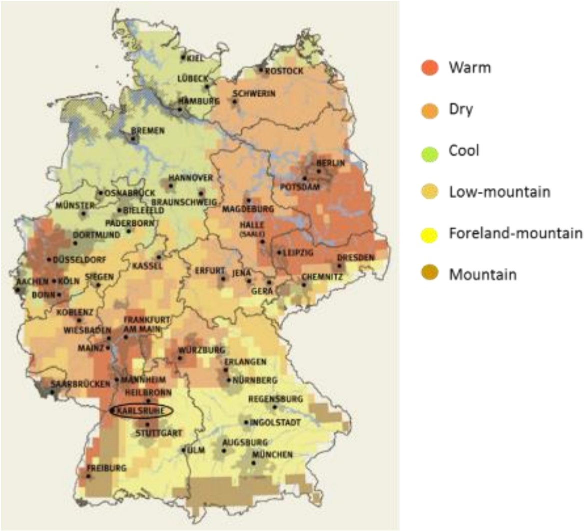

Figure 10: Cartographic representation of climate zones for Germany.
Source:Umwelt Bundesamt (2015).

There are four relevant regional climate models for Germany:

- The dynamic REMO (REgional MOdel) regional model from the Max Planck Institute for Meteorology.
- A further dynamic regional climate model, COSMO-CLM (formerly CLM = Climate Local Model). This model was developed amongst 25 different institutions, including the Karlsruhe Institute of Technology (KIT).
- The WETTREG, developed by the private sector.
- The statistical regional model STAR of the Potsdam Institute for Climate Impact Research (PIK).

In 2006, a complete analysis of the climate change scenarios for Germany was published for the first time, by the Max Planck Institute of Meteorology (MPI-M). Based on these scenarios, the researchers developed the regional models (REMO) using the calculated temperatures and precipitation conditions in the country until the year 2100. These are high-resolution models: 10x10 km, therefore they allow an exceptionally detailed overview of the various regions of Germany. The researchers concluded that average annual temperatures in Germany could rise by 2.5°C to 3.5°C by 2100, compared to the period from 1961 to 1990 (Schwarz et al., 2007).

The REMO models are based on the IPCC (Intergovernmental Panel on Climate Change) scenarios A2, A1B and B1, which cover the period from 2001 to 2100, and take into account different assumptions about demographic, social, economic and technical structures of the country. The IPCC have worked with 40 different scenarios, which are divided into four main families:

- A1: characterized by rapid economic growth, a global population that reaches 9 billion in 2050 and then gradually declines, the quick spread of new and efficient technologies, and a convergent world - income and way of life converge between regions. Extensive social and cultural interactions worldwide. The A1B subfamily assumes a balanced emphasis on all energy sources.
- A2: characterized by an independently operating world, with self-reliant nations, continuously increasing population, regionally oriented economic development, and therefore low emissions.
- B1: assumes a more integrated world, and more ecologically friendly, with rapid economic growth as in A1, but with rapid changes towards a service and information economy. Population rising to 9 billion in 2050 and then declining. It assumes reductions in material intensity, the introduction of clean and resource efficient technologies, and a emphasis on nations towards global solutions for economic, social and environmental stability.
- B2: assumes a more divided world, but more ecologically friendly. The population continuously grows but at a slower rate than in A2. Intermediate levels of economic development are achieved.

In the optimistic scenario, B1, the country has sustainable economic growth, adopting clean energy sources, and reducing material and product intensity. Under this scenario, according to the REMO models, a relatively low temperature increase of 2.5°C would occur. The scenarios A1B and A2 produce higher temperature increases, because they consider less sustainable development, with mixed energy sources and high economic growth. Figure 11 illustrates the temperature increase for Germany under the A1B scenario for the years 2071-2100 compared to the reference period 1961-1990. The temperatures in winter could increase by about 3.5°C and summer temperatures by about 4°C for the, where these highest temperatures would be experienced in the south-west of Germany (Schwarz et al., 2007).

The global IPCC A1B scenario describes a world of rapid economic growth, with a mix of energy sources between fossil fuels and renewables, the rapid introduction of new technologies, which might be material intensive, and a global population that reaches its maximum in the mid-century. Therefore, it is considered a more realistic scenario than B1 and it is more often used for modelling purposes and the development of sustainable policies. Regarding the CO_2 concentrations, A1B represents a medium climate change scenario with a CO_2 level increase from 367 ppm (year 2000) to 703 ppm by the year 2100 (IPCC, 2014).

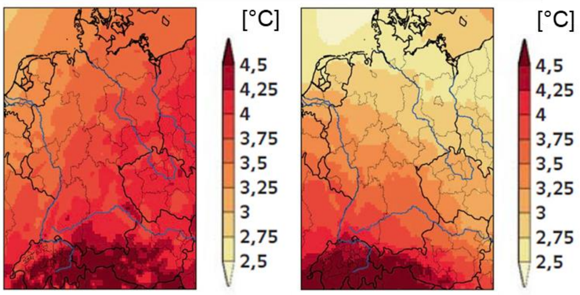

Figure 11: Annual mean temperature increase in ° C under the prognoses of the A1B scenario. Winter (left) and summer (right).

Source: MPI-M 2006 (Schwarz et al., 2007).

In terms of extreme weather events, there is partial evidence for extreme rainfalls and storms. However, some studies suggest that there is a 50% probability of heat waves occurring more frequently, such as the one experienced in 2003. The heat wave of 2003 was the largest natural disaster in European history; it killed nearly 30,000 people in Europe; 7,000 of them in Germany. The probability of occurrence the of hot days (T > 30°C) in the months of July and August has risen over the last one hundred years, and especially markedly during the last twenty years, at almost all the weather stations in Germany (Schwarz et al., 2007; Zebisch et al., 2016).

3.2.1 Climate change in Karlsruhe and the region

The analysis of vulnerability suggests that without adaptation strategies (business-as-usual scenario), the regions at highest risks are located in the southwest (upper Rhine rift) and the central parts of eastern Germany. In southwest Germany especially, the high temperatures will cause problems. This region, where the highest temperatures are measured at present, is expected to show the strongest warming in the country in the near future (2021 to 2050) and far future (2071-2100). The risks require special attention in terms of the health sector and the economic sectors of agriculture and forestry. The risk of flooding in the early spring will increase, owing to a shift of precipitation from summer to winter, as well as an increase in extreme rainfall events (Zebisch et al., 2016).

A recent ensemble evaluation by the German Weather Service (DWD) concluded that the mean annual temperature in southern Germany could rise by up to 2.5°C in the near future, and by 4°C by the end of the century (compared to the reference period 1961 to 1990): these results confirm the prognoses of the IPCC. In Karlsruhe, the number of warm days (T>20°C) has almost doubled in the weather trend since 1878, and the number of ice days has halved in the same period (City of Karlsruhe, 2013). In these prognoses, the city of Karlsruhe was classified in the warm climate group, where the future weather scenarios predict a strong increase in the number of hot days, i.e. the maximum daily temperatures are above 30°C, and warm nights, i.e. the minimum night temperatures are above 20°C. It is also expected that the heat island effect will be exacerbated in the metropolitan regions by the strong development and expansion of impermeable zones, as well as the temperature rise (Umwelt Bundesamt, 2015).

3.3 Weather files for simulations

The German Weather Service (DWD) has had an official weather station in Karlsruhe since 1876, located in the Hertzstraße in the northwest of the city. The station has provided daily readings measured under the international standard rules for over 130 years, being one of the stations with the longest series of measurements in Germany. However, in 2008, this weather station, like many others in the country was closed, and a new station was opened in Rheinstetten, where open fields prevail, and, therefore, the conditions are entirely different from those in the city centre, as it has been also measured by the city council.

Figure 12 illustrates the heat island effect that the city of Karlsruhe experiences. In this graphical representation, it can be seen that, even at very early hours in the morning (04:00), the temperature difference between the city centre and the suburbs is quite high. Due to a comparatively high area of impermeable surfaces and low area of vegetation, the city heats up to a temperature 10°C higher than its surroundings, which can lead to an enormous health burden for the urban population (City of Karlsruhe, 2016).

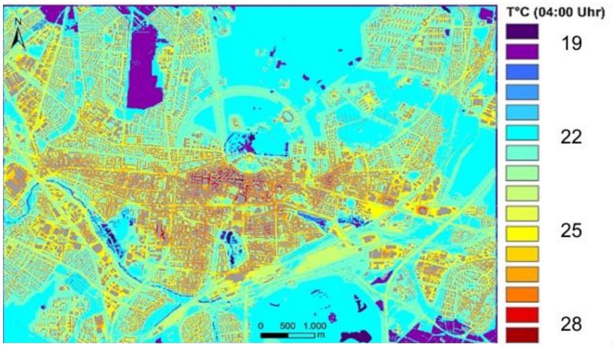

Figure 12: Temperature field in Karlsruhe at 04:00, 2m during a high-summer typical weather situation. Source: City of Karlsruhe (2016)

In January 2009, the Karlsruhe Institute of Technology (KIT) set up its own stations, at the site of the old DWD station, as well as the station in Rheinstetten, on the premises of the university and outside in the Hardt forest at 200m, to compile data in different parts of the city.

For simulation purposes, the German Weather Service has a total of 15 sets of weather files for the country, which represent the current conditions (year 2010) and the near future scenario (year 2035). For these two scenarios, there are three available conditions: Test Reference Year (TRY), Design Summer Year (DSY) and Design Winter Year (DWY). These weather files are specially compiled datasets containing different meteorological data for each hour of the year. They are intended to represent medium, but typical for the year weather conditions, and they are usually based on the recorded data of a minimum 10 years (German Weather Service, 2017). For the city of Karlsruhe, the available weather data comes from the reference city of Mannheim, which is located 54 km away from Karlsruhe.

As mentioned in the previous section, in general, the warmest months in Karlsruhe (June, July, and August) have average or high temperatures around 26°C. However, the number of hot days has increased in the last few years, which has resulted in weeks where the daily temperatures rise to 35°C and the temperature does not fall below 20°C at night.

As a further example, Figure 13 shows the outdoor temperatures recorded from June 20th, 2017 to June 23rd, 2017. The blue line corresponds to the weather station used by the German Weather Service, located in Rheinstetten. The green line shows the temperature recorded in the city centre. From this graph, two points can be highlighted: the first is that a hot day in the city centre is usually followed by a warm night. The second point of note is that, as expected, the temperature in the suburbs falls at a faster rate and reaches lower values, where the difference could be as much as 4°C or even 5°C. Although this is a comparison of just one week, and the reference weather files result from a statistical analysis spanning over ten years, these data also confirm the studies observing the heat island effect, and suggest a closer look at the temperature behaviour during the last couple of years.

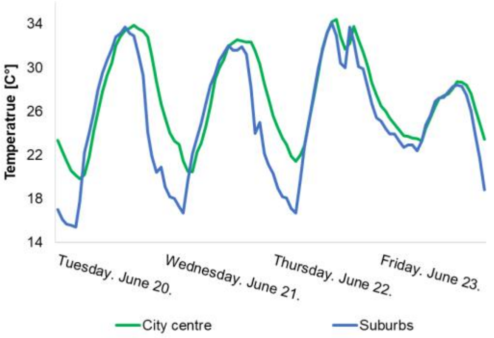

Figure 13: Comparison of outdoor temperatures in Karlsruhe: city centre vs. suburbs.

These data are also compared with the available weather files. For that, similar temperature profiles were sought, as illustrated in Figure 14. From these data, what is important to notice is that the temperature profiles of the TRY2010 and the DSY2035 are more similar to the temperatures measured in the suburbs, rather than those from the city centre. In fact, the hot days in these weather files are usually followed by nights with temperatures lower than the 20°C.

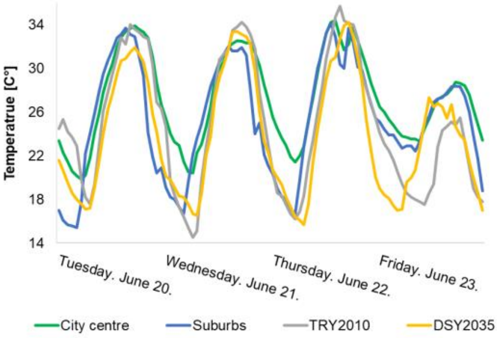

Figure 14: Comparison of outdoor temperatures recorded vs. weather files.

For a comparison exercise, the number of hot days and warm nights were quantified. The following results were found: 14 and 3 for the TRY2010; 21 and 6 for the DSY2010, and 40 and 7 for the DSY2035 respectively. However, the recorded data showed that in the summer of 2017 there were in total 11 hot days and 12 warm nights (City of Karlsruhe, 2017), and in the summer of 2018 there were 26 hot days and 14 warm nights (City of Karlsruhe, 2018). This means that, although the future weather conditions predict double the number of current hot days, there is not a corresponding increase in the number of warm nights. These results could imply that neither the figures for DSY2010 nor those for DSY2035, for the reference city of Manheim, are considering the heat waves that the city of Karlsruhe has been experiencing.

In addition, a weather file with similar conditions to those in Karlsruhe, of hot days and warm nights, was sought. As a result, the French Mediterranean city of Marseille was found. From Figure 15 and Figure 16 it can be seen that the daily and nightly temperatures, as well as the solar radiation of this city, are very similar to the hot days and warm nights of the city centre of Karlsruhe. From this exercise, it can be concluded that Karlsruhe is experiencing hot weeks that are more similar to the Mediterranean conditions, and although, this behaviour is not spread throughout the complete summer period, it is should be emphasised that this condition is present for several days and is not considered by the reference weather files.

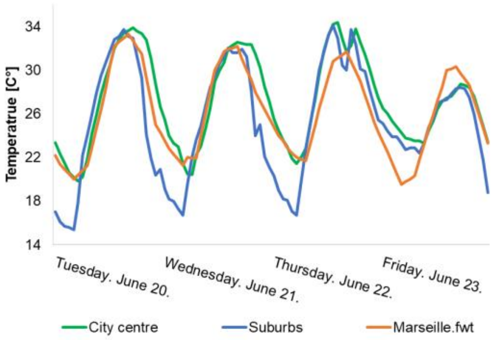

Figure 15: Comparison of outdoor temperature: Karlsruhe vs. Marseille.

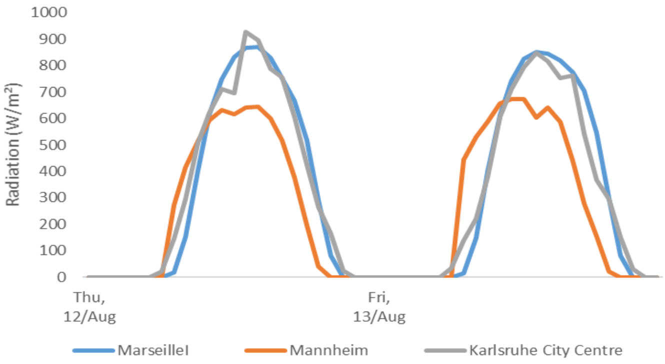

Figure 16: Comparison of radiation: Karlsruhe vs. Marseille.

To complete the analysis of the available data files, the frequency of temperatures per month was quantified.as shown in Figure 17 to Figure 21 to and summarized in Table 1. From these figures, the following aspects can be highlighted:

- The temperature frequency distribution of the city of Marseille is quite similar to the records of Karlsruhe in the city centre only during the month of June. During the other summer months, the temperatures in Marseille are significantly higher, as expected in a Mediterranean city. Therefore, it is desired to clarify that only conditions similar as heat waves in Karlsruhe are comparable to the normal conditions of a Mediterranean city. This city is therefore only taken as reference for critical conditions, but in general, the climate in Karlsruhe, even in the near future, is milder than a Mediterranean city.

- The average warmest month in the city was August according to the TRY2010. In the city records of 2017, and in the weather files of DSY2010 and DSY2035 the warmest month is July.
- Considering that, schools have summer break for over a month, usually from the end of July until the beginning of September, it was decided to select only one month for the simulations, considering the critical but not exceptional conditions. Therefore, it was decided to simulate the base-case-scenario with the month of July of the DSY2010 and the near future scenario with the same month of the DSY2035.

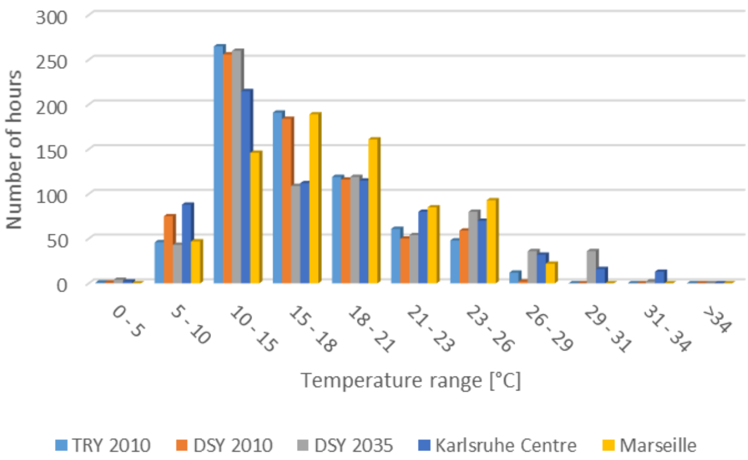

Figure 17: Frequency distribution of outdoor temperatures. Comparison of weather files and records in the city of Karlsruhe. Reference month: May.

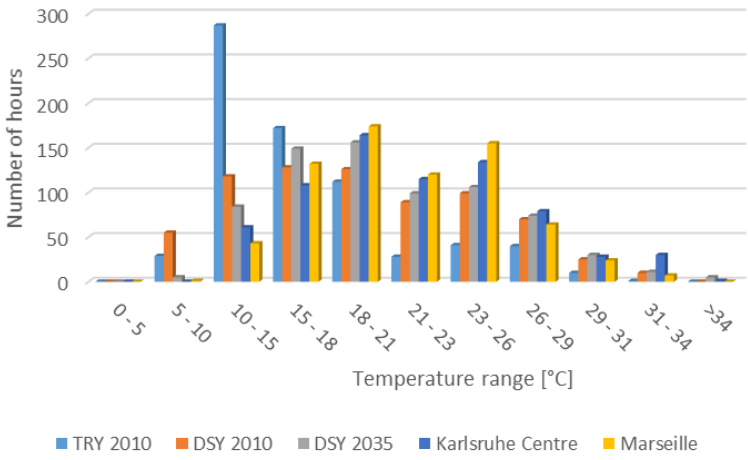

Figure 18: Frequency distribution of outdoor temperatures. Comparison of weather files and records in the city of Karlsruhe. Reference month: June.

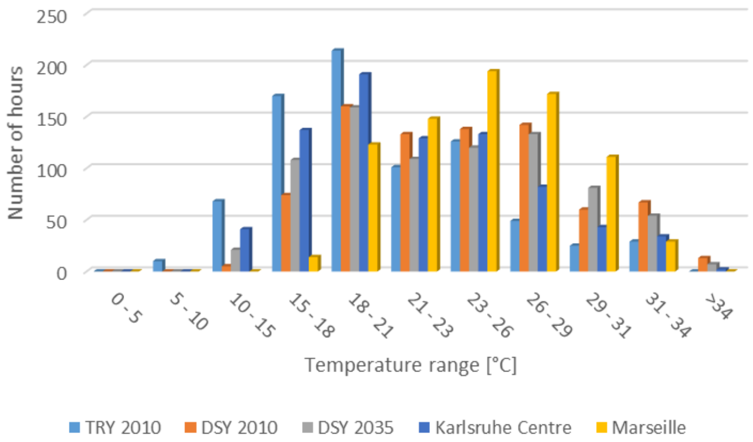

Figure 19: Frequency distribution of outdoor temperatures. Comparison of weather files and records in the city of Karlsruhe. Reference month: July.

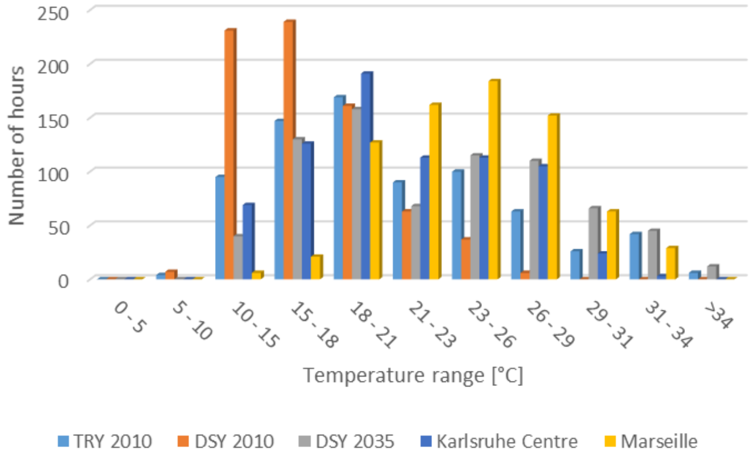

Figure 20: Frequency distribution of outdoor temperatures. Comparison of weather files and records in the city of Karlsruhe. Reference month: August.

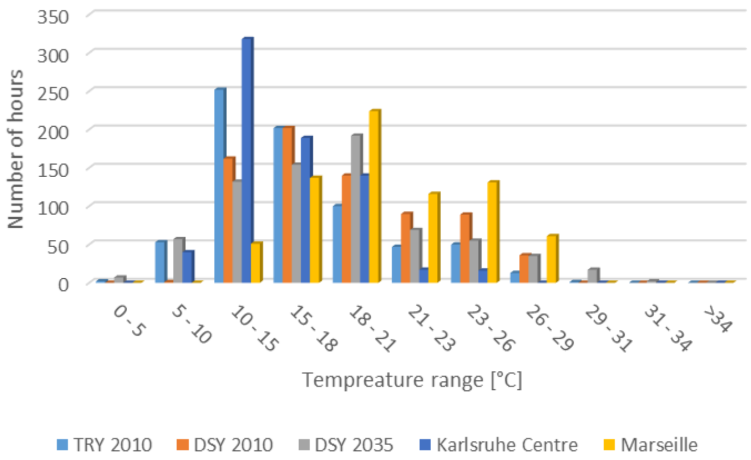

Figure 21: Frequency distribution of outdoor temperatures. Comparison of weather files and records in the city of Karlsruhe. Reference month: September.

Table 1: Frequency distribution of outdoor dry bulb temperatures. Comparison of weather files and records in the city of Karlsruhe. Period: May to September.

Range [°C]	Number of hours			
	TRY2010	DSY2010	DSY2035	Karlsruhe records 2017
0 - 5	3	1	11	2
5 - 10	142	138	105	128
10 - 15	967	769	536	704
15 - 18	879	809	646	672
18 - 21	704	686	776	785
21 - 23	324	416	393	445
23 - 26	358	421	466	460
26 - 29	173	256	377	283
29 - 31	56	85	223	109
31 - 34	57	77	113	80
>34	6	13	24	3

4 Building stock analysis

4.1 Public and school buildings in Karlsruhe

Karlsruhe is the second largest city of the state of Baden Württemberg, with 305 616 habitants by December 2018 and a density of 1 760/km^2 (City of Karlsruhe, 2019b). It has an area of 17 342 hectares, of which 40% are devoted to constructions (buildings and traffic areas), 21% to agricultural activities and 26% comprise forest (City of Karlsruhe, 2018).

Karlsruhe was founded in 1715 as a planned city with a baroque style. Although it was highly affected by the World Wars, many of the buildings before 1918 still stand. The stock of buildings in Karlsruhe is over 155 000, including residential and non-residential units (City of Karlsruhe, 2015). The Office for Building Construction and Management (*HGW: Amt für Hochbau und Gebäude Wirtschaft*) looks after approximately 950 public urban units, grouped into approximately 260 objects[3]. The types of buildings include schools, kindergartens, sports facilities, multi-purpose halls, and administrative buildings.

This study began with the examination of the available databases for these buildings, starting with the distribution into the different types and their energy consumption and associated costs. The city has kept records of this information since 2013 and produces a report every two years. Table 2 summarizes the quantity and classification of the public buildings in the city, where it can be seen that most of them are educational. The traditional schools, classified as primary, secondary, middle, high and technical schools, represent 25% of such buildings, in terms of numbers and 45% in terms of area. The energy consumption of these buildings represents around 13% of the total. However, looking at the associated costs, they represent 42% and 31% of the total heating and electricity costs respectively. This information suggests that energy efficiency plans focused on school buildings could have a significant impact on the performance of this sector in the city. Furthermore, if such plans represent energy reduction, there is an important potential in cost savings. The potential benefit revealed by this analysis is one of the reasons why this project was focused on school buildings.

The German education system has various pre-university schools. This research will look only into school buildings with more than six classrooms, classified into primary, middle and high schools. Table 3 shows the number of these school buildings classified by their construction periods, and Figure 22 highlights that most of the current schools in Karlsruhe date from 1850 to 1918 and the decade of the 1960s. Therefore, finding refurbishment solutions for these two groups will cover a significant part of the school building stock of the city.

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[3] Units are single buildings and objects can combine buildings that are part of the same property.

Table 2: Energy consumption and costs of public buildings in Karlsruhe. School buildings represent approximately 25% of the public buildings and their energy consumption is around 13% of the total. However, in terms of heating costs, they represent 42%.

Group	Type	Objects	Area	Energy use - Heating (2013)		Energy use - Electricity (2013)	
		[#]	[m^2]	Consumption [kWh/m^2]	Costs [Thousand €]	Consumption [kWh/m^2]	Costs [Thousand €]
A	Administrative buildings	26	73902	140	743	40	613
B	Primary, secondary and secondary technical schools	49	160831	160	1646	20	459
C	Middle schools	4	42668	140	363	20	236
D	High schools	12	101618	130	820	20	427
E	Special schools	8	18229	130	154	20	60
F	Vocational schools	13	115830	120	904	30	717
G	Music schools	2	1864	180	21	20	8
H	School sport halls	20	19570	210	285	30	110
I	Sports and entertainment halls	14	42373	170	460	40	332
J	Kindergartens and day nurseries	44	16256	160	176	30	85
K	Youth homes and counselling centres	20	19602	150	241	30	114
L	Homeless shelters	2	3343	290	53	40	30
M	Funeral services	7	2240	220	33	70	28
N	Senior care and residential homes	2	10384	180	127	40	97
O	Yards and parking lots	14	25607	230	399	30	188
P	Fire brigades and civil protection	17	12316	230	204	40	86
Q	Other buildings	5	5949	370	145	20	5
	Total	259	672582	3200	6774	540	3595
B,C,D		65	305117	430	2829	70	1122
B,C,D	Participation in total	25%	45%	13%	42%	12%	31%

Table 3: Number of school buildings in Karlsruhe. Classification by school type and construction period.

	To 1850	1850 - 1918	1918 -1948	1949 - 1957	1958 - 1968	1969 - 1978	1979 - 1983	1984 - 1994	1995 - 2001	2002 -	Total
Primary and secondary schools	1	17	2	7	24	7	0	1	0	1	60
Middle schools	0	2	0	0	0	1	0	1	0	0	4
High schools	0	8	0	3	2	3	0	0	0	1	17
Total	1	27	2	10	26	11	0	2	0	2	81

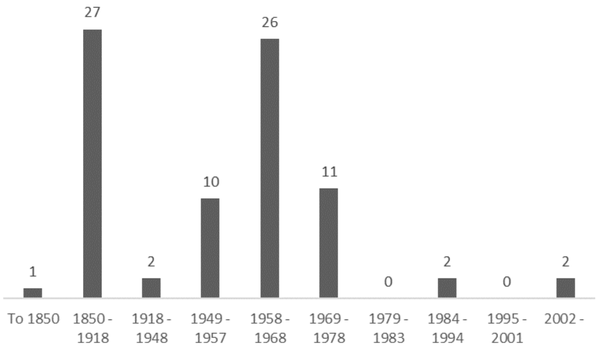

Figure 22: Number of total schools per construction period. Most of the current schools in Karlsruhe date from 1850 to 1918 and the decade of the 1960s.

To select an adequate sample of buildings to study, the database was analysed by gathering the following information of the school buildings in a single matrix:

- Generalities:
  - School classification: primary, secondary, middle and high schools.
  - Location: address, part of the city.
  - Year of construction.
  - Main façade materials: concrete, brick, stone, glass, etc.
- Geometrical properties:
  - Orientation.
  - Areas: gross floor area, net space area, main and secondary usable areas, functional area, construction, traffic area, etc.
  - Volume and surface areas.
  - Volume and surface areas.
  - Number of floors.

    - Form: “L”, “I”, “H”, square, etc.
    - Classrooms heights.
    - Window-to-wall ratio (estimated)[4].
    - Surface area to volume ratio (estimated).
- Energy: heating and electricity consumption (2013 – 2015).
- Heating and electricity savings (2015 vs. 2013).
- CO_2 emissions related to energy and electricity consumption.
- Equipment:
    - HVAC.
    - Window types: insulation glazing, single glazing, double glazing.
    - Window frame materials.
    - Windows’ dimensions and width to height ratio (to classify them as vertical or horizontal).
    - Classrooms’ main floor finishing
    - Classrooms’ main door materials.

The purpose of gathering this information was to identify trends or similarities amongst the buildings and to identify if there was a relation between the energy consumption and the building characteristics, such as year of construction, orientation, window-to-wall ratio (WWR), or surface-area-to-volume ratio (SAV).

4.2 Relations between energy consumption and building properties

4.2.1 Construction period

At the European level, the Energy Performance of Buildings Directive (EPBD) is the main legislative instrument that promotes energy efficiency in the building sector. It was inspired by the Kyoto Protocol and therefore committed all the EU countries to set binding emission reduction targets. The first version, which came into force in 2003, introduced Energy Performance Certificates (EPCs), establishing a common methodology for the calculations of energy performance. It also set minimum energy performance for new buildings and refurbished large existing buildings (>1000 m²), and required the inspection of boilers and air conditioning systems.

For its part, Germany has even older regulations. In 1977, after the first oil crisis, the country implemented the Thermal Insulation Ordinance (*Wärmeschutzverordnung*) to reduce the heating demand in new buildings. The EPBD was incorporated into this legislation in 2002 and the name changed to EnEv, In the EnEv version of 2009, the energy efficiency requirements for new buildings were tightened by another 30%. Figure 23 illustrates the effect of these regulations in both residential and non-residential buildings in Germany. In general, the newer the buildings, the lower the required level of consumption for heating. However, in terms of electricity, the trend is

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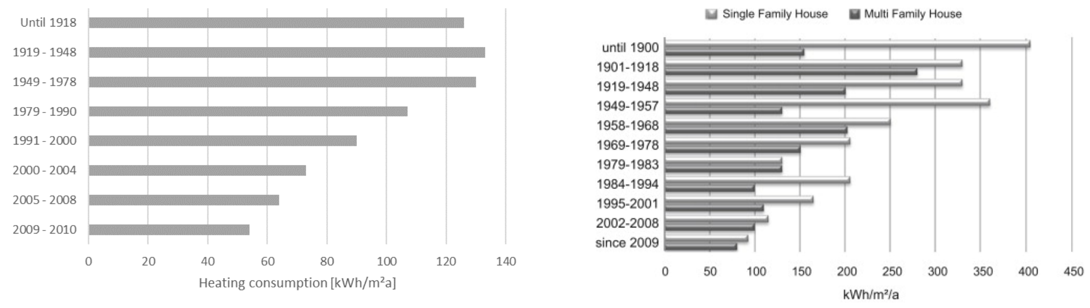
[4] The dimensions of windows and surface areas were not available in the database. The estimations were made with views on Google Maps or by extrapolating measures from available photographs and plans.

not so clear. In this case, the consumption of older buildings is similar to the consumption of the new ones, as illustrated in Figure 24.



(a)
Source: German Environment Federal Office (Kemmer et al., 2017)

(b)
Source: Fraunhofer Institute (Bauermann et al., 2011)

Figure 23: Buildings' heating consumption in Germany per construction period: (a) Non-residential buildings. (b) Residential buildings.

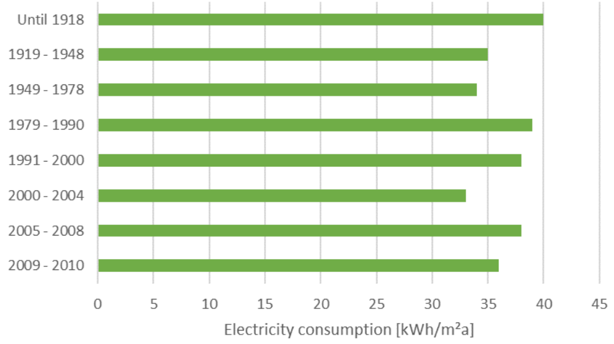


Figure 24: Buildings' electricity consumption in Germany. Source: Federal Statistical Office (2015)

4.2.2 Geometry

The surface-area-to-volume Ratio (SAV) defines the compactness of a building. The more compact a building is, the lower its heating demand should be, because the heat losses are reduced. The SAV depends on both the size of the structure and on its shape. Geometrically speaking, the element with the lowest SAV is a sphere, but in terms of buildings, the closer they resemble an equilateral cube, the lower the SAV would be. Buildings with more edges or exotic forms tend to present more heat losses. In Germany, typical detached and semi-detached houses have values from 0.6 to 1.0, terraced houses from 0.4 to 0.6, and apartment buildings from 0.3 to 0.5 (Baunetz, 2016).

The window-to-wall-ratio (WWR) has a trade-off effect. Large vertical windows allow more daylight, which improves visual comfort and can reduce the energy consumption of artificial lighting. During the winter, they allow more solar gains but, at the same time, more heat losses, while during the summer, their potential of higher ventilation rates will be appreciated but they lead to undesirable solar gains. Therefore, windows are a crucial element that requires an adequate design.

An adequate WWR would thus depend on various parameters, such as the building use, the location, and the window materials, amongst others. However, some rules of thumb, in general, tend to reduce the energy consumption, limiting the ratio to 25% (Baker and Steemers, 2000). In terms of user satisfaction, Boyce suggested that for an acceptance of 85%, a ratio of 32% would be recommended, while a ratio of 25% would result in 50% acceptance (Boyce, 1981).

Other authors have quantified the effect of WWR on energy consumption under different conditions. For instance, Fenga et al. (2017) showed that in almost zero energy buildings in severely cold regions of China, and depending on the orientation, an increase in 5% in the WWR would represent an increase of 3% in the heating demand. Marino et al. (2017) analysed the overall effect of the WWR in relation to heating and lighting consumption in buildings in various Italian cities. Their simulations suggest that, even though the lighting consumption exponentially decreases as the WWR increases, in the overall effect, the energy consumption increases by approximately 5% for every 10% increase in the WWR, in the WWR ranges from 25% to 55%.

4.2.3 Characterisation of school buildings

The city database gathers general information about the buildings that the city authorities manage (HGW, 2016). Unfortunately, it does not include specific information, such as the construction details of the buildings. Therefore, the first task was to obtain an overview of the buildings with the available information.

One of the first features that stands out is that most of the classrooms are oriented towards the south or the southeast, which is considered the most appropriate location to increase solar gains in the winter and reduce the heating load, which is usually the highest. This, however, could be a disadvantage during the summer. The second piece of available information refers to the equipment. Only two technical schools are provided with air conditioning systems and four more high schools have these systems in computer rooms. In terms of mechanical ventilation, just a few of them are provided with a working system to extract or extract and supply air, as can be seen in Figure 25.

The additional information that could affect the energy performance of the schools is related to the window types and frame materials, which is summarized in Figure 26. It is interesting, that although the percentage is low, there are many classrooms that still have single glazing and wood cracked frames, which mean that these should be soon replaced to reduce their heating demand. This also represents an opportunity to upgrade the windows so they can achieve a good performance in the summer season as well.

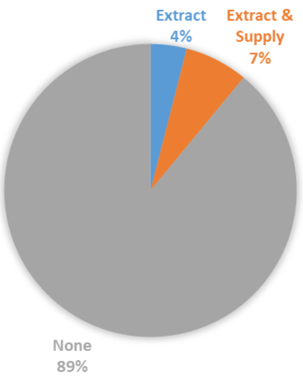
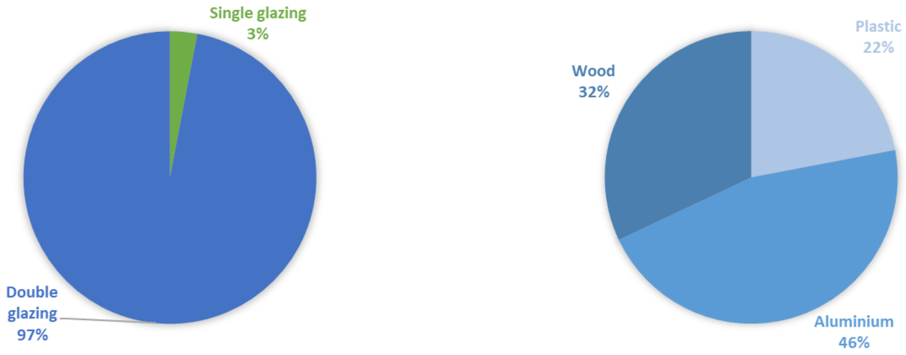


Figure 25: Available mechanical ventilation in school buildings in Karlsruhe. Most of the schools use natural ventilation through window opening to allow fresh air into the classrooms.



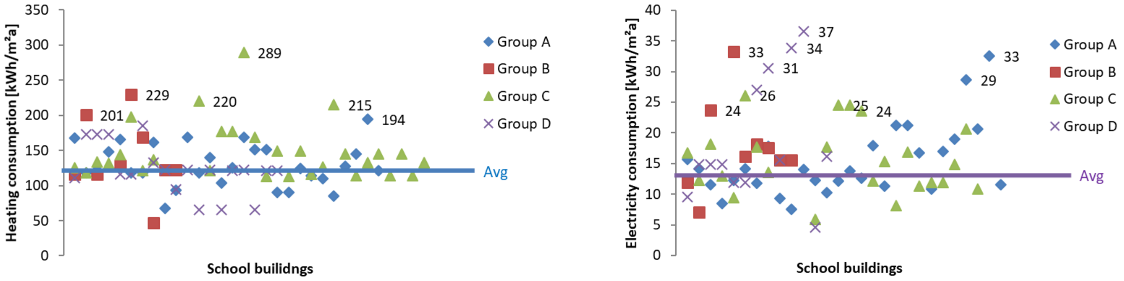
(a) (b)

Figure 26: Features of windows in the school's classrooms. (a) Glazing type. (b) Frame material.

In order to analyse further properties of the school buildings and their relation to their energy performance, they were divided into four groups according to their construction period:

- Group A: from 1848 to 1918
- Group B: from 1949 to 1957
- Group C: from 1958 to 1968
- Group D: from 1969 to 1978

The average heating and electricity consumption for all the school buildings from 2013 to 2015 is shown in Figure 27, where it can be seen that no particular trend can be identified. In terms of heating, the highest consumption belongs to a building from Group C, and the lowest to a building from Group B. However, the heating consumption of the rest of Group B seems to be rather scattered, while for Group C it tends to be closer to the average consumption for all school buildings. The average heating consumption of all the school buildings is 138 kWh/m²a and the statistical mode is 116 kWh/m²a. The group with the lowest average heating consumption is Group A, as can be seen from the summary in Table 4.



(a) (b)

Figure 27: Energy consumption of school buildings in Karlsruhe by construction periods. (a) Heating consumption. (b) Electricity consumption. The highest consumers in terms of heating are schools constructed in the 1960s, while the highest electricity consumers date from the 1970s.

Table 4: Summary of heating consumption and geometry properties of school buildings in Karlsruhe.

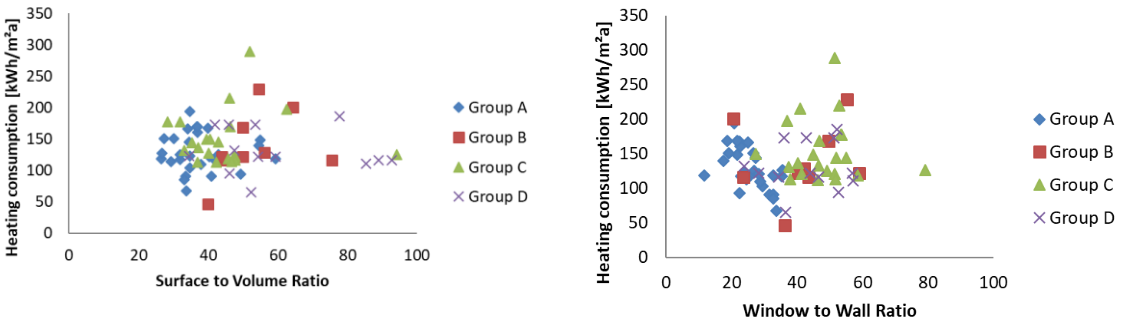
Group / Construction period		Heating consumption [kWh/m^{2}a]			Electricity consumption [kWh/m^{2}a]			WWR			SAV		
		Max	Avg.	Min	Max	Avg.	Min	Max	Avg.	Min	Max	Avg.	Min
A	1848 - 1918	194	129	67	33	15	8	36	26	12	59	38	27
B	1949 - 1957	229	139	47	33	18	7	59	41	21	76	51	35
C	1958 - 1968	289	152	113	26	16	6	79	48	27	74	45	28
D	1969 - 1978	186	131	65	37	19	5	57	43	24	83	60	34

According to the Federal Ministry of Traffic, Construction and City Development (2009), the average consumption of heating and domestic hot water is around 150 kWh/m^{2}a and 15 kWh/m^{2}a of electricity in school buildings in Germany. The energy requirements for a comparable new building would be 56 kWh/m^{2}a for heating and domestic hot water and 12 kWh/m^{2}a for electricity. Considering then, the recorded values, it can be seen from Table 4 that the average heating consumption of the school buildings from Groups A, B and C are below the national average. Nonetheless, all the groups have school buildings with consumption well above this reference value. Some of the school buildings show very low consumptions, near to one-third of the national average. This may be due to the smaller size of some primary schools and the difference in schedules; many of these primary schools only operate half a day.

Regarding the electricity consumption, the general picture is similar. Although the average consumption of all the school buildings groups is around the national average, some buildings double this consumption and some of them have even one-third of the consumption. Although this might be explained by the size and schedules, the management of these buildings also plays an important role. In general, all the groups have scattered values, although Group C tends to be closer to the average of all the school buildings, and Group D tends to have the highest consumptions. The average electricity consumption of all the school buildings is 16 kWh/m^{2}a and the statistical mode is 12 kWh/m^{2}a.

The schools and some Karlsruhe municipal offices are actively involved in the rational use of energy and water through the programme “EinSparProjekt”. According to the city administration, the thoughtful use of water and energy can reduce their consumption up to 15%, without sacrificing comfort. There are currently about 30 schools involved. The results of this project might be already reflected in and also explain the data in Table 4.

Once the generalities were observed, the geometric properties were analysed in relation to the energy consumption. The data show that Group A buildings have lower SAVs and lower WWRs than the other buildings. While for the other buildings the SAVs and the WWRs are around 50%, for Group A these values are lower, at around 40%, as can be seen in Figure 28. This can also be seen in the design of buildings: while buildings from the 19th Century tend to have higher rooms, vertical windows and massive walls, the buildings from the 1960s and 1970s tend to have lower room heights, horizontal windows, and lighter wall constructions, as shown in Figure 29 and Figure 30.



(a) (b)

Figure 28: Relationship between heating consumption and geometric building properties: (a) Heating consumption vs. surface-to-volume Ratio, (b) Heating consumption versus window-to-wall ratio.

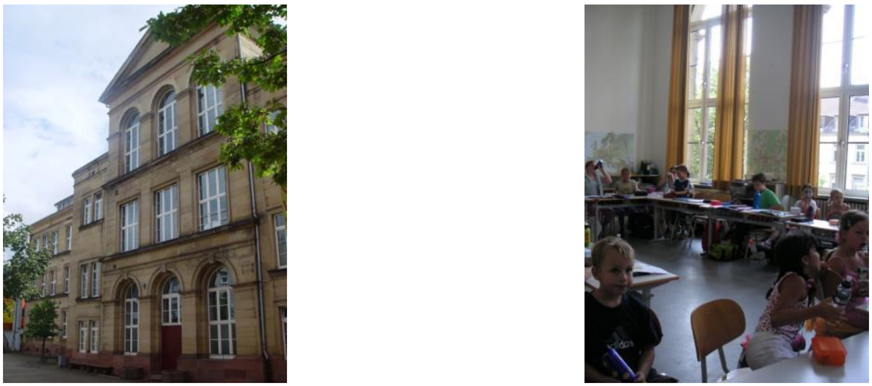


Figure 29: Example of a school building from the 19th Century in Karlsruhe: Gartenschule. Source: HGW (2016).

Figure 30: Example of a school building from the 1970s in Karlsruhe: Sophie Scholl Realschule Karlsruhe. Source: HGW (2016).

Figure 28 suggests, however, that there is no clear relationship between the SAV and the WWR of the different building groups and the heating consumption. As mentioned previously, there should be a direct and inverse relation between the heating consumption and these characteristics, taking out the extreme values. Correlation coefficients were calculated to stablish a statistical relationship between the two variables, giving as a result 0.05 and 0.12 for the heating consumption in relation to SAV and WWR respectively, showing that this relationship is weak. Additional statistical relationships were tested for each of the building groups; however, no strong connection was found, as can be seen from Table 5.

In a similar way, the WWR was analysed together with only the electricity consumption, as it was explained above that it could decrease the lighting consumption. However, for this case the data was also scattered, as illustrated in Figure 31, with a correlation coefficient of 0.12. No other relationships seem to connect these two variables, as can be seen from the results in Table 6.

Table 5: Statistical relationships between schools´ heating consumption and surface-to-volume ratio and window-to-wall ratio

Group / Relationship	Coefficients of determination - Heating consumption vs SAV (R²)				
	Exponential	Linear	Logarithmic	Polynomial	Potential
Group A	7,00E-05	8,00E-05	2,00E-05	0,001	5,00E-05
Group B	0,1846	0,1509	0,1987	0,6661	0,2527
Group C	2,00E-05	0,0014	0,0033	0,0336	0,0002
Group D	0,004	0,0096	0,0083	0,0158	0,0042
Group / Relationship	**Coefficients of determination - Heating consumption vs WWR (R²)**				
	Exponential	Linear	Logarithmic	Polynomial	Potential
Group A	0,307	0,2996	0,2309	0,3723	0,2388
Group B	0,0213	0,0184	0,0017	0,2838	0,003
Group C	0,0026	0,001	4,00E-05	0,0242	0,0008
Group D	0,0069	0,0073	0,0085	0,0185	0,0065

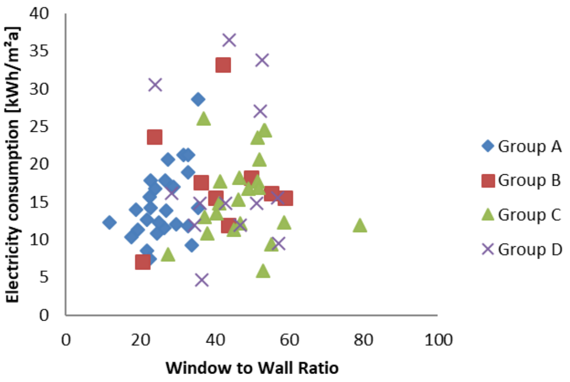


Figure 31: Electricity consumption versus window-to-wall ratio of school buildings in Karlsruhe.

Table 6: Statistical relationships between schools´ electricity consumption and window-to-wall ratio

Group /	Coefficients of determination - Electricity consumption vs WWR (R^2)				
Relationship	Exponential	Linear	Logarithmic	Polynomial	Potential
Group A	0,182	0,2165	0,1876	0,2334	0,1596
Group B	0,0532	0,0067	0,0203	0,1388	0,0882
Group C	0,0025	0,0018	0,0106	0,0996	0,0127
Group D	0,0006	2,00E-05	0,0012	0,0244	0,0001

Since no clear relation was found between the energy consumption and the buildings’ characteristics, initially, the buildings with the highest consumptions of heating and energy are of interest, as they represent an important potential for savings. However, as was mentioned above, key information to undertake energy and thermodynamic simulations is unavailable. Therefore, before making the final selection of the buildings to study, the construction types were investigated, as discussed in the next section.

4.2.4 Building construction features

The classification of buildings by age is founded on the similar characteristics in terms of layouts and building materials that were used in every time period. It is common to find that buildings constructed in the same periods, not only have analogous geometric features, but also the energy performance tends to relate to these, as the thicknesses and u-values correspond to the statics and construction procedures typical of the epoch.

In Europe, usually the first distinction that is made in terms of construction types relates to the buildings dated before the end of the First World War, that is 1918, and those built after the Second World War, in the late 1940s and the early 1950s, as the destruction of the cities demanded a rapid redevelopment of the urban settlements. In this classification, significant changes in terms of wall thickness can be identified, which could have a significant effect on the thermal and energy performance of the buildings.

In Germany, for the period before the First World War, two periods are identified: one pre-industrial phase (until about 1870) and the period until the beginning of the Weimar Republic (1850 to 1918), when the first standardizations of procedures and materials were introduced (Weglage et al., 2010).

The characterization of the different building epochs is mainly summarized in four main sources. The first, TABULA - Typology Approach for Building Stock Energy Assessment, is a project founded by the Intelligent Energy Europe Programme of the European Union and coordinated by the IWU - Institute for Housing and Environment. Its main target was gathering information about building construction types in Europe and establishing base cases, with the participation of 16 countries. Subsequently, the project tracked the implementation of energy-saving measures and their effect on consumption in practice. The case studies of refurbishment processes in those countries allowed energy performance indicators to be set, which would enable key actors and stakeholders at different levels to ensure high quality renovation plans. Although TABULA's focus is on residential buildings, the database still provides valuable detailed information about construction details that are not available for non-residential buildings in other sources. The TABULA project has been followed up by the EPISCOPE project, since 2013 (German Institute for Housing and Environment, 2016).

The second and third sources refer to two German compendia: the "*Typical building constructions from 1860 to 1960*" (Ahnert, and Krause, 2009) and the "*Energy certificate - The big compendium*" (Weglage et al., 2010). The fourth source, although is from the United Kingdom, also gathers information from typical buildings around Europe: the "*Evolution of Building Elements*" (University of West England, 2009).

The main construction details of each construction period are summarized from the previous sources as follows.

- Before 1918:

Until 1850, the artisanal embossed timber construction was common, with corresponding static over-dimensioning, as it was built not according to standards, but according to experience. The masonry construction started to dominate from 1850, with both exposed masonry and with air layers (Weglage et al., 2010).

By the end of the 19th Century, non-residential buildings and houses with over three storeys often had thick walls of various layers of bricks, stones, or both, at the ground floor level, with fewer layers at higher levels of the buildings.

Prestigious or symbolic buildings use more stone than brickwork. In countries like Germany and the United Kingdom, sedimentary stones such as limestone and sandstone are the most common ones.

Depending on the thickness of the walls, common U-values range from 1.7 W/(m²K) to 2.4 W/(m²K). The common practice also included tilted roofs out of clay tiles.

➢ From 1949 to 1957:

The predominant features of this epoch were the materials and cost-saving designs. In the former East Germany, the first buildings were built in prefabricated blocks (Weglage et al., 2010). The blocks were usually made with an aggregate of stone or industrial waste (clinker and breeze were common). Cavity walls and wooden beam ceilings were common during this period. Original (uninsulated) walls have U-values around 1.5 W/(m²K).

➢ From 1958 to 1968:

The main characteristic of this period was the increase in the height of both residential and non-residential buildings. With the replacement of limes by cement mortars, the U-values decreased to around 1.2 W/(m²K).

➢ From 1979 to 1983:

The first oil crisis took place and the first Heat Insulation Ordinance and DIN 4108 were implemented. The U-values started decreasing to around 1.0 W/(m²K), using cavity walls with brick external leaves and inner leaves consisting of light concrete blocks finished with plasters. Lightweight blocks were made from aerated concrete, mixing cement, lime, sand, pulverized fuel ash, and aluminium powder. Once these materials are mixed with hot water, the aluminium powder reacts with the lime to form micro pockets of hydrogen.

➢ From 1984 - 1994:

The second Heat Insulation Ordinance was implemented. The *Passivhaus* Standard was introduced, as a voluntary scheme in the design and construction of low-energy buildings. The first Passivhaus residences were built in Darmstadt in 1990, and in 1996, the Passivhaus-Institut was founded to promote and control Passivhaus standards.

➢ From 1995 onwards:

The Heat Insulation Ordinance has been updated and the Energy Performance of Buildings Directive (EPBD) established emission reduction targets.

This summary shows how the construction materials, procedures, and standards have changed with time and how they have influenced the U-values of the envelope, which has a significant effect on the thermal comfort and the energy performance. The typical wall constructions and U-values of each period are illustrated in Figure 32.

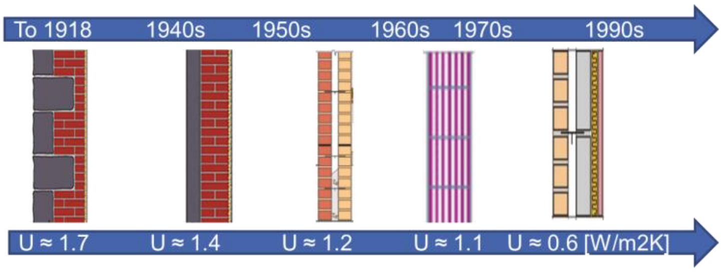


Figure 32: Typical wall U-values according to construction periods.

4.3 Building selection

The purpose of this study is to find solutions to overheating that can be applied to the schools of Karlsruhe. Therefore, typical buildings likely to be subjected to potential refurbishments in the future should be chosen so that they are representative of the different building groups. In that way, the first criterion is to select buildings that match the typical construction types that have been previously described. On the other hand, since the city seeks to improve the buildings in a way that is mindful of the energy performance, the first analysis intended to explain consumption patterns merely through the building's characteristics. However, as shown in the previous section, this analysis revealed that there is no apparently clear relationship.

Under this overview, all the buildings were ranked according to their heating and electricity consumption, and a small number of buildings of the highest consumers from each group were chosen, as illustrated in Figure 33, looking that the available information that was as complete as possible.

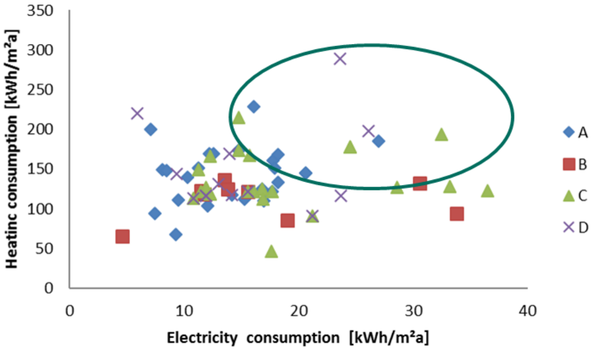
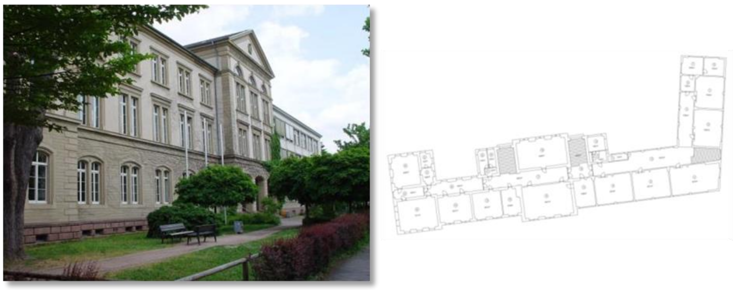


Figure 33: Average heating and electricity consumption of school buildings in Karlsruhe. The target group of buildings to be selected included the highest consumers, so that the outcomes of the study could directly improve their performance.

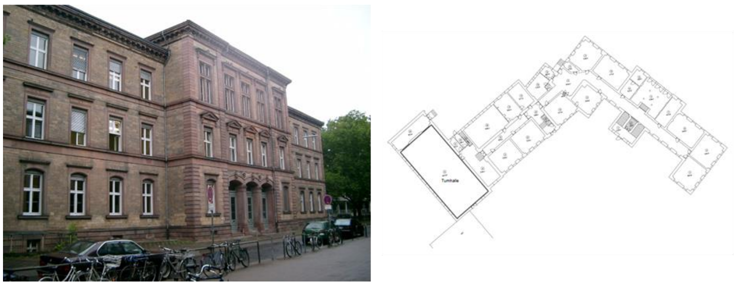
The selected buildings are briefly described as follows:

- Group A



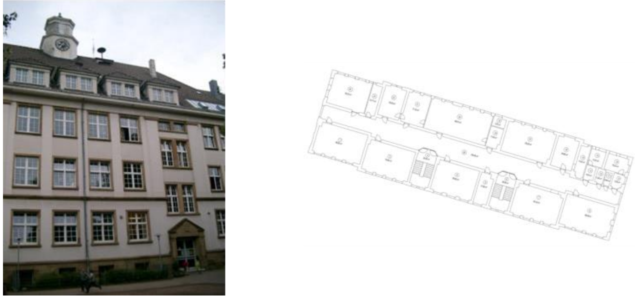
Bismarck-Gymnasium
- Category: High school
- Construction year: 1873
- Location: city centre
- Gross floor area: 7.326,69 m^2
- Net floor area: 6.175,55 m^2
- Main use area: 3.073,35 m^2
- Heating consumption: 125 [kWh/m²a]
    - Savings (2015): -9%
- Electricity consumption: 17 [kWh/m²a]
    - Savings (2015): -3%

Figure 34: Construction details of the Bismarck Gymansium high school
Source: City database (HGW, 2016)



Kant-Gymnasium
- Category: High school
- Construction year: 1873
- Location: city centre
- Gross floor area: 8587,65 m^2
- Net floor area: 6914,78 m^2
- Main use area: 4015,29 m^2
- Heating consumption: 114 [kWh/m²a]
    - Savings (2015): -12%
- Electricity consumption: 12 [kWh/m²a]
    - Savings (2015): 0%

Figure 35: Construction details of Kant-Gymnasium high school
Source: City database (HGW, 2016)



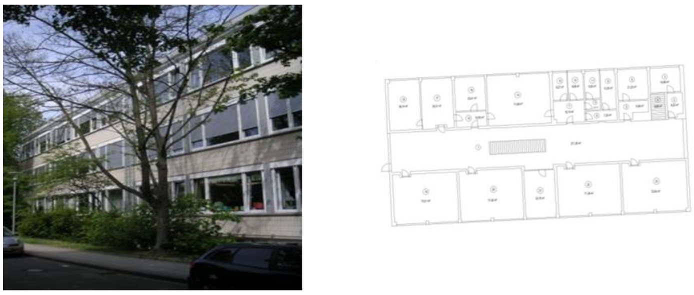
Pestalozzischule
- o Category: Primary and Middle school
- o Construction year: 1914
- o Location: Suburbs
- o Gross floor area: 7.031,17 m^2
- o Net floor area: 5.707,97 m^2
- o Main use area: 3.247,10 m^2
- o Heating consumption: 151 [kWh/m²a]
  - o Savings (2015): 15%
- o Electricity consumption: 18 [kWh/m²a]
  - o Savings (2015): 2%

Figure 36: Construction details of Pestalozzischule primary and middle school
Source: City database (HGW, 2016)

➢ Group B

Adam-Remmele-Schule
- o Category: Primary and technical school
- o Construction year: 1961
- o Location: Suburbs
- o Gross floor area: 3.630,54 m^2
- o Net floor area: 3.406,65 m^2
- o Main use area: 2.014,60 m^2
- o Heating consumption: 131 [kWh/m²a]
  - o Savings (2015): -11%
- o Electricity consumption: 13 [kWh/m²a]
  - o Savings (2015): -7%

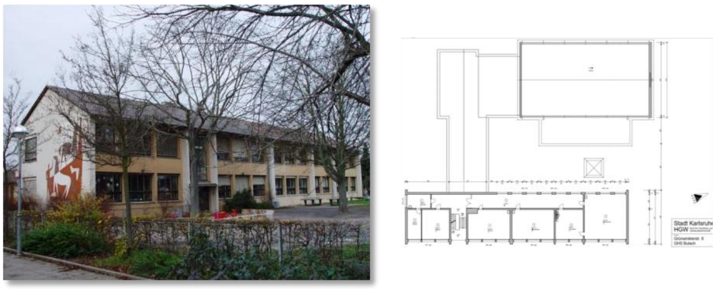
Figure 37: Construction details of Adam-Remmele-Schule primary and technical school
Source: City database (HGW, 2016)



Schloßschule:
- o Category: Primary school
- o Construction year: 1963
- o Location: Suburbs
- o Gross floor area: 4.139,55 m^2
- o Net floor area: 3.713,46 m^2
- o Main use area: 1.918,72 m^2
- o Heating consumption: 178 [kWh/m²a]
  - o Savings (2015): -30%
- o Electricity consumption: 25 [kWh/m²a]
  - o Savings (2015): 3%

Figure 38: Construction details of Schossschule primary school
Source: City database (HGW, 2016)

- Group C



Grundschule Bulach:

- Category: Primary school
- Construction year: 1956
- Location: Suburbs
- Gross floor area: 3.101,37 m^2
- Net floor area: 2.689,94 m^2
- Main use area: 1.426,27 m^2
- Heating consumption: 168 [kWh/m²a]
  - Savings (2015): -8%
- Electricity consumption: 18 [kWh/m²a]
  - Savings (2015): -8%

Figure 39: Construction details of Grundschule Bulach primary school
Source: City database (HGW, 2016)

Max Planck Gymnasium:

- Category: High school
- Construction year: 1956
- Location: Suburbs
- Gross floor area: 4211,72 m^2
- Net floor area: 3756,90 m^2
- Main use area: 2285,64 m^2
- Heating consumption: 122 [kWh/m²a]
  - Savings (2015): -16%
- Electricity consumption: 16 [kWh/m²a]
  - Savings (2015): 3%

Figure 40: Construction details of Max Planck Gymnasium high school
Source: City database (HGW, 2016)

- Group D

Sophie-Scholl

Category: Middle school

- Construction year: 1977
- Location: City
- Gross floor area: 12.552,32 m^2
- Net floor area: 11.356,47 m^2
- Main use area: 5.931,42 m^2
- Heating consumption: 122[kWh/m²a]
  - Savings (2015): -1%
- Electricity consumption: 37 [kWh/m²a]
  - Savings (2015): -18%

Figure 41: Construction details of Sophie- Scholl middle school
Source: City database (HGW, 2016)

The selected school buildings have an average main use area of around 3000 m², where the smallest is the Bulach Primary School, hosting 80 pupils, and the largest is the Sophie Scholl Middle School, hosting 500 pupils. Most of the schools in the city are located in the suburbs but two high schools representative of Group A are located in the city centre. The location of the selected schools is illustrated in Figure 42.

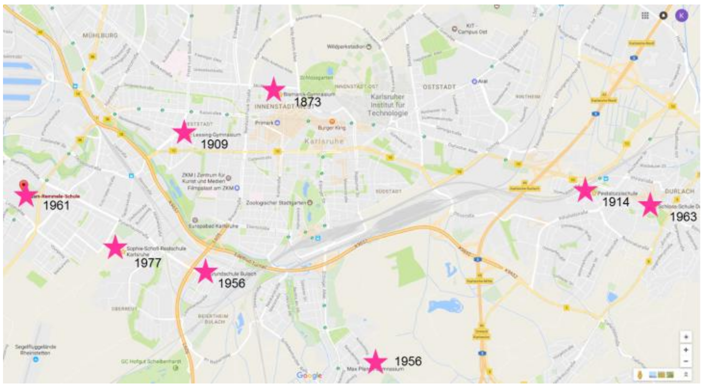


Figure 42: Location of selected school buildings to simulate in the study. Two buildings are located in the city centre and six in the suburbs, reflecting the usual distribution of schools.

Source: Google maps

Massive envelopes made of stones and brickwork, as shown in Figure 34, Figure 35, and Figure 36, characterise the school buildings of Group A. The buildings of the decades of the 1950s and the 1960s, shown in Figure 37, Figure 38, Figure 39, and Figure 40, have similar constructions, but in order to cover the typical constructive features of the school buildings in the city, they were divided into two groups, where the largest buildings were classified as medium weight, with massive external walls and lightweight internal partitions. Lightweight partitions are common in school buildings, as they are preferred in order to have more flexible room sizes and be able to adjust them more easily according to the needs of the school. The Sophie Scholl School, shown in Figure 41 was selected as being one of the largest school buildings in the city and with a typical lightweight construction.

5 Building Modelling

5.1 Generalities

The evaluation of the chosen buildings was made by means of Building Performance Simulations (BPS) using the Energy Plus engine of DesignBuilder. DesignBuilder is a sophisticated software that allows the verification of energy, lighting, comfort and CO_2 balances of a building, using a computer-based, mathematical model created on the basis of fundamental physical principles of the buildings components.

In general, the Finite Difference solution algorithm was used, as it was required to include the effect of Phase Change Materials (PCMS) properties in simulations. The wind exposure was set to normal, as there were no tall buildings or barriers close to the buildings. The natural ventilation strategy was evaluated with a fix schedule to establish the base case scenario and as automatically calculated in the subsequent alternatives, to take into account the effects of window openings, cracks, buoyancy and wind driven pressure differences crack dimensions etc. The doors were set up to remain closed as it was desired to analyse the effect of natural ventilation in the most usual conditions of classrooms and not with cross ventilation.

The posterior daylight simulations were undertaken with the Radiance engine of DesignBuilder. The calculations take place at a working plane height of 0.85m, under overcast day conditions (as the internationally agreed standard used to describe the amount of light from the sky), and with a grid size of 0.05m.

Further simulations inputs and specifications of the pre-simulation phase are described in this chapter.

5.2 Simulation inputs

The building models were created with the input of boundary conditions and parameters. The boundary conditions are those variables set by the nature of the project, such as the weather or the occupancy, and, therefore, less subject to being influenced. The parameters constitute those variables that could be influenced by the designer and therefore are of interest in the simulation analysis, such as the construction materials, the geometry and building dimensions and the HVAC systems, amongst others.

Even though the database of the city is quite large, not all the information required to create the models was available. Essential pieces of information such as the construction details were among the missing items. In order to obtain such details as accurately as possible, questionnaires were designed to be presented to architects related to the buildings. The gathered information was then matched with the typical constructions according to the literature and visits to the school buildings.

Figure 43 segregates the parameters into the available and missing information from the database and Figure 44 summarizes the sources of the required information to create the building models.

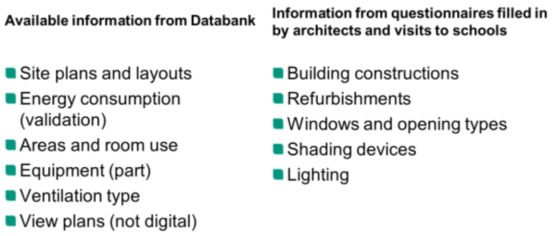


Figure 43: Required information for the building modelling process: available vs. missing information.

Figure 44: Sources of the parameter and boundary conditions.

The main simulation inputs are briefly described as follows:

- Geometry

As shown in section 4.3, most of the selected schools have rectangular shapes, with the largest facades of the classrooms facing south or southeast. This orientation allows more solar gains during winter with an accompanying decrease in the heating loads. During summer, the sun is at a higher angle and therefore there is less direct radiation than during winter. Nevertheless, a façade with this orientation is subjected to significant heat gains that can lead to indoor overheating.

The geometry and orientation are features that significantly influence the indoor comfort and energy performance of buildings. In existing buildings, however, these factors are not parameters that can be influenced by the designer.

The plans of the selected school buildings were found digitally in the city database, while the views were available in physical scale plans. Therefore, this information is considered in general complete and reliable. In general, the school buildings of Group A have higher rooms (around 4.5 m), massive walls, vertical windows and lower window-to-wall ratio (~22%), while buildings from Group C and Group D have lower room heights (around 3.8 m), horizontal windows, higher window-to-wall ratios (~36%); in addition the constructions seem lighter and they have more compact plans.

- Constructions

As previously described, the buildings’ constructions were, in general, classified into heavy, medium and light weight. The materials were selected by matching and completing the information from the literature review and the questionnaires. According to this information and the dimensions of the plans, the U-values, or thermal transmittance, were calculated. Nevertheless, as can be seen in Table 7, the U-values do not match exactly the typical values found in the literature review, due to the fact that the 19th Century buildings have very thick walls.

It was found that the school buildings were mostly uninsulated, except for some schools, where pitched roofs allowed the installation of a layer of mineral fibres or expanded polystyrene (EPS). The external walls of the buildings from Group A and Group B are mainly made of stone and brickwork or only brickwork without cavities. The buildings of Group C and Group D are believed to be made of light concrete or brickworks. None of the buildings had insulation in the external walls. It was observed during the visits to the schools that although some of them still had single glazing in the envelope, the classrooms were almost always equipped with double-glazing. The construction features of the selected buildings are summarized in Table 7 and the detailed information is found in Appendix A.

Table 7: Description of selected buildings.

Epoch	*Main construction characteristics*	*# of buildings, main façade orientation & location*
Prior to 1914 (Group A)	External walls: massive walls made out of stone and brickwork or only brickwork. U≈1.5 [W/m^{2}K]. Partitions made out of brickwork and gypsum. U≈1.2 [W/m^{2}K]. Roofs: unoccupied pitched roofs with semi-exposed insulated ceiling. U≈0.2 [W/m^{2}K]. Windows in classrooms: clear double-glazing U≈2.7 [W/m^{2}K].	Buildings 1&2: South. City centre Building 3: Southeast. Suburbs.
1950s - 1960s (Group B)	External walls: massive walls made out of brickwork. U≈1.5 [W/m^{2}K]. Partitions made out of studs and gypsum. U≈1.9 [W/m^{2}K]. Roof 1: unoccupied pitched roofs with semi-exposed insulated ceiling. U≈0.2 [W/m^{2}K]. Roof 2: Uninsulated flat roof. U≈1.1 [W/m^{2}K]. Windows in classrooms: clear double-glazing U≈2.7 [W/m^{2}K].	Building 1: South. Suburbs. Building 2: East. Suburbs.
1950s - 1960s (Group C)	External walls: lightweight walls made out of brickwork or concrete blocks. U≈1.3 [W/m^{2}K]. Partitions made out of studs and gypsum. U≈1.1 [W/m^{2}K]. Roof 1: Insulated flat roof. U≈0.4 [W/m^{2}K]. Roof 2: Uninsulated flat roof. U≈1.3 [W/m^{2}K]. Windows in classrooms: clear double-glazing U≈2.7 [W/m^{2}K].	Building 1: South. Suburbs. Building 2: South-east. Suburbs.
1970s – 1980s (Group D)	External walls: lightweight walls made out of concrete. U≈0.9 [W/m^{2}K]. Partitions made out of studs and gypsum. U≈1.7 [W/m^{2}K]. Roof: Insulated flat roof. U≈0.5 [W/m^{2}K]. Windows in classrooms: clear double-glazing U≈2.7 [W/m^{2}K].	Various. Suburbs.

- Openings

The selected buildings have different window arrangements, as can be seen from Figure 45 to Figure 50. As was mentioned before, the buildings of Group A have higher ceilings and therefore the windows tend to be vertical and also higher. The architects of the epoch designed the buildings this way to allow more daylight into the indoor spaces. Their windows usually have more than one vertical opening option, which means it is possible to open the largest window from the side or from the top (bottom-hung), and it is also possible to open a small top window, also from the top. In the other buildings, the windows tend to be horizontal due to the lower floor to ceiling height. In these cases, it is also rare to find more than one vertical opening option.

The visits to the school showed that the windows usually remained closed during classes and they were open in the bottom-hung position during the breaks. The windows were not completely open for safety reasons: in many cases, the edge of an opened window could represent a danger for the pupils, since they could easily hit their heads on it.

Figure 45: Window opening details of Bismarck-Gymnasium school. Source: author.

Figure 46: Window opening details of the Pestalozzi school. Source: author.

Figure 47: Window opening details of Adam Remmele school. Source: author.

Figure 48: Window opening details of Schlossschule school. Source: author.

Figure 49: Window opening details of Bulach school. Source: author.

Figure 50: Window opening details of Sophie Scholl school. Source: author.

The models also require a discharge coefficient to be established for the windows. The discharge coefficient (Cd) describes the flowrates through an orifice. Some studies suggest that for more accurate results when simulating natural ventilation strategies, this coefficient should not be treated as a constant (Heiselberg & Sandberg, 2006). However, in practice, it is difficult to estimate the parameters required calculating it, and therefore standard values are often used (Iqbal et al., 2015). A discharge coefficient value of 0.6 for a sharp-edged rectangular opening is often used for windows, regardless of the opening angles (opening areas) and pressure and temperature differences across the opening (Heiselberg et al., 2000) Based on this suggestion, for this study, a discharge coefficient of 0.6 is taken for all the window openings in all the school buildings.

During the school visits, it was also possible to observe that most of the schools were equipped with blinds but usually they did not have external fixed shading devices.

- Equipment and lighting

It was observed in the school visits that standard classrooms were usually equipped only with a video projector and a computer. Therefore, the value for the internal gains due to this parameter is taken as 2 W/m², as suggested by the CIBSE Guide A: Environmental Design (CIBSE, 2015).

The school visits also allowed the types of lights used in some of the classrooms to be observed. In general, they used tubular light bulbs of 60W and on average there were 12 of them installed in the classrooms. With these values, the lighting power was calculated at 11W/m². It was assumed, however, that artificial lighting is not used in the warmest months (and perhaps the brightest as well) of the summer. Therefore, for the calculation of overheating, heat gains due to artificial lighting are not taken into account.

- Occupancy

The occupancy profiles were based on the average conditions, where the schools host around 24 pupils per classroom and deliver 7 class hours of 45 minutes, with 10 minutes' break between them, one long break of 30 minutes and one-hour lunch breaks. In this German State, the schools usually have a summer break from the end of July to the middle of September. For this investigation, the simulations are undertaken for the month of July of the DSY2035.

The metabolic rate was set up as 90 W/m^2, as suggested by Havenith in his study on metabolic rate of children and adolescents during various school activities (2007). This study compiled data from 81 subjects and showed that metabolic rate values in children are significantly lower than in adults.

5.3 Calibration of the models

Energy performance models are powerful tools that allow energy conservation measures to be evaluated, integrating boundary conditions and parameters, as previously explained. As each model acts as a decision support tool, which comprises various complex calculations, a certain degree of confidence is required. There are five main techniques to validate software and calibrate the models (Firth, 2011):

- Code checking
- Inter-model comparison
- Predicted behaviour
- Analytical tests
- Empirical calibration

Code checking involves two conditions; first, that the software to be used has an open source (available to the users), and second, that the modeller is confident with the programming skills required to adapt or change calculation methods within the code.

Inter-model comparison is also often used to validate software. In this technique, a well-known building is simulated and the outputs between programs are compared. The well-known building is usually a laboratory or test facility, where the inputs and outputs of the model can be supported with controlled real data. To facilitate these two tasks, standard test procedures have been developed, such as the BESTEST (Building Energy Simulation Test), the CIBSE TM33 (Tests for software accreditation and verification) and the ASHRAE Standard 140 (Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs - ANSI Approved). The software used in this study, DesignBuilder, and its engine, Energy Plus, have been validated by both BESTEST and ASHRAE 140 (DesignBuilder, 2006; Energy Plus, 2018).

The predicted behaviour might not be an official technique but is still a valuable method always used by modellers. With this technique, the output is scrutinised in order to see if the model behaves qualitatively in an expected manner. For instance, it can be verified that the heating system is only operating during the winter season, that the internal heat gains correspond to the established profiles, or that the airflows occur through the openings and under the conditions established.

Through the analytical tests, simulation results are compared with values that can be calculated by analytical means. Although the analytical results are numerically accurate, this technique is very limited, since the dynamic and heterogeneous conditions imply the need for complex calculations and iterations.

Finally, in empirical calibration, theoretical predictions are compared with experimental measures, such as indoor temperatures or energy consumption. This method, although highly accepted, is usually time-consuming and could be expensive, since it requires sensors and loggers. Moreover, there are other limitations: for example, when measuring temperatures, it is required to find matching outdoor temperatures in the weather files, which might be a very difficult task, especially for consecutive days.

Comparing energy consumption is also a common empirical calibration technique, although a bit risky. Several studies have shown the gap between design and energy performance and, in many cases, such circumstances are attributed to user behaviour (Schakib-Ekbatan et al., 2015; Hong, 2017). Consequently, it would not be recommended to use energy consumption data directly to fine-tune the models.

It can be concluded that validating building performance models is an extremely difficult task, and the methods described above highlight just how risky it is to place reliance on the absolute values predicted by such models. However, building modelling tools have been developed with the support of years of research, including validations and improvement processes, showing, as in the reports of BESTEST, that their algorithms reflect with great confidence the conditions of real buildings (Neymark, 2002). Therefore, the use of software validated by at least one of the standard recognized procedures together with one or two calibration techniques, guarantees a fair degree of confidence that the simulations´ outcomes can be used as guidelines and decision-making tools (Firth 2011).

For this study, validated software was selected, and predicted behaviour, as well as empirical comparisons, were chosen as calibration techniques. The procedures carried out are described below.

5.3.1 Temperature measurements

Temperature measurements were made during the summer of 2017 to get a clearer view of the indoor temperatures in the classrooms and the window opening practices. For this purpose, six classrooms were chosen in two school buildings; one from Group A constructed in 1877 and one from Group B, constructed in 1956. Indoor temperatures and indoor CO_2 levels were recorded from June 20th to June 30th, where the maximum daily temperature was 34°C. In this way, it was possible to observe the behaviour of buildings under high temperatures, even for a few days.

As mentioned above, the first task to allow the comparison was to find days with similar day and night temperatures. The first approximation to determine if the temperatures were similar was represented graphically, then deterministically through the Coefficient of Variation of the Root Mean Square Error (CVRMSE). The Root Mean Square Error (RMSE) is a tool often used in the calibration of building energy models (Lam, 2008), and in this case, since the indoor temperatures were going to be compared based on the external temperatures, which would already be different, it was decided to normalize this indicator.

The RMSE and the CVRMSE were calculated through Equation 1and Equation 2 respectively.

Equation 1: RMSE

$$RMSE = \sqrt{\frac{\sum_{i=1}^{24}(T_{sim} - T_{rec})^2}{24}}$$

Equation 2: CVRMSE

$$CVRMSE = \frac{RMSE}{T_{recmax} - T_{recmin}}$$

Where: T_{sim} is the simulated temperature, or the outdoor temperature of the weather files.

T_{rec} is the recorded temperature.

T_{recmax} is the maximum-recorded temperature.

T_{recmin} is the minimum-recorded temperature.

The RMSE is calculated under a base of 24, since is calculated hourly and for each day.

Figure 51 shows graphically the recorded outdoor temperatures for the warmest week of the period when the measurements took place, and the outdoor temperatures of the days with similar profiles found in the weather files. It is difficult to find consecutive days with very similar profiles. In this case, the best match is found in the first three days, where the maximum day temperatures are around 32°C – 34°C, and the minimum night temperatures are around 20°C – 22°C. During the next days, the temperatures in the city dropped more than 5K but it was not possible to find consecutive days with such a feature in the weather files.

The minimum calculated CVRSME was 8% and the maximum was 20%.

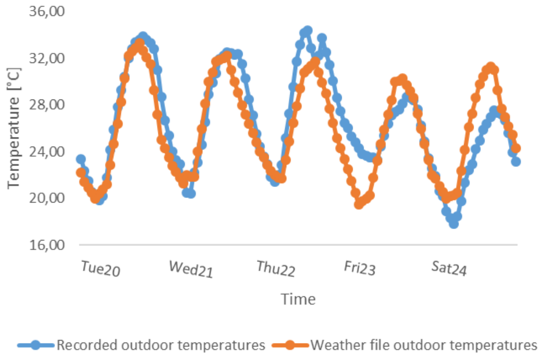


Figure 51: Comparison of outdoor temperatures: recorded temperatures vs. similar temperatures found on the weather files.

The daily CVRMSE for the indoor temperatures varied from 10% to 15% in school building B1 and from 8% to 18% in school building C2, as can be seen in Table 8, which displays the these calculated values per day and for each room. According to the ASHRAE Standard, the acceptable tolerance when comparing a building energy model with actual data should be ±15% (ASHRAE, 2002). However, for this case, the CVRMSEs of the recorded and the TRY outdoor temperatures fluctuate between 8% and 20%. Since the indoor CVRMSE is lower than the outdoor CVRMSE, it is considered that the simulation's results are within the acceptable range.

Table 8: Calculated Coefficients of Variation of the Root Mean Square Error per day and for each room, comparing the recorded indoor temperatures and the outputs of the simulations.

ID	CVRMSE 20.06.17	CVRMSE 21.06.17	CVRMSE 22.06.17	CVRMSE 23.06.17	CVRMSE 26.06.17	CVRMSE 27.06.17	CVRMSE 28.06.17	CVRMSE 29.06.17
B2R1	12%	10%	15%	15%	11%	15%	10%	11%
B2R2	10%	12%	15%	15%	10%	10%	12%	12%
B2R3	15%	12%	12%	14%	12%	15%	13%	11%
C2R1	10%	16%	18%	18%	18%	17%	10%	11%
C2R2	12%	12%	8%	18%	15%	12%	9%	11%
C2R3	11%	16%	15%	12%	14%	16%	11%	17%

It is important to mention that, for this study, although the CVRMSE gives a clear idea of how well the models represent the actual buildings, it is more relevant to observe that the temperatures follow fairly the same pattern. That feature indicates that the model is able to predict the temperature fluctuations according to the building features and the actual profiles (i.e. occupancy and window opening). From Figure 52 to Figure 57 it is shown that, in general, the temperatures start rising at around 07:30, when the classes begin, until approximately 12:30. From this point onwards, the indoor temperature decreases. Both the recorded and the model temperatures fluctuate at the same pace. The occupancy hours of the classrooms were identified with the help of the CO_2 measurements.

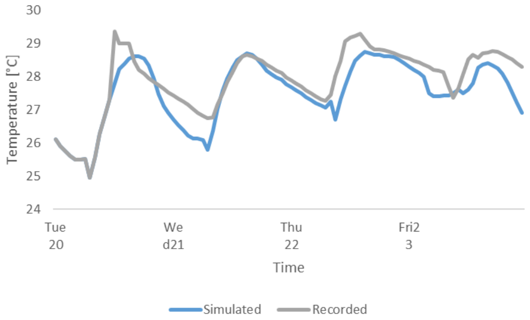


Figure 52: Comparison of indoor temperatures in building B2, room 1: recorded vs. simulated.

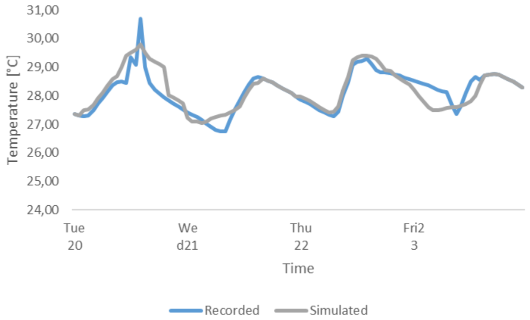


Figure 53: Comparison of indoor temperatures in building B2, room 2: recorded vs. simulated.

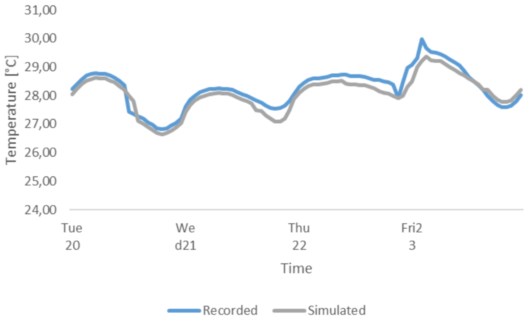


Figure 54: Comparison of indoor temperatures in building B2, room 3: recorded vs. simulated.

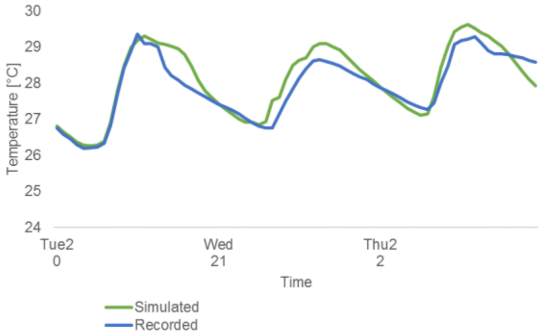


Figure 55: Comparison of indoor temperatures in building C2, room 1: recorded vs. simulated.

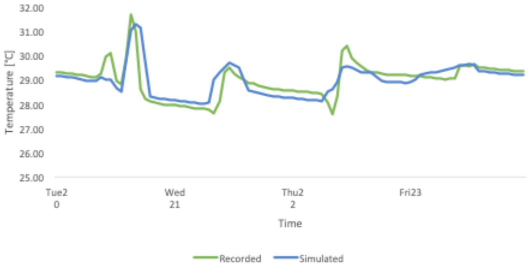


Figure 56: Comparison of indoor temperatures in building C2, room 2: recorded vs. simulated.

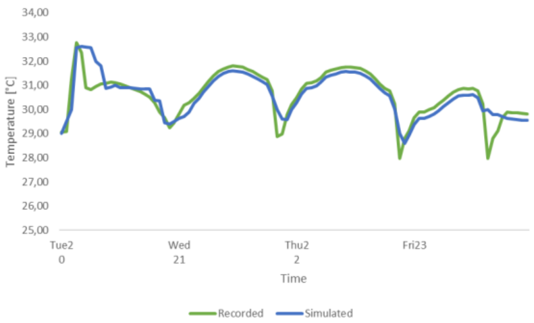


Figure 57: Comparison of indoor temperatures in building C2, room 3: recorded vs. simulated.

In order to achieve the previous results, it was necessary to first adjust the occupancy details of each classroom. In the previous section, it was mentioned that, schools usually start their activities around 07:30 to 08:00 and end at around 15:30, depending on the school and the type. The CO_2 measurements suggest, however, that all the classrooms are not occupied during the complete teaching day. In fact, most of them seem to operate only during the morning. For instance, the CO_2 levels shown in Figure 58 suggest that in this room there are classes from around 07:30 to 12:00. In this case, the CO_2 levels start rising from 400 ppm up to a peak of 1100 ppm and then decrease again. During this period there is only one zone where the levels decreased, suggesting that the windows were opened during a short break, allowing the levels to drop from approximately 1000 ppm to 800 ppm.

In the case represented in Figure 59, it seems that the classroom is occupied until 14:00, but in this case, the windows were opened more frequently, a practice that allowed the CO_2 concentration levels to be maintained at a lower level than in the previous classroom.

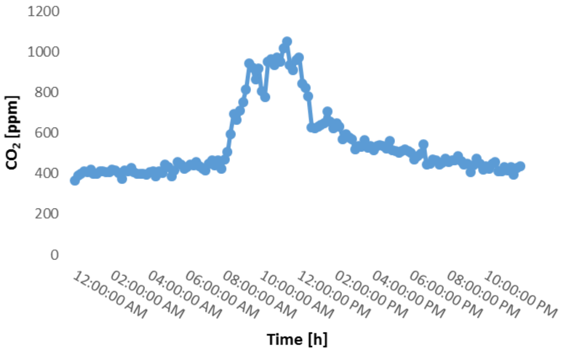


Figure 58: Recorded CO_2 indoor concentration levels on Thursday 22:06:2017 in classroom 2OG14 of school building C2.

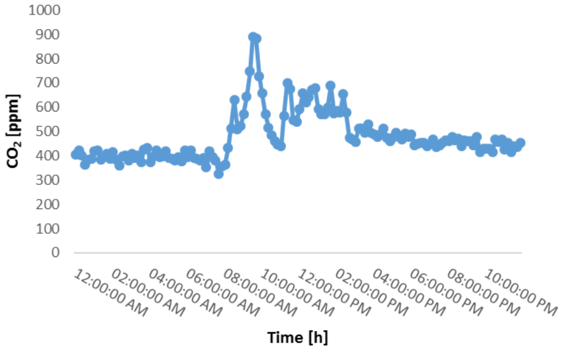


Figure 59: Recorded CO_2 indoor concentration levels on Wednesday 28:06:2017 in classroom 2OG14 of school building C2.

These examples, which actually represent quite well the situation of the other analysed classrooms, provided a view of the indoor conditions, where the following observations are highlighted:

- The occupancy in each classroom varies. In most cases, they are occupied only during the mornings but in other cases, they are also used for a couple of hours during the afternoon. This last practice is more common in specialised classrooms such as computer rooms or laboratories. For the calibration purposes, these occupancy profiles were analysed individually and set up in the simulation inputs. However, for the subsequent simulations, the classrooms are set up as continuously occupied, for two main reasons; first, because classrooms are meant to be available for classes during the complete day, and there is no specification or restrictions on whether they are used or not. Second, because more specific time schedules would complicate the simulations unnecessarily and actually underestimate overheating concerns.

- The CO_2 graphs suggest different behaviours in different classrooms; in some cases, it seems that the windows are barely open during the teaching periods, and in others that they are opened during short breaks. This last practice is consistent with the behaviour observed during the visits to the schools and the conversations with the school buildings' teachers and managers. Therefore, this strategy is taken for the simulation of the base case scenarios. Naturally, different behaviours will have different impacts on the classrooms' overheating. Therefore, the subsequent simulations would try to find and suggest more adequate window opening strategies.

It is important to mention that it is assumed that the changes in CO_2 levels are due to window opening practices and not to changes in the number of pupils between classes.

- The CO_2 measurements showed that high levels of concentration are reached inside the classrooms, up to 1500 ppm. Although there are no compulsory requirements for air quality in German schools, these levels should be kept below 1000 ppm, as discussed by Camacho Montano et al. (2018). This situation also suggests that new ventilation strategies are needed in order to avoid detrimental effects on health or cognitive performance.

- Although uncommon, some graphs showed sharp peaks in the recorded indoor temperature measurements, which are usually not present in the simulation outputs. In the simulations, although the same high temperature levels are reached, they do not change so drastically as in some of the recorded rooms. This difference is less than 1°C, therefore it was not considered an issue that requires special attention.

- The adjustments made in the models to achieve the best match between the simulations and the recorded data included the time schedules of the classes, the window opening times, the area of the window opening and the number of pupils. In terms of the window openings, they were mainly simulated as bottom-hung windows with opening angles of 30°. In some cases, the best match was found opening only a few windows and in other cases allowing a couple of windows to be completely opened. Regarding the number of pupils, the school visits showed that, in general, there is available space for around 25 children. Nonetheless, in some of the simulations run for the calibration, the size of the class was reduced.

- The measured indoor temperatures revealed that high temperatures persist over the night-time. The data shows that, during the warm week, the indoor temperature at the start of classes is around 26°C - 28°C. In some case it can be observed that this temperature decreases a few degrees between around 07:00 – 08:00, suggesting that the windows are opened before the pupils arrive, but then the temperatures start rising again, reaching up to 32°C, even before the midday. These indoor temperatures start slowly decreasing after the occupied time, suggesting that the windows are left open for a while, but then remain steady at a high value during the whole night, which would mean that the windows are left completely closed.

Figure 60 shows the temperature patterns of one of the most critical classrooms in a 24-hour resolution. In this case, the classes start at 29°C, where the outdoor temperature is around 22°C, which implies that the indoor conditions might be quite uncomfortable. The indoor temperature rises to 32°C at 12:00 where the outdoor temperature still a few degrees lower. After the midday, the indoor temperatures slowly decrease by around 3°C but then remain steady until the next day.

This situation suggests that there might be a potential for night cooling but this is definitely not a strategy currently put in place in the schools.

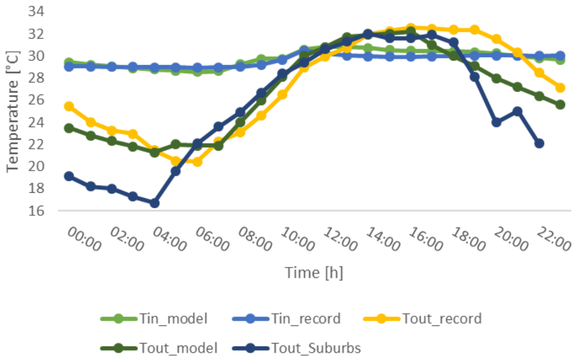


Figure 60: Comparison of indoor and outdoor temperatures in one day. Example of one classroom.
Where: Tin_model is the simulated indoor temperature; Tin_record is the recorded indoor temperature; Tout_model is the outdoor temperature of the weather files; Tout_record is the outdoor temperature recorded in the city (HGW, 2017) and Tout_suburbs is the outdoor temperature recorded in the suburbs (official temperature) (Meteoblue, 2017)

5.4 Energy consumption comparison

The energy consumption predictions of the models were compared with the data for energy consumption in the city records. This information however, cannot be used as a validation method, since the data for heating and electricity consumption correspond to school totals, and in many cases, a school has more than one building. Moreover, as mentioned before, the energy consumption is highly influenced by the users and buildings' managers and, therefore, the values in the data may not represent the building performance. Nevertheless, the comparison between the model's calculations and the reality gives an overview of the assumptions made and the actual performance of the building.

The city of Karlsruhe specifically keeps records of the energy consumption for the general heating and electricity consumption, but they are not further segregated by end use. On the other hand, the models of this study only take into account the energy consumption for heating, auxiliary energy, lighting, and basic equipment. Therefore, the predictions of energy consumption by the simulations are compared not only with the city records, but also with the consumption distribution found in the literature.

According to the Ministry of Environment, Climate and Energy of the Baden-Württemberg State, 90% of the energy in the schools in the state is used in heating, 9% in electricity and 1% in Domestic Hot Water. The major consumption in electricity is in lighting, 60%, followed by auxiliary energy, 15%, office and building devices with 12% and ventilation 7% (Ministry of Environment, Climate and Energy of Baden-Württemberg, 2016).

The results of this analysis are summarized in Table *9*. To compare the electricity consumption, the lighting and the equipment consumptions were calculated as 60% and 15% of the total electricity consumption found on the database. These values correspond to the average of the consumption of three years; from 2015 to 2017. The heating consumption predicted by the models is directly compared with the average consumption recorded in the city records, for the same three years.

From the results, it can be highlighted that, in general, the models predict heating consumptions similar to the current consumptions of these school buildings. The maximum difference between these two values is 15%. In terms of electricity consumption for lighting and equipment, however, there are some models that predict higher values than the actual consumption, as exemplified in buildings B2 and C2

In order to further analyse this data, it is required to benchmark the consumptions of these schools. It was stated in Section 4.2.1 that buildings in Germany have an electricity consumption of around 33 kW/m²a to 40 kW/m²a, and the non-residential buildings have a heating consumption of around 55 kW/m²a to 135 kW/m²a, depending on the construction year. Regarding school buildings, the Federal Ministry of Transport, Building and Urban Development claims that the average consumption of school buildings in Germany is 15 kW/m²a and 150 kW/m²a for electricity and heating respectively. Furthermore, the Heat Insulation Ordinance of 2007 (EnEV 2007) requires that school buildings have a maximum electricity consumption of 15 kW/m²a, regardless of the school's size, and a heating consumption of 150 kW/m²a for school buildings with a net area of ≤ 3500 m² and of 125 kW/m²a for school buildings with a net area of less than 3500m². The Heat Insulation Ordinance of 2009 (EnEV) requires the reduction of energy consumption, through building refurbishments, to 10 kW/m²a of electricity consumption, and 90 kW/m²a to 105 kW/m²a heating consumption, depending on the building size. (School of the Future, 2015).

With this data, it can be deduced that three of the school buildings selected for this study have an electricity consumption below the average national consumption and within the regulated values. Those are the schools A2 from 1873, B2 from 1963 and C2 from 1956. These last two school buildings are also in the building for which the models predict a higher consumption. It can be assumed that these schools are actively trying to reduce their electricity consumption, but further analysis is not possible at the moment, since there are no records of the consumption for the specific uses.

In terms of heating, the selected school buildings have better performance: only two school buildings have consumption levels above the reference value of 150 kW/m²a, which are school B2 from 1963 and C1 from 1956. For these school buildings, the models predict lower heating consumption. Therefore, it would be recommended to look further into why their consumptions are so high, especially in building C1, which is a small building, and as a primary school, most likely operates only during the mornings. However, further analysis of the energy consumption of these buildings is out of the scope of this study.

Table 9: Comparison of predicted vs. actual data on energy consumption in school buildings.

School ID		Electricity consumption [kWh/m^2]	Lighting consumption (60%) [kWh/m^2]	Equipment consumption (15%) [kWh/m^2]	Heating consumption [kWh/m^2]
A1	Actual	16,99	10,19	2,55	99,24
	Model	-	11,12	2,46	100,36
	Difference	-	-9%	3%	-1%
A2	Actual	10,60	6,36	1,59	96,26
	Model	-	5,71	1,81	89,99
	Difference	-	10%	-14%	7%
A3	Actual	18,61	11,17	2,79	99,66
	Model	-	10,91	2,13	105,54
	Difference	-	2%	24%	-6%
B1	Actual	19,16	11,50	2,87	138,21
	Model	-	11,00	3,29	151,55
	Difference	-	4%	-14’%0	-10%
B2	Actual	14,00	8,40	2,10	178,5
	Model	-	11,12	2,46	161
	Difference	-	-32%	-17%	10%
C1	Actual	24,53	14,72	3,68	167,78
	Model	-	13,53	3,48	142,3
	Difference	-	8%	5%	15%
C2	Actual	15,00	9,00	2,25	122
	Model	-	11,12	2,46	114,68
	Difference	-	-24%	-9%	6%
D1	Actual	42,50	25,50	6,38	95,37
	Model	-	26,18	5,49	92,95
	Difference	-	-3%	14%	3%

6 Investigated measures

6.1 Understanding overheating

The previous sections exposed the necessary prerequisites to carry out the study. First, an extensive literature review was undertaken to establish the state of the art. It was suggested that more comprehensive guidelines for designers to make decisions on refurbishment to reduce the risk of overheating was required, while other aspects require further investigation and quantification. The climatic characteristics of the region were then analysed in detail, comparing the historical records, represented in the weather files, some current records, the differences between the conditions of the city centre and the suburbs, and the predicted climate for the near future. Subsequently, a characterization of the buildings of the city was made, complementing the data of the city with theoretical information, and the buildings to study through the dynamic thermal simulations were chosen. The previous chapter explained which data are required to carry out the simulations, how they were obtained and how the models were calibrated. From now on, the theoretical analysis of overheating in classrooms will begin. For this, this chapter will explore why this condition is generated and based on that analysis, which potential low-invasive measures could be implemented.

Indoor discomfort during summer is caused by the interaction of several aspects that can be divided into three groups; the climatic conditions, the building design and construction, and the features related to the specific use. In terms of climate, two main factors influence discomfort; overheating due to the solar radiation, and the humidity. Although the earth is closer to the sun in winter than in summer, the steep angle of the sun during summer prevents its rays from spreading and increases the amount of energy at a single spot. In addition, the longer days increase the hours of warm temperatures. Humidity for its part has a more related impact on people´s comfort. The higher the humidity, the more water vapour the air contains, and warm air can hold more moisture than cooler air. As humidity starts to rise, the body sweat struggles to evaporate, as the air has already water vapour, which causes discomfort because the body is not able to cool itself down. The influence of the wind is also more related to comfort because the air movement increases the latent heat removal, as it increases the evaporation rate moisture off the skin.

Within the second group, one of the most influencing features is the thermal mass, which often used as the feature determining the absorption of heat by the building fabric. Its value in controlling overheating arises from the heat capacity of the materials to absorb a significant amount of heat with only a small increase in its own temperature. The effect of the thermal mass is a result of three properties: the thermal capacity of the material (the heat contained by a unit mass of the material when it increases in temperature by 1°C), the thermal conductivity (rate of heat flow in the material) and the density (mass per unit volume). These characteristics combine to produce a property known as the admittance, where a material with high admittance changes its temperature more slowly than the air temperature around it. This thermal mass acts as a reservoir for heat, which is then released to a colder space. Such heat needs to be removed; therefore, the air movement plays again a significant role as it speeds up the transfer process and replaces the warm air with fresher air if it is available. Because of this, the thermal mass can only reduce overheating when night ventilation can take place since the lower temperatures at this time induce the pressure difference required to promote that effect. (Orme and Palmer, 2003).

Glazing also influences the heat transfer and the greenhouse effect. Solar radiation passes through glass and heats internal surfaces, which re-radiate long wave infra-red radiation that cannot pass through glass (Designing Buildings, 2019). Therefore, besides revising the u-values it is important to look into the total energy and solar transmittance.

Another factor with high influence within this second group is the building orientation. In the northern hemisphere, the goal is to face the sun and obtain a maximum solar gain, as the higher energy consumption comes from heating the indoor spaces during winter. Therefore, the buildings main facade should face the south; or in other words, the interior spaces of the main use of the buildings must be located as far as possible on south-facing facades. In summer, although the sun is a higher angle, this façade is highly susceptible to overheat, therefore, shading should also be provided. The same applies for the east and west façades; the east façade receives solar radiation since early hours in the morning, and the west façade receives it in the afternoon, when the temperatures are highest during the day. This suggests that there is a trade-off between comfort and building performance throughout the year. This issue will be analysed later in this study.

The building layout and geometry also has an impact on indoor thermal comfort through several features. For instance, spaces with significant heights such as atria, or rooms with high floor-to-ceiling distances could help improving thermal comfort during the summer, as the warm air tends to rise. With a good provision of fresh air, it will provide comfort to people inside a room, and as it gets hot (either from the heat of people or equipment), it will begin to rise. If this exhaust air can leave the premises, it will give way to the entrance of more fresh air. In this sense, windows play a significant role as well as their dimensions and opening options could determine the amount of air entering o leaving a space.

Corridors or indoor yards are also features of the buildings’ layouts that could induce higher air movement. Courtyards, for instance, are one of the oldest plan forms for dwellings going back thousands of years and appearing as a distinctive form in many regions in the world. In this type of design, which is part of the so-called vernacular architecture, usually, the rooms around the courtyard have doors and large windows facing onto the yard and small windows high up on the back wall facing out onto the street. The rooftops provide shade, while the opened areas, which usually have plants or water ponds, provide fresh air to the indoor space, as they promote cross ventilation (Yang, Clements-Croome, 2012).

Heating, Ventilation and Air-Conditioning (HVAC) systems together with other equipment play a different role; while they contribute to the internal heat gains, mechanical ventilation and air-conditioning systems are measures that would actively control indoor conditions.

The third group comprises the characteristics related to the use of the building, that is, the number of people per unit of area, the occupation schedules, and the behaviours and ways of people interacting with the building.

6.2 Influencing factors at existing buildings

With this overview in mind, each of the factors influencing overheating are analysed for the school buildings of the city. As it was mentioned in Chapter 3, the effect of the climatic features in the city of Karlsruhe are investigated in this study through the simulations under the current weather conditions, represented by the Design Summer Year of 2010 (DSY2010) and the near future conditions represented by the Design Summer Year of 2035 (DSY2035).

In terms of the building design, in existing buildings, some measures can be implemented. Naturally, the orientation of the building cannot be changed, but, the rooms can be organized to take advantage of this feature; for instance, computer rooms, which already have high internal heat gains, could be located in the north facades instead of the south facades, where the solar heat gains are higher.

Regarding equipment, it is assumed that standard classrooms will not significantly change during the next years and will continue having as usually a laptop, a video projector and perhaps an intelligent screen, but it is expected that the energy consumption will not increase considerably. It is also assumed that lighting is not used during these months of the summer.

The measures that are most likely to change and/or be influenced are then the thermal mass, the ventilation strategy through windows opening, the shading devices, and the windows types. Figure 61 summarizes the factors that influence overheating in classrooms, where those mentioned in the boxes will be analysed in this investigation. It is worth mentioning that this study evaluates for now only passive measures, as it is desired to first, avoid significant increases on energy consumption, and second, take into consideration that some of the studied buildings have a historic character that should be preserved, and therefore, invasive refurbishments are not allowed.

The nature of the measures to be evaluated will be explained below, together with an estimate of their costs, which were consulted with various sources. However, it is important to mention that the prices given are general references, as the final offers are negotiated with the clients depending on the size of the projects and other factors.

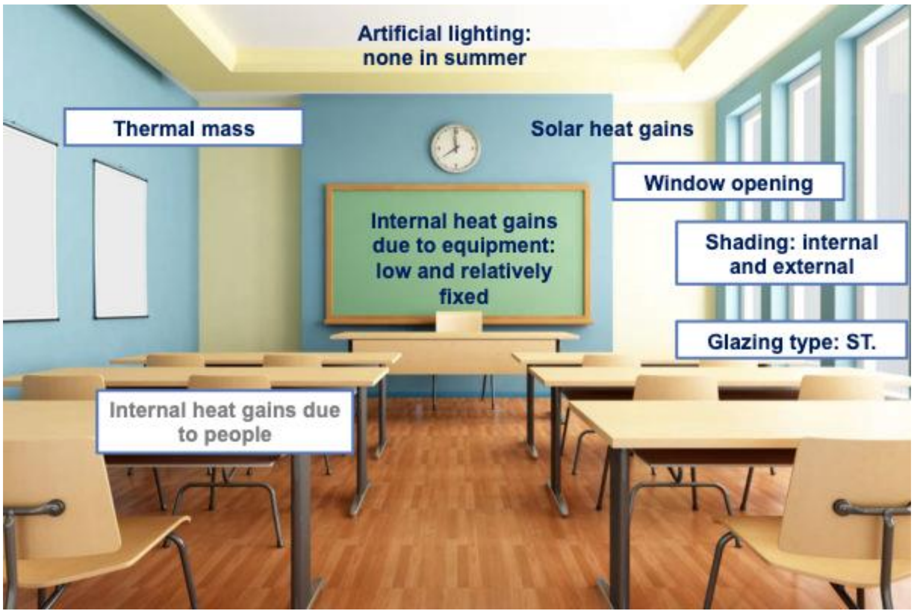


Figure 61: Factors that influence thermal comfort in classrooms.

The factors inside boxes will be analysed in this study in all the phases. The internal heat gains due to equipment and lighting will be considered with a fixed value and the internal heat gains will be studied under the sensitivity analysis but will not be treated as a potential refurbishment measure. Picture source Eschoolnews (2017).

6.3 Selected measures

6.3.1 Natural ventilation

The natural ventilation through side windows is the main strategy currently used to reduce the indoor temperature in the classrooms during the summer. The site visits showed that in general, the classrooms are ventilated usually only during the breaks. During classes, most of the windows remain closed, or are just tilted as shown in Figure 62, to avoid external noises, and assure children´s safety. The simulated alternatives are described in Table 10.

Table 10: Window opening strategies used for simulations

Base case	Tilted windows, opened 30° from the bottom only during class breaks (10 minutes).
Alternative 1	Tilted windows, opened 30° from the bottom only during class breaks (10 minutes) and during the whole night.
Alternative 2	Tilted windows, opened 30° from the bottom opened continuously as long as the outer temperature is lower than the inner.

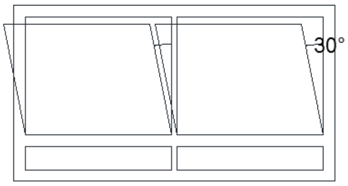


Figure 62: Representation of usual opening of windows in classrooms.

The alternative 2 can be achieved, either by automatic windows or by someone who minds this difference in temperatures. The price of automatic windows could vary from 600 to 1000 € per room, depending on the size and including rain sensors. A programmable interface could cost around 240 euros, a switch interface about 110 euros and a control pad about 180 euros. Depending on the window size, the costs are more than 1 000 euros. However, the purchase of the control technology is a one-time investment (Kaeferportal, 2018).

6.3.2 Shading devices

As it was mentioned in Section 5.1, the site visits showed that most of the schools have blinds located outside the windows but usually they do not have external fixed shading devices. The base case was simulated without blinds, and as an alternative, blinds were put in place with solar and visible transmittance of 0.6, and solar and visible reflectance of 0.2, which are characteristics of typical venetian blinds as those usually found in the classrooms. The operation was set up with a schedule profile covering 30% of the glazing from 09:00 to 11:00, and 60% of the glazing from 11:00 to 15:30 (time when the occupancy in classrooms is over).

Louvers and overhangs were studied as potential external shading devices alternatives, with projections of 0.5, 1.0 and 1.5 meters. The costs for these devices with these projections were estimated in 80 €/m^2, 90 €/m^2 and 105 €/m^2 for louvers and 65 €/m^2, 80 €/m^2 and 90 €/m^2 for overhangs (Eurolam, Alfitec, personal communications, July 2018).

6.3.3 Glazing

Windows play a very important role in the performance of a building. In the United States for example, approximately 35% of the energy lost in buildings is attributed to inefficient windows, and in some states, around 40% of a typical building's cooling requirements are due to solar heat gain through windows (U.S. Department of Energy, 2017)

Several types of windows and glazing technologies can improve the performance of a building. Thermal insulation windows make reference when at least one of the glass layers is coated. With the coating, the loss of heat can be significantly reduced. The coatings consist of precious metals or metal oxides. To avoid damage during use and cleaning, they are usually located in the space between the panes, usually at the outside of the inner pane of the insulating glass. Similarly, to this glazing, sun protection windows use ultra-thin low-E coatings made of precious metals. Even with them, rather high light transmittance can be achieved with simultaneous reduction of the total energy transmission. Unlike thermal glazing, where the coating is placed at the outside of the inner pane, in sunscreens, this is normally done at the inside of the outer pane of the insulating glass. In the case of high-quality glazing, a combination of sun protection coating and heat-insulating coating is frequently chosen today (Baunetz, 2019). The most recent technologies are now referenced as smart glass because they are capable of reacting to changing local conditions; features that are not feasible in the conventional windows. Smart glasses are typically classified into chromic glazing and liquid crystal.

When looking into glazing to reduce the risk of overheating, the emissivity is one of the main features to consider. The emissivity is the ability of a material to radiate energy. Standard clear glasses have an emittance of around 0.85 over the long-wave portion of the spectrum, meaning that it emits 85% of the energy possible for an object at its temperature. It also means that 85% of the long-wave radiation striking the surface of the glass is absorbed and only 15% is reflected. By comparison, low-E glass coatings can have an emittance as low as 0.05. Such glazing would emit only 4% of the energy possible at its temperature, and thus reflect 95% of the incident long-wave, infrared radiation. Window manufacturers' product information may not list emittance ratings. Rather, the effect of the low-E coating is incorporated into the U-factor for the unit or glazing assembly. The solar reflectance of low-E coatings can be manipulated to include specific parts of the visible and infrared spectrum. This is the origin of the term spectrally selective coatings, which selects specific portions of the energy spectrum, so that desirable wavelengths of energy are transmitted, and others specifically reflected.

A glazing material can then be designed to optimize energy flows for solar heating, daylighting, and cooling depending on the season or the specific requirement. The low emissivity of *low-e* is a glass treated with an invisible metallic coating that reflects (or absorbs) heat and light by reducing the amount of light that enters in a room without blocking the visible light. However, it slightly hazes the windows permanently and there is no control over it (Efficient Windows Collaborative, 2018). To overcome this limitation the chromic glasses were developed. These glasses are either thermochromic or electrochromic, where the thermochromic windows change their tint level based on surface temperature, so it continuously adapts tint to sunlight to manage heat. They can be installed the same as traditional windows since no power supply is required, but they cannot be manually controlled and they add weight to the structure (Efficient Windows Collaborative, 2019). The electrochromic windows are coated with a layer of metal oxide inside dual panes of glass. The glass turns darker as a small electrical voltage is applied to the oxide causes electrically charged lithium ions to move between the layers in the glass and hit the electrochromic material. The tinting process can take up to 30 minutes in some applications, depending on the glass size, but the voltage needed for tinting is minimal: it is estimated that 100 such windows use about as much energy as a single 75-watt light bulb over the same period. Recent advances in electrochromic materials have led to the development of reflective hydrides, which become reflective rather than absorbing, and thus switch states between transparent and mirror-like. In contrast to electrochromic windows, in the liquid crystal windows the tinting process is very fast, usually just seconds, but they require a continuous voltage current when the glass is in a transparent or translucent state; from 3W/m^2 to 10W/m^2. The degree of transparency is controlled by the applied voltage; at no voltage, the liquid crystal glass is translucent with a slight grey or blue tint.

To reduce overheating in indoor spaces, the reflective characteristics of sun protection glazing are recommended. For simulation purposes, this study uses two types of this kind of glazing, with different solar and light transmittance coefficients. Additionally, one electrochromic glazing is analysed, as summarized in Table 11. It is worth mentioning, that the electrochromic glazing is relatively new in the German market and therefore their prices are considerably high in comparison to traditional glazing. Their prices could vary from 600 €/m² to 2500 €/m² (Fensterversand, 2018).

Table 11: Characteristics of double glazing used in the simulations.

Glazing type	Total solar transmission (ST)	Light transmission.	U-value [W/m^{2}K]	Costs [€/m^2] *
Clear glazing (Base Case)	0.70	0.78	2.7	200
Sun protection glass - classic	0.47	0.60	1.3	270
Sun protection glass - silver	0.32	0.50	1.2	320
Electrochromic	0.4/0.07	0.60/0.05	1.1	600

* The costs are taking from the following references: Saint-Gobain (2018), (Energieheld, personal communication, July 2018), (Bewertet, personal communication, November 2018)

6.3.4 Phase Change Materials

In addition to heat dissipation and solar and heat protection, the heat modulation is another passive measure used in buildings. Through Phase Change Materials (PCMs) the thermal energy can be stored and then released at a shifted period. When using PCMs into the building walls, the latent heat is absorbed in the panels at a constant temperature, and then released as the temperature decreases. Since this process usually happens during the night, ventilation during the period is required so that the panels can change phase completely.

The PCMs are classified into three types: organic, inorganic and eutectic, where the organic paraffin is one of the most common elements used in wall applications. Four mean physical characteristics should be analysed to guarantee that the PCMs achieve a suitable freeze/melt cycle: a large change in enthalpy, large specific heat capacity, large thermal conductivity and little sub-cooling (Akeiber H., et al. 2016). For this study, plates with a specific heat of 1970 J/kgK where chosen. The costs were estimated at approximately 100 €/m2 (Trockenbau Spezialist, 2018) (Bauer-Ewert B., 2010) (Lehm Bau Shop, 2018).

7 Analysis of overheating

7.1 Overheating at base case scenarios

The on-site measurements presented in Chapter 5 gave an insight into the current thermal conditions of the classrooms. The data showed that the indoor temperature can reach as high as 32°C, which might suggest that overheating is already occurring in the schools.

With the models calibrated and standardized to the same occupancy, the first simulations were run to analyse rooms in different locations and find the warmest ones. The analysis included the comparison between facades and storeys. Figure 63 show the example of the temperature difference between a room in the south façade and a room in the north façade; in this case approximately 3°C. Figure 64 shows the slight differences between the indoor temperatures of three classrooms in the middle of the south facing façade and located on three different storeys.

The different colours of the rooms in the figures represent the different types of spaces in the schools, as described in Chapter 5. The subsequent analyses will be carried out for the standard classrooms.

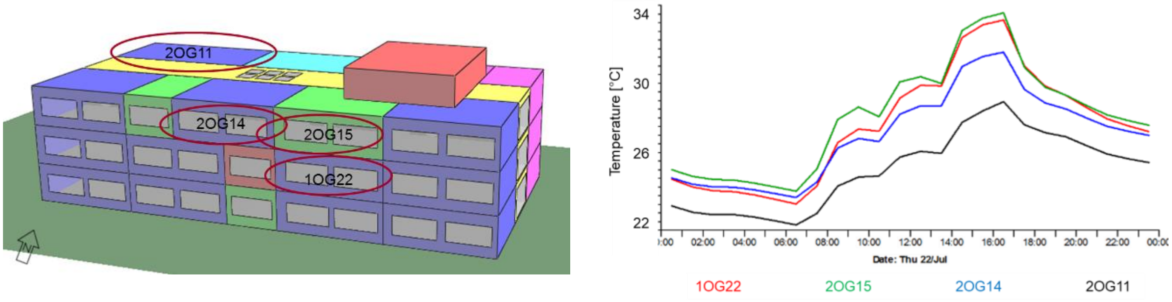


Figure 63: Comparison of indoor daily temperatures of four different classrooms in school building B1.

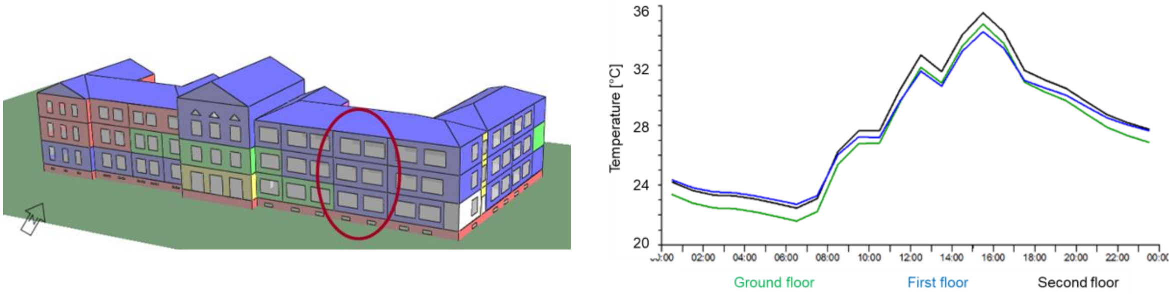
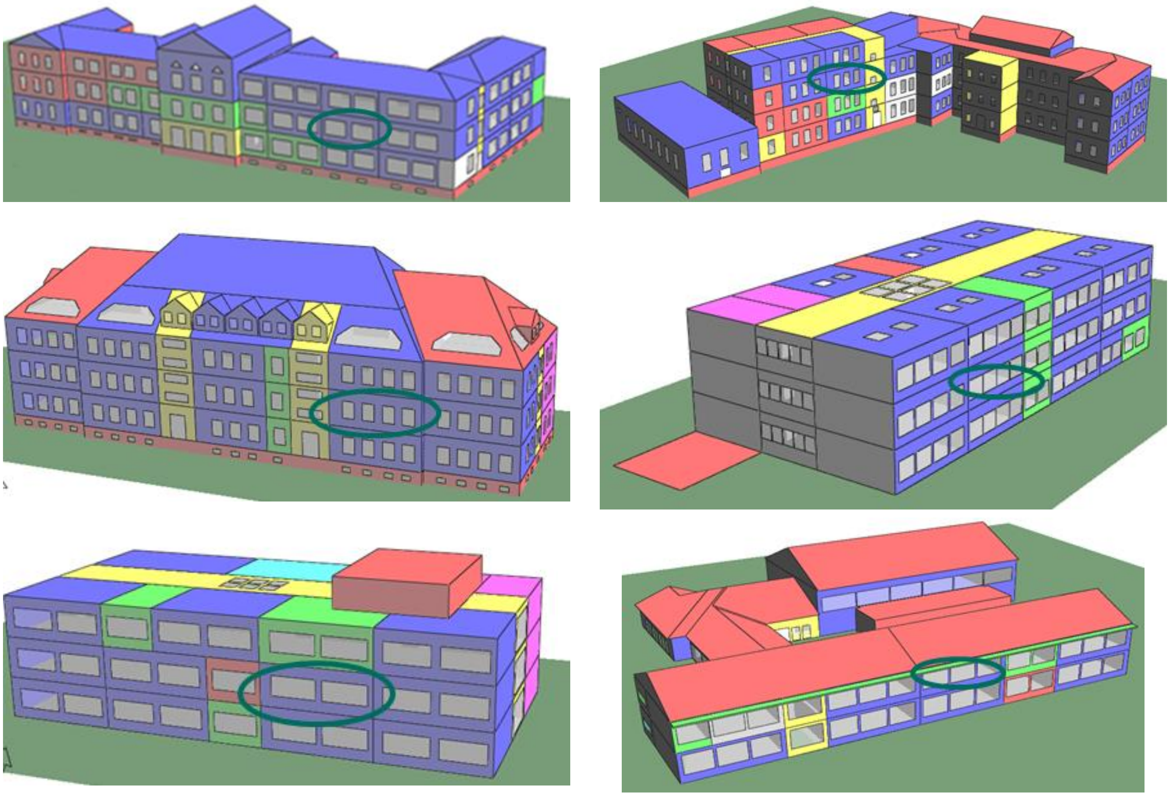


Figure 64: Comparison of indoor daily temperatures of three classrooms located on different storeys.

Given that it was assumed that the standard classrooms have the same internal heat gains (in amount and timing), only one of the south façade rooms was selected to conduct the subsequent simulations, as one that represents the most critical situation. However, a room on the upper floor was not always chosen, since, sometimes, given the design of the buildings, these may represent unusual situations. For example, the school buildings A3 and B1 have skylights, and therefore the solar heat gains are higher and do not represent the situation of most classrooms. Figure 65 shows the selected classroom for each school building.



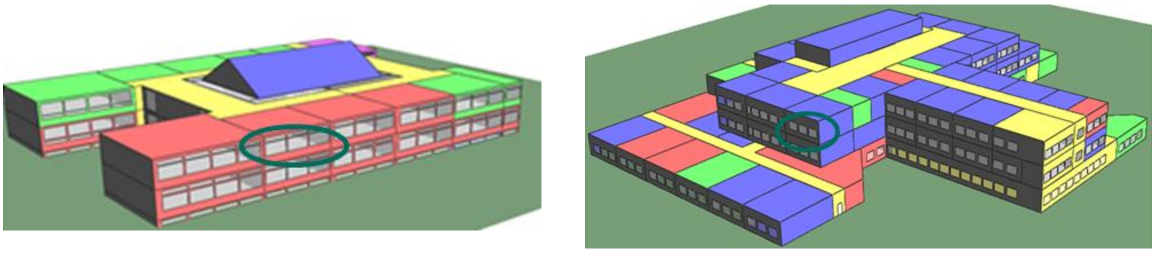


Figure 65: Selection of representative classrooms in each building. One of the warmest classrooms in the south façade was chosen to conduct the subsequent simulations.

The selection of a classroom from each school building to simulate was the final step, allowing the base case scenarios to be established, first for the present weather conditions, represented by the DSY2010, and second for the near-future conditions, represented by the DSY2035. The simulations were carried out for a period of one month, and it was assumed that there were no school holidays during this period. Therefore, the classrooms would be occupied for a total of 154 hours.

The objective was to find the number of discomfort hours according to the standard EN 15251. This standard presents a set of acceptable indoor operating temperatures, based on the external running mean temperature. The standard divides the temperatures into three categories, as shown in Figure 66, where Category I corresponds to a high level of occupants' expectation and is recommended for sensitive and fragile persons. Category II corresponds to a normal level of expectations and is usually recommended for new buildings, and Category III corresponds to a moderate level of expectation and may be used for existing buildings (EN 15251, 2007). The standard recommends that the reference temperatures are not exceeded in more than 5% of the hours when the building is occupied.

Some studies suggest that school pupils have a better cognitive performance at lower temperatures, which implies that Category I would be more suitable for the analysis (Chatzidiakou et al., 2014). The EN 15251 also recommends Category I for sensitive subjects; however, for existing buildings, it recommends using the Category III. Taking into account these two criteria and the fact that the analysed buildings have different performances due to their wide range of construction periods and characteristics, it was decided to use Category II as the reference target. It is also important to mention that this model corresponds to an adaptive comfort model, which is only valid for non-air-conditioned buildings.

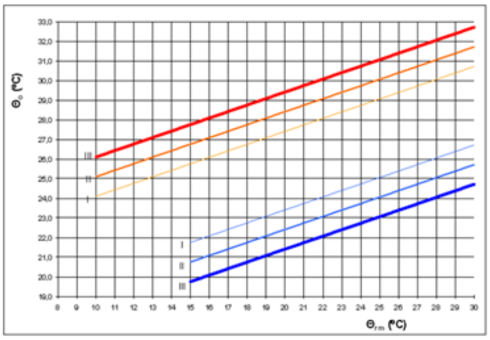


Figure 66: Acceptable indoor temperatures according to standard EN 15251. The thick lines represent the limits for Category III, the medium lines represent the limits for Category II, and the think lines represent the limits of Category I.

The upper acceptable limit of Category II is represented by Equation 3.

Equation 3:

$$T_{in} = 0.33 \times T_m + 18.8 + 3$$

Where Tin is the limit value of indoor operative temperature in °C, and Tm Is the outdoor running mean temperature in °C.

The results, as summarized Table 12, suggest that under the DSY2010, the school buildings in Group A have around 18% of discomfort hours, while this rises to 22% for Group B and 25% for Group C and Group D. If no measures are implemented in the schools, by 2035 the percentage of overheating could rise to approximately 27%, 31%, and 37% respectively, which means a rise in overheating of about 10%.

Table 12: Discomfort hours at base case scenarios.

School ID	Construction year	Discomfort hours 2010	% occupied time	Discomfort hours 2035	% occupied time
A1	1873	30	19%	43	28%
A2	1873	28	18%	41	27%
A3	1914	28	18%	40	26%
B1	1961	35	23%	48	31%
B2	1963	33	21%	46	30%
C1	1956	37	24%	54	35%
C2	1956	38	25%	56	36%
D1	1977	42	27%	61	40%

These figures suggest that the situation is already critical, and that measures are required to significantly reduce overheating, especially considering that pupils have been found to prefer temperatures between 2 °C and 4 °C lower than those preferred by adults (Teli et al., 2012).

Taking into account that the refurbishment plans cover various years and, furthermore, that renovations expect to increase the life span of buildings by 20 years or more, the following simulations, which seek to improve the thermal environment of the classrooms, are undertaken using the DSY2035 as a base.

7.2 Sensitivity analysis - Background

The building energy models used are created through simulation software packages that take the building's physical and operational characteristics as inputs and use the equations of physical phenomena and climate information to calculate the thermodynamic changes and, with these, the envelope's response, the internal environmental conditions, the systems' loads, and the energy consumption. Since there are several parameters to be evaluated, sensitivity analyses (SA) are used to observe the system response following a modification in the design parameters, thus identifying those, which have a significant influence on the results.

The methods for the analysis are often divided into two groups: local and global, where both have been used in the analysis of building performance, including the evaluation of thermal comfort and energy consumption (Gagnon et al., 2018; Lam et al., 2009). Local Sensitivity Analysis (LSA) focuses on the effects of the inputs around a steady point: therefore, it relies on an OAT methodology (one-parameter-at-a-time). Global Sensitivity Analysis (GSA) evaluates the effect of an input by varying other input parameters at the same time. Consequently, the global approaches are highly computationally demanding, but provide a broader view of the parameters' effects.

GSA includes regression methods, screening-based, variance-based and meta-modelling approaches, as summarized by Tian (2013). It uses a probabilistic framework where the effect of the range and shape of input´s probability density function (PDF) are incorporated. The assignment of an individual PDF for each input parameter is an important and often difficult task. However, in most cases, this function can be more easily identified if the range of variation is reduced (Heiselberg et al., 2009).

Kristensen and Petersen (2016) compared different sensitivity analysis methods and found that both local and global approaches were able to identify the same cluster of the most sensitive input parameters in building energy models, but the ranking differed. They concluded that the suitability of the chosen method depends on the purpose of the sensitivity analysis: if it is an initial analysis, LSA provides the most significant parameters to evaluate in the model, but if the requirement is to prioritize measures, then a GSA should be conducted.

Based on this overview, the work reported in this chapter seeks to test two SA methods to compare the results and try to identify key design parameters to reduce overheating in the selected classrooms. It was decided to undertake a Differential Sensitivity Analysis (DSA) as a local approach reference, since it allows the direct effect of one parameter to be explored. The Taguchi Method together with the Analysis of Variance (ANOVA) was chosen as the alternative global approach, as it allows the effects on overheating to be evaluated by changing more than one parameter at a time, within a reasonable computational time cost.

To conduct a Differential Sensitivity Analysis, dimensional or non-dimensional Influence Coefficients (IC) can be calculated. It is recommended to use dimensional coefficients when the inputs belong to the same general measure, for instance, when comparing the effect of the length of overhangs and louvres as external shading devices. In such case, the dimensions refer to the same characteristic and therefore they can be easily compared. This study evaluates different parameters; therefore, non-dimensional coefficients are more suitable. These coefficients are calculated by looking for a point of elasticity, usually the base case scenario, as suggested by Spitler et al. (1989), following Equation 4:

Equation 4*:*

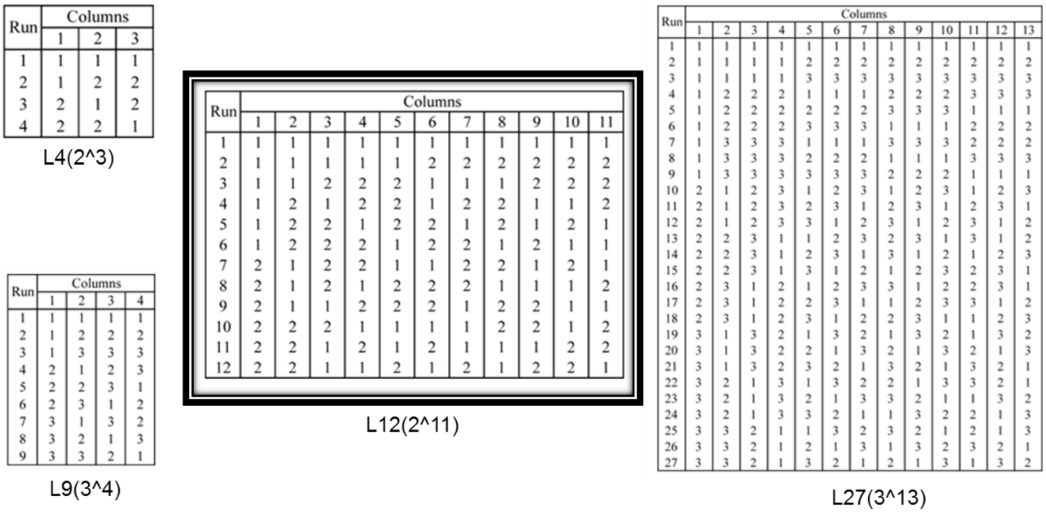
$$IC = \frac{OP - OP_{BC}}{OP_{BC}} \div \frac{IP - IP_{BC}}{IP_{BC}}$$

where, OP is the output, IP is the input and BC the base case. The mean and standard deviations of the ICs are also calculated to establish the relative sensitivity of the parameters. The output corresponds to number of discomfort hours caused by overheating, which is evaluated, as previously mentioned, under the standard EN 15251:2007.

The Taguchi Method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. It was developed by Genichi Taguchi in the 1990s as a statistical tool to improve the quality of manufactured goods and, since then, it has been applied to several fields, including engineering and biotechnology, amongst others (Karna and Sahai, 2012). The parameter design of the Taguchi Method includes the following steps:

- Identification of the problem and the main function to evaluate;
- Determination of the parameters and their number of levels (ranges to analyse);
- Selection and assignment of the appropriate orthogonal array;
- Execution of experiments / simulations;
- Analysis of the results using the S/N ration and ANOVA;
- Determination of parameter's effect and classification.

In this case, the objective function, as before, is to minimize the number of discomfort hours due to overheating. The selection of the suitable orthogonal array depends on the number of attributes and their levels, i.e. the number of building parameters and their possible ranges. For this study, two levels were considered suitable, in order to take into account the most likely value (base-case scenario) and an improvement. The orthogonal arrays are fixed, as shown in Figure 67, where L4, L9, L12 and L27 are the most common matrices. L4 is used to analyse up to three parameters, with two levels, L9 up to four parameters, with three levels, L12 up to eleven parameters, with two levels and L27 up to thirteen parameters, with three levels.



Run	Columns		
	1	2	3
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

L4(2^3)

Run	Columns			
	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

L9(3^4)

Run	Columns										
	1	2	3	4	5	6	7	8	9	10	11
1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	2	2	2	2	2	2
3	1	1	2	2	2	1	1	1	2	2	2
4	1	2	1	2	2	1	2	2	1	1	2
5	1	2	2	1	2	2	1	2	1	2	1
6	1	2	2	2	1	2	2	1	2	1	1
7	2	1	2	2	1	1	2	2	1	2	1
8	2	1	2	1	2	2	2	1	1	1	2
9	2	1	1	2	2	2	1	2	2	1	1
10	2	2	2	1	1	1	1	2	2	1	2
11	2	2	1	2	1	2	1	1	1	2	2
12	2	2	1	1	2	1	2	1	2	2	1

L12(2^11)

Run	Columns												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

L27(3^13)

Figure 67: Most common arrays of the Taguchi Method.

The experimental results are then transformed into a signal-to-noise (S/N) ratio. Taguchi recommends the use of the S/N ratio to measure the quality characteristics deviating from the desired values. Usually, there are three categories of quality in the analysis of the S/N ratio, i.e. the-lower-the-better, the-higher-the-better, and the nominal-the-better (Yang and Tarng, 1998). In this case, the-lower-the-better was selected, as the objective function is to minimize overheating. With this value, the distribution effect and the rankings were then designated. The ANOVA was then performed to observe the effect of the parameters in percentage, and with it, their classification as dominant, significant or neutral.

The base case scenarios and the changes of the selected measures to test these two methods are described as follows:

- Internal heat gains: in the summer, the pupils are responsible for the main internal heat gains. The base-cases were simulated with 22 pupils and the perturbation with 28 pupils.

- Ventilation: the base-case scenarios were simulated as previously described, with windows opening only during the breaks. An ideal ventilation strategy in terms of heat exchange between the indoor and outdoor conditions in the summer would be to open the windows as long as the outdoor temperature is lower that indoors. However, in order to calculate an IC, it is required to have a specific numerical value, and this is the point where the first limitation of the ICs is found.

  It was thus decided to analyse the effect of natural ventilation through the effect of different opening areas. For this purpose, the windows were open continuously during the class period and the opening areas varied from 30% to 60% (with side opening). Changing the area of the window opening naturally is different from a tempereature dependent ventilation strategy, but unfurunately is the avaialbe option to analyse the strategy under ICs. For the Taguchi Method, the second option was simulated with continuous ventilation.

- Shading: to calculate the ICs, as these require a numerical value different from zero, the base case was simulated with a louvre 0.5m in length and the second case with one 1.0m long. For the Taguchi Method, the base cases were simulated without external shading devices, as this is the usual practice in the schools.

- Glazing: the base cases were simulated with clear glazing (Solar transmittance ST=0.7) and the perturbation was simulated with upgraded windows with solar protection (ST=0.3).

- Phase Change Materials - PCM: the base cases were simulated with the partitions described in section 5.1, with heavyweight partitions in the school buildings of Group A and lightweight partitions in the other groups. The second case was simulated with PCMs. In this case, to calculate the IC, the input value corresponded to the change in the heat capacity, which changed in general by approximately 10 units; from around 22 kJ/m²K to 35 kJ/m²K.

7.3 Sensitivity analysis results

7.3.1 Results of Influence Coefficients (ICs)

The analysed parameters have different natures: the number of pupils refers to internal heat gains, external shading devices and glazing seek to reduce the solar heat gains, while infiltration and the ventilation strategy refer to the air movement in the space and also heat transfer. Because of these differences, a direct comparison to rank the significance of the parameters through ICs is not recommended. However, the ICs give a view of the overall effect of the measures in reducing the number of discomfort hours; the larger the IC, the more important the design parameter would be, as it tends to exert greater influence on the indoor temperature. The negative sign indicates that there is an inverse linear relationship with the output; for instance, the higher the infiltration, the lower the overheating. Table 13 and Figure 68 show the calculated ICs and the mean and standard deviation for each measure.

From these results, it is interesting to see that, in terms of the ICs, the highest values in all the types of school building are achieved by the natural ventilation strategy and the change in the solar transmittance of the windows. However, the standard deviation for the ICs of natural ventilation is quite high, above 0.15, which suggests that the difference between values is above 15% and the results require further analysis. The only strategies with standard deviations lower than this threshold are the external shading and the solar transmittance of windows. To understand better what these coefficients mean, each parameter is now analysed individually.

Table 13: ICs for passive measures in the selected school buildings

School ID	Class size	Natural ventilation	ST windows	External shading	PCM
A1	0,479	-0,875	0,868	-0,390	0,130
A2	0,966	-0,795	0,900	-0,431	0,148
A3	0,892	-0,754	0,885	-0,341	0,138
B1	0,350	-0,697	0,631	-0,361	0,451
B2	0,389	-0,681	0,617	-0,278	0,292
C1	0,488	-0,750	0,877	-0,427	0,537
C2	0,562	-0,814	0,872	-0,564	0,497
D1	0,727	-0,362	0,758	-0,216	0,121
Mean	0,607	-0,716	0,801	-0,376	0,289
Standard deviation	0,230	0,156	0,118	0,105	0,180

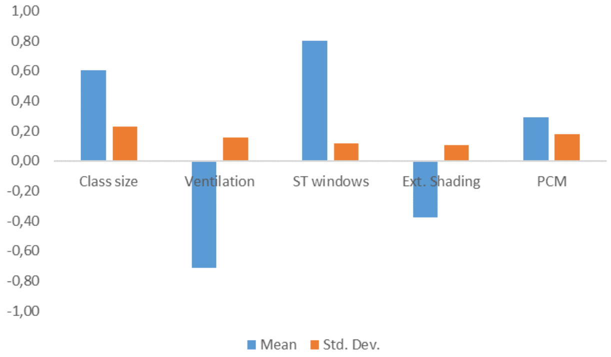


Figure 68: Mean and standard deviation of calculated Influence Coefficient

- Class size: one of the main challenges of designing school buildings is that they have a high occupancy density; usually higher than other types such as office buildings. It was observed during the school visits that, although some classrooms have space available for 28 pupils, usually a class group has around 24 pupils and the almost never less than 20. With 20 pupils, the internal heat gains would be around 1800 W and with 28 pupils around 2700 W per room, which means that the effect should be significant. A change in the class size, however, cannot be considered as a strategy, since the schools have little flexibility with regard to the number of pupils per class.

The calculated mean IC for all the schools is 0.6, which, although is not the highest, is still significant. The calculation of the ICs suggests that two other strategies would have a higher effect on reducing overheating. The effect of the internal heat gains will be scrutinized in the parametric analysis.

- Natural ventilation: according to the ICs, natural ventilation is the one of the two parameters that help the most to reduce overheating in classrooms: in all of the school buildings, except for the lightweight building (D1), the value is above 0.68.

However, as mentioned above, the ICs for this strategy only give an idea of the effect of different opening areas. It is expected that larger areas allow more fresh air and therefore reduce overheating, but in practice, this strategy is more complex than that. The effect of natural ventilation on the reduction of overheating depends on the outdoor temperature, the wind pressure, speed, and direction, the layout of the windows, and also the buoyancy effect. Although the software considers all these properties, the ICs limit a comprehensive evaluation of ventilation strategies, as the required input is a single numerical value. Since it was decided to use the opening area, the opening schedule had to be standardized to the class periods, and this is not an ideal strategy to reduce overheating, since in the afternoon the outdoor temperatures could be higher that the indoor temperatures. For this reason, it is considered that the overall effect of the natural ventilation strategies through window opening should be evaluated using other methods in addition to the ICs.

- Solar transmittance of windows: according to the ICs, this strategy helps the most to reduce overheating in the schools. Furthermore, the standard deviation for all the buildings and amongst the groups is quite low. The reason for that is that the relationship between the solar transmittance and the reduction in overheating is relatively linear in the range of the most common glazing types (solar transmittances between 0.7 and 0.3) for all the school buildings, as suggested by Figure 69.

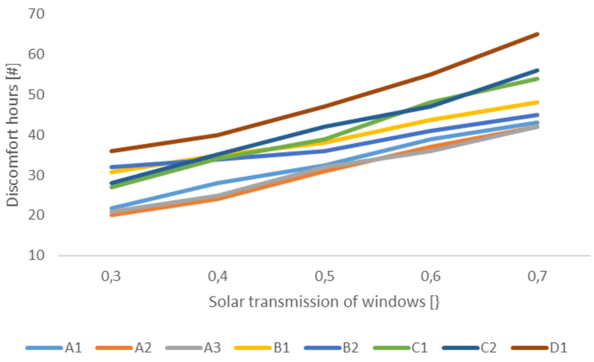


Figure 69: Number of discomfort hours at different solar transmittances of windows in the selected school buildings.

Such a relationship enables a more extensive use of the IC. For instance, taking the calculated mean IC is possible to analyse the effect of different values of solar transmittance, solving for the output value of Equation 4.

To illustrate an example, the following values are used in Equation 4:

- IC=0.8, which is the mean value for all the schools.

- OP_{BC} is the number of overheating hours of a school in the month of the simulation, for example 41, which is the average number of overheating hours in a month in 2035 of the schools from Group A.
- IP_{BC} is the solar transmittance of the base case, which was established as 0.7.
- IP is the solar transmittance value of a window that needs to be evaluated, for instance 0.5.
- This would give a result of 32 hours of overheating, and with windows with a solar transmittance of 0.3; the number of hours of overheating would be reduced to 22, keeping all the other parameters at the base-values.

This example illustrates how the ICs can be used in a faster and easier way. In order to conduct the initial analysis, this tool allows the effect of strategies to be compared when they have been previously calculated through the thermodynamic simulations and when there is confidence in the results and little difference between values of the same nature. Then, if this information is combined with the costs, the designers would then have an overview of the implications of the parameter.

In this case, the effect of glazing types on the reduction of overheating was compared, but only based on their solar transmittance. It is important to keep in mind that different glazing types also differ in other characteristics, and thus the outputs may be different.

- External shading: the behaviour of the external shading is similar to the behaviour found with the change of the solar transmittance of windows. The standard deviation of the ICs at all the schools is low, 0.1, which could allow a similar analysis to be conducted as in the previous example, to establish what would be the overheating reduction when the length of a louvre is extended. For instance, with a mean IC of 0.38, and a base-case of 46 overheating hours in one month, the implementation of louvres of 1.0m or 1.5m would reduce this number of overheating hours to 28 and 20 hours respectively.

  It is important to mention that the ICs are also quite sensitive to the selection of the point of elasticity. In this study this point was taken as the base-cases, as the most common scenarios. However, if this point changes, the outcomes could be quite different, which is a further limitation.

- PCMs: for the effect of the phase change materials on the reduction of overheating ICs of around 0.3 were produced, with a standard deviation of almost 0.2. This would mean that the effect is not particularly strong and is different between one building and another. Therefore, this effect will be scrutinized in the parametric analysis.

7.3.2 Results of the Taguchi Method and ANOVA

Once the first sensitivity analysis was carried out, the Taguchi Method and ANOVA were implemented to rank the parameters under a global view. The advantage of the Taguchi Method is that it allows the effect of mixing parameters to be analysed without the need to use all the possible combinations. With the orthogonal arrays that have been widely used in many engineering applications, as previously mentioned, it was possible to mix the five parameters of interest with only 11 simulations per school building[5].

Table 14 shows first the resulting orthogonal array, with the two different options used to evaluate each parameter, and second the predicted overheating hours for the eight schools. Table 15 shows the distribution of the effect of each parameter (as a percentage) and its consequent classification as dominant (D), significant (S) or neutral (N), according to the results of the ANOVA.

Table 14: Number of discomfort hours due to overheating combining different parameters using the Taguchi Method.

Simulation	Standard Orthogonal Array					Overheating hours by school [%]							
/ Parameter	Class size	Ventilation	ST windows	External shading	PCM	A1	A2	A3	B1	B2	C1	C2	D1
1	22	Just breaks	0,3	No	No	9	7	6	16	14	17	18	25
2	22	Just breaks	0,7	Yes	Yes	11	8	7	17	14	19	20	25
3	22	Continuous	0,7	Yes	No	5	5	5	12	8	13	17	22
4	22	Continuous	0,7	No	Yes	7	6	6	13	10	15	18	24
5	22	Continuous	0,3	Yes	Yes	3	3	4	8	6	12	11	24
6	26	Just breaks	0,3	Yes	Yes	9	7	7	15	12	16	17	25
7	26	Just breaks	0,7	No	Yes	13	11	9	18	17	22	23	29
8	26	Just breaks	0,7	Yes	No	12	9	8	19	17	21	21	29
9	26	Continuous	0,3	No	Yes	4	4	5	10	7	13	17	25
10	26	Continuous	0,3	Yes	No	4	3	4	8	6	12	12	23
11	26	Continuous	0,7	No	No	7	6	6	14	10	14	17	23

Table 15: Distribution of parameter effect in the selected school buildings

School ID	Class size		Natural ventilation		ST windows		External shading		PCM	
	%	C	%	C	%	C	%	C	%	C
A1	21	S	42	D	12	N	25	S	0	N
A2	15	N	45	D	13	N	27	S	0	N
A3	17	S	47	D	15	N	20	S	1	N
B1	22	S	35	D	11	N	29	D	3	N
B2	26	S	34	D	20	S	18	S	2	N
C1	18	S	24	D	24	S	22	S	12	N
C2	19	S	20	S	25	S	16	S	20	S
D1	11	N	17	S	17	S	20	S	35	D

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[5] The L12 arrangement suggests 12 simulations, but as can be seen in Figure 67, if there are only 5 parameters (that would be up to column 5). The first and the second runs (simulations) are exactly the same; therefore, by the end only 11 simulations have been undertaken.

From the previous results, some aspects should be highlighted:

- Under the global perspective, the ranking of the parameters differs. The Taguchi Method and ANOVA suggest that the natural ventilation strategy is the parameter with the highest potential to reduce overheating, as it is classified as "dominant" in most of the schools. Class size and external shading come next, with similar distributions, although the latter seems to be more significant. This observation is also confirmed by the overheating results shown in Table 14, where it can be noticed that a lower number of discomfort hours is in general achieved when there is continuous ventilation, followed by external shading.

- This method suggests that lower solar transmittance of the windows and the use of PCMs will have a more significant effect in the lightweight buildings than in the others.

7.3.3 Conclusions of the sensitivity analysis

The sensitivity analysis is a tool used to find the most significant parameters inside a model or in an experiment and, when possible, rank them. In this study two methods were tested to see if it was possible to obtain guidance on the most appropriate refurbishment methods to reduce overheating in school buildings, especially in classrooms, considering the predicted changes in the climate of the city.

The results of both the methods suggest that the ventilation strategy is a priority. However, the ranking of the influence of the parameters and their effect differs from the local and global perspectives. Furthermore, it does not provide a clear guidance on the most appropriate measures for the different school types. When the number of variables to study is high, the calculation of ICs or the classification through the combination of the Taguchi Method with ANOVA can be quite useful to select the most influential cluster. Nevertheless, when the variables are few, as in this case, their influence is not clear enough. Therefore, further analyses have to be made.

Both methods have advantages and limitations. On one hand, establishing ICs allows a fast overview of the parameters to be obtained, but its use is quite limited for several reasons: the need to specify numerical values for the inputs, their dependence on the point of elasticity, and the need to relate to the same physical characteristics, i.e. the same units, in order to deliver more appropriate comparisons. Therefore, this tool should be used carefully, and it is advised that extrapolations should not be made. Nonetheless, the use of ICs could be a valuable tool for designers when the correlation is linear and the ICs allow the results of previously calculated ICs to be obtained without requiring simulations to be conducted again, as was shown to be the case for the relationship between overheating and some ranges of the length of external shading devices and the solar transmittance of windows.

On the other hand, an intermediate method between the local and the full global approaches, allows more appropriate comparisons between the different measures. This is firstly because it does not limit the nature and the values of the parameters, and secondly because it combines changes in the measures at the same time. For instance, with this method it was possible to see that the lower solar transmittance of the windows and the use of PCMs play a more important role in the lightweight buildings.

However, this tool is still limited and does not provide specific guidance on potential measures to refurbish the schools. At this point, the simulations are only considering overheating as the objective function, but the costs of such measures are also a decisive feature when selecting the appropriate refurbishment plans. Furthermore, for each measure there are more options that can be analysed, for instance more ventilation strategies or glazing types where both the solar transmittance and the u-values change. For these reasons, the following step involves undertaking an optimization process that allows such aspects to be analysed as well.

7.4 Optimization process

Given that the sensitivity analyses did not provide clear guidelines on the most appropriate measures to reduce overheating in classrooms according to the different building types, optimization was then chosen as further method to evaluate passive measures. Optimization also allows another important aspect to be included when choosing refurbishment measures: costs.

The optimization approaches are in general classified into two groups: conventional gradient-based methods and gradient-free direct methods, where the latter are more suitable for building studies since they enable the evaluation of both linear and nonlinear functions to be carried out (Magnier and Haghighat, 2010). The most well-known and widely used gradient-free approach is the Genetic Algorithm, developed by Holland in the 1970s, inspired by Darwin’s theory of natural selection.

Genetic Algorithms are based on stochastic approaches and their main advantage is that a large number of solutions (population) can be used in each iteration, instead of improving one single solution. The multi-objective algorithm chosen for this research was the NSGA-II, developed by Deb (2001). This algorithm has been successfully employed in several studies regarding building optimization (Chantrelle et al., 2011; Magnier & Haghighat, 2010; Son & Kim, 2018). Multi-objective algorithms allow more than one objective function to be optimized. This approach is based on Pareto fronts, or Pareto-efficient allocations, where a group of variables that perform better than the others is identified. Usually, in multi-objective optimization problems, a single solution is not able to simultaneously maximize (or seek for minimums depending on the case) all the objective functions, and the goal of a multi-objective optimization problem may consist in finding those variants that are better than others with regard to, at least, one objective function and, at the same time, not worse concerning all the remaining objective functions. Such variants are called non-dominant variants and belong to the so-called Pareto front. (Carlucci and Pagliano, 2013)

In this study, the multi-objective algorithm is used to optimize the thermal comfort during the summer and the investment costs. Due to the complexity and quantity of the simulations and iterations that take place in an optimization process, they require a significant amount of time. Therefore, this process was carried out again for only one classroom per building, which represents a critical condition. The initial population for the optimization was set up as 20, the maximum population size was 50, and the maximum generations were 200. With these parameters, the number of iterations oscillated from 3900 to 4000 for each classroom and took between 24 to 48 hours.

It is expected that the optimization process will give clearer guidance in selecting the most appropriate measures to refurbish schools, which will improve the indoor thermal conditions of classrooms during the summers of the near future and at the same time incur the lowest possible costs. Therefore, two changes were made in terms of which parameters to evaluate. First, the size of the class was removed, since it does not represent a measure that could be recommended to the designers, and as mentioned above, school authorities have little flexibility in changing the number of pupils of a class. On the other hand, it was decided to include the use of blinds, as a tool that can be used with a better strategy and with no additional costs. The thermal comfort was evaluated, as previously, under the standard EN 15251:2007. The graphic results are shown in Figure 70 to Figure 77, and the specific Pareto fronts are shown in Table 16 to Table 19.

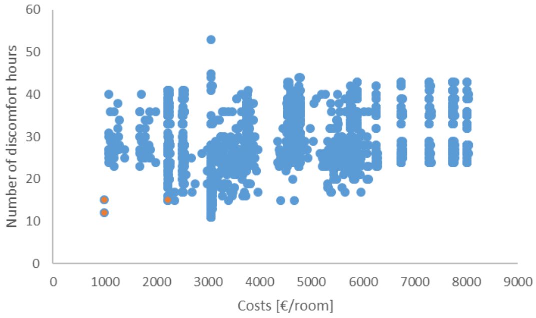


Figure 70: Optimization results: Building A1. Objective function: minimize discomfort hours and passive measures costs.

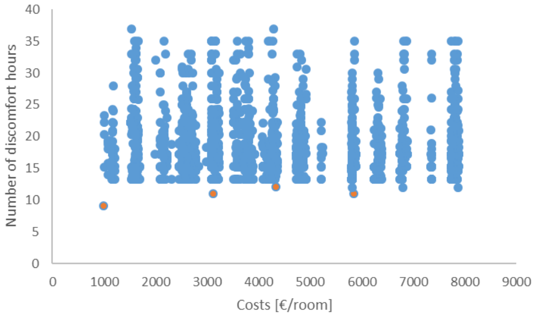


Figure 71: Optimization results: Building A2. Objective function: minimize discomfort hours and passive measures costs.

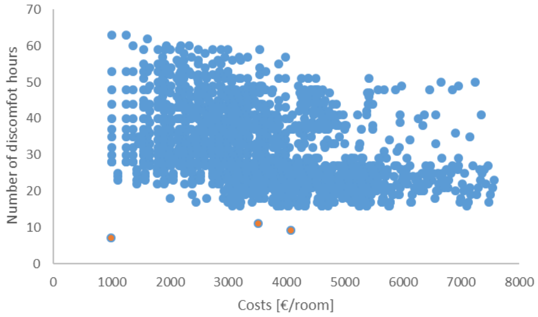


Figure 72: Optimization results: Building A3. Objective function: minimize discomfort hours and passive measures' costs.

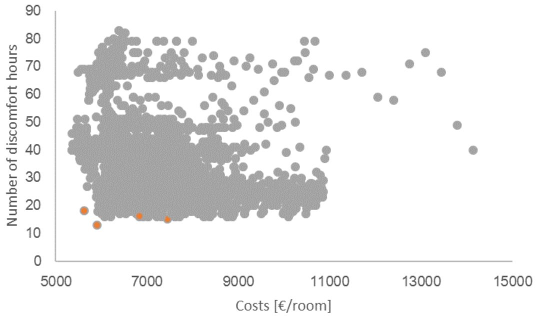


Figure 73: Optimization results: Building B1. Objective function: minimize discomfort hours and passive measures' costs.

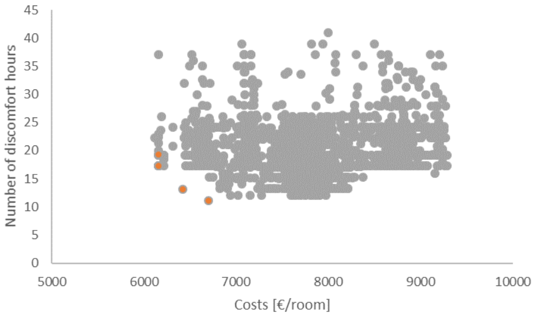


Figure 74: Optimization results: Building B2. Objective function: minimize discomfort hours and passive measures' costs.

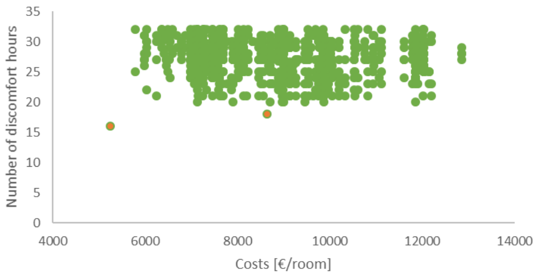


Figure 75: Optimization results: Building C1. Objective function: minimize discomfort hours and passive measures' costs.

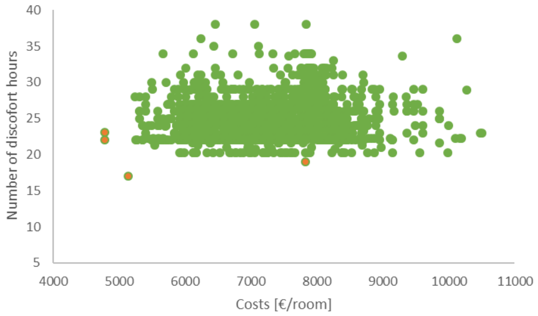


Figure 76: Optimization results: Building C2. Objective function: minimize discomfort hours and passive measures' costs.

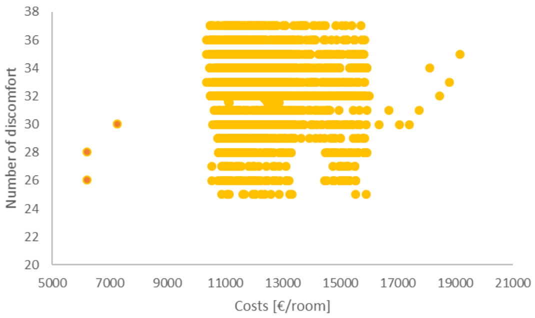


Figure 77: Optimization results: Building D1. Objective function: minimize discomfort hours and passive measures' costs.

Table 16: Pareto fronts of future scenario – Group A

School ID	External window open strategy	Local shading type	Glazing type	Partitions	Window shading	Discomfort hours [#]	Discomfort hours [%]	Costs [€/room]
A1	Continuous ventilation	No shading	Clear glazing (ST=0.7)	Heavy partitions	With blinds	12	8%	1000
	Continuous ventilation	No shading	Clear glazing (ST=0.7)	Heavy partitions	Without blinds	15	10%	1000
	Breaks and night	1.0m louvre	Sun prot. glazing classic (ST=0.47)	Heavy partitions	With blinds	15	10%	2355
A2	Continuous ventilation	No shading	Clear glazing (ST=0.7)	Heavy partitions	With blinds	9	6%	1000
	Breaks and night	No shading	Sun prot. glazing silver (ST=0.32)	Heavy partitions	With blinds	11	7%	3120
	Just breaks	No shading	Electrochromic	Heavy partitions	Without blinds	11	7%	5850
	Breaks and night	No shading	Sun prot. glazing classic (ST=0.47)	Heavy partitions	With blinds	14	9%	2633
A3	Continuous ventilation	No shading	Clear glazing (ST=0.7)	Heavy partitions	With blinds	7	5%	1000
	Breaks and night	1.5m overhang	Sun prot. glazing silver (ST=0.32)	Heavy partitions	With blinds	9	6%	4088
	Just breaks	1.5m overhang	Sun prot. glazing classic (ST=0.47)	Heavy partitions	With blinds	11	7%	3528

Table 17: Pareto fronts of future scenario – Group B

School ID	External window open strategy	Local shading type	Glazing type	Partitions	Window shading	Discomfort hours [#]	Discomfort hours [%]	Costs [€/room]
B1	Continuous ventilation	No shading	Sun prot. glazing silver (ST=0.32)	Light partitions	With blinds	13	8%	5906
	Continuous ventilation	0.5m louvre	Sun prot. glazing classic (ST=0.47)	Light partitions	With blinds	15	10%	7458
	Breaks and night	No shading	Sun prot. glazing silver (ST=0.32)	Light partitions	With blinds	17	11%	6538
	Just breaks	1.0m overhang	Sun prot. glazing classic (ST=0.47)	Light partitions	With blinds	18	12%	5630
B2	Continuous ventilation	No shading	Sun prot. glazing silver (ST=0.32)	Light partitions	With blinds	11	7%	6702
	Breaks and night	No shading	Sun prot. glazing silver (ST=0.32)	Light partitions	With blinds	13	8%	6426
	Continuous ventilation	No shading	Sun prot. glazing classic (ST=0.47)	Light partitions	With blinds	16	10%	5811
	Breaks and night	1.0m louvres	Sun prot. glazing classic (ST=0.47)	Light partitions	With blinds	18	12%	5655

Table 18: Pareto fronts of future scenario – Group C

School ID	External window open strategy	Local shading type	Glazing type	Partitions	Window shading	Discomfort hours [#]	Discomfort hours [%]	Costs [€/room]
C1	Breaks and night	0.5m louvres	Sun prot. glazing silver (ST=0.32)	Light partitions	With blinds	16	10%	5250
	Just breaks	No shading	Electrochromic	Light partitions	Without blinds	18	12%	8640
C2	Continuous ventilation	1.0m overhang	Sun prot. glazing classic (ST=0.47)	Light partitions	With blinds	17	11%	5137
	Just breaks	No shading	Electrochromic	Light partitions	Without blinds	21	14%	7836
	Breaks and night	0.5m louvres	Sun prot. glazing silver (ST=0.32)	Light partitions	Without blinds	22	14%	4790
	Just breaks	1.0m overhang	Sun prot. glazing silver (ST=0.32)	Light partitions	Without blinds	23	15%	4790

Table 19: Pareto fronts of future scenario – Group D

School ID	External window open strategy	Local shading type	Glazing type	Partitions	Window shading	Discomfort hours [#]	Discomfort hours [%]	Costs [€/room]
D1	Breaks and night	No shading	Electrochromic	Light partitions	Without blinds	26	17%	6235
	Just breaks	No shading	Electrochromic	Light partitions	Without blinds	28	17%	6235
	Just breaks	1.5m louvre	Sun prot. glazing silver (ST=0.32)	Light partitions	Without blinds	29	19%	3696
	Breaks and night	1.0m overhang	Clear glazing (ST=0.7)	PCMs (2 internal walls)	Without blinds	30	19%	7275

7.4.1 Analysis of the optimization results

Despite the many iterations, few Pareto fronts were found, approximately three to four per building. Due to the number of parameters and possible strategies, many combinations reduce overheating, but considering the costs reduces the number of solutions significantly. However, similarities between the building types were found, and are described as follows.

- It can be seen that in the three buildings of Group A, a low percentage of discomfort hours can be achieved by optimizing the ventilation strategy only, i.e. by opening the windows day and night, as long as the outdoor temperature is lower than the indoor temperature. If such a measure can be implemented, it would not be required to add external shading or decrease the solar transmittance of the windows. This could be attributed to the high thermal mass of these buildings, which allows the envelope to absorb the heat and release it when the outdoor temperature drops, leading to a shift and decrease of the peak indoor temperatures.

- In Group B, which represents buildings with heavyweight envelopes but lightweight partitions, the combination of at least two passive measures is required. In these cases, if the facades and the internal partitions were not altered, it would be required to reduce the solar transmittance of the windows, and to increase the ventilation during the day and night. If, on the other hand, the night ventilation would not be possible, then it would be required to add external shading.

- In the optimization results of Group C and Group D, it can be observed that if it is desired not to intervene in the current constructions, electrochromic glazing would be required, and even then, the discomfort cannot be reduced below 10%.

Once the Pareto fronts were identified, one of the strategies was implemented in the schools, to observe the overall effect. Figure 78 shows an example of the comparison of the indoor temperatures between the base case scenario and one of the improvements for one school in Group A and one in Group C. As previously shown, the passive measures have a higher effect in Group A than in Group C, but also from Figure 78, it can be seen that in Group A, it is possible to achieve a higher number of hours with temperatures in the lower ranges which are recommended for better cognitive performance of school children. Although there are still some hours at the highest temperatures in Group C, it can be seen that these are still significantly reduced by the passive measures.

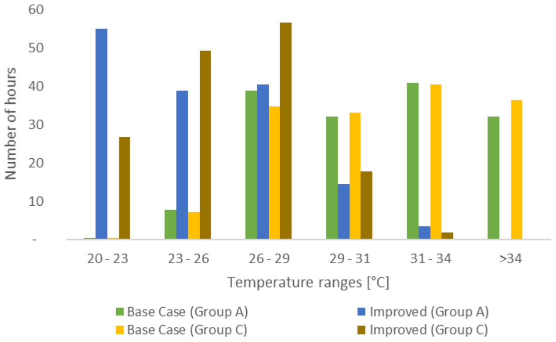


Figure 78: Comparison of the effect of passive measures in heavyweight vs. lightweight buildings

It can be concluded that the optimization process gives a clearer view of the effect of the analysed parameters on overheating, which gives a direction for the possible recommendations for future refurbishments in the schools. It was desired, however, to gain a deeper understanding of these results. Therefore, a further parametric analysis was conducted, which will be discussed in the next section.

7.5 Overheating at heat waves

As it was mentioned, the probability of occurrence of heat waves in cities such Karlsruhe is rising, and at the moment, the weather files of the city of reference Mannheim, do not seem to reflect this phenomenon. It was found that the city of Marseille, in France, had days in the weather files with temperature and radiation profiles similar to those measured in Karlsruhe during a warm week in 2017.

Just to get an idea of the effect of the passive measures during such days, one of the Pareto fronts for each building was chosen, and simulations were undertaken to quantify the number of discomfort hours due to overheating using the weather files of the city of Marseille as an example. Table 20 compares first the number of discomfort hours at the base-case with the two weather files, and then shows the reduction in overheating achieved by the selected ventilation strategy and glazing type from the Pareto fronts.

It can be clearly seen that under these new conditions, the night cooling potential is lower; while in Karlsruhe the classrooms implementing continuous ventilation would achieve an overheating reduction of around 22%, in Marseille this reduction would be around 14%. In this case, the highest reduction is 23% and is achieved by the D1 School, which is simulated with electrochromic glazing.

It is important to remark that in this case, the simulated week is considered to represent a heat wave because for four consecutive days, the day temperature is above 30°C and the night temperature is above 20°C. The simulations previously performed, under the DSY2035, considered such hot days and warm nights but no during consecutive days.

Table 20: Reduction of overheating at heatwaves conditions, exemplified by the weather data of the city of Marseille.

ID	Discomfort hours 2035 warm week [#]	Discomfort hours 2035 warm week [%]	Discomfort hours Marseille [#]	Discomfort hours Marseille [%]	External window open strategy	Glazing type	Discomfort hours after refurbish Marseille [#]	Discomfort hours after refurbish Marseille [%]
A1	9	30%	11	37%	Continuous ventilation	Clear glazing (ST=0.7)	6	20%
A2	8	27%	11	37%	Continuous ventilation	Clear glazing (ST=0.7)	6	20%
A3	8	27%	10	33%	Continuous ventilation	Clear glazing (ST=0.7)	6	20%
B1	10	33%	12	40%	Continuous ventilation	Sun prot. glazing classic (ST=0.47)	8	27%
B2	9	30%	11	37%	Continuous ventilation	Sun prot. glazing silver (ST=0.32)	8	27%
C1	11	37%	13	43%	Breaks and night	Sun prot. glazing silver (ST=0.32)	10	33%
C2	11	37%	14	47%	Continuous ventilation	Sun prot. glazing classic (ST=0.47)	9	30%
D1	13	43%	13	43%	Breaks and night	Electrochromic	6	20%

8 Parametric analysis

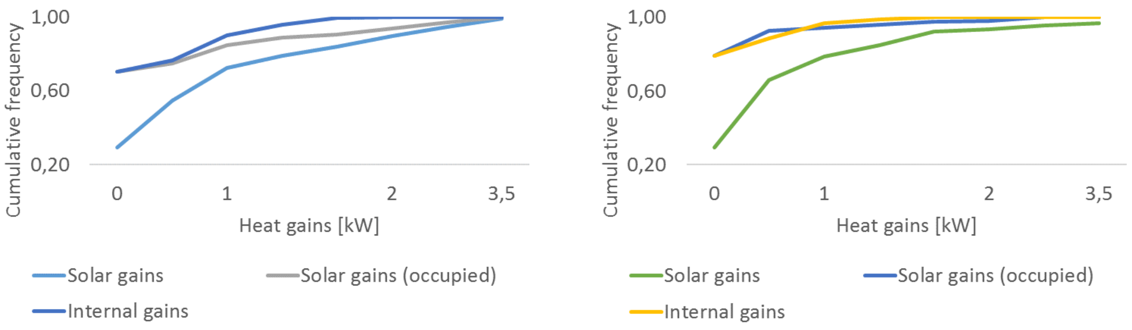
8.1 Temperature distribution

The optimization process revealed the optimum combination of low invasive measures that reduce overheating in classrooms while minding the costs and the climatic conditions of the near future. However, what is more interesting is that it was found that such combinations have similarities amongst the different building types. To better comprehend these results, the measures were further scrutinized through a parametric analysis, which allowed their effects on reducing overheating to be quantified and compared, and further relationships and the trade-off between various factors to be examined.

One of the highlights observed from the sensitivity analysis as well as in the multi-optimization results was that natural ventilation seemed to be very effective in the group of the buildings from 1850 to 1918, reducing the number of discomfort hours due to overheating from around 40 hours to 12, while for the other groups at least one more measure was required. Moreover, in the buildings of Groups B to D, none of the Pareto fronts suggested the reduction of overheating below 5% of the occupied hours.

Because of that finding, one of the next aspects to be analysed regards the comparison between the heat gains in the different building types by the cumulative frequencies of the internal and solar gains, as shown in Figure 79. As mentioned previously, the main internal heat gains during a warm month in summer arise from the pupils in the standard classrooms, but this data also includes the gains due to equipment such as a video projector and a computer. The graphs also distinguish between the solar heat gains during the whole day and during the occupied time.

For all the simulated school buildings, the effect of internal heat gains is greater than the effect of solar gains. However, in the 19th Century buildings, the solar heat gains in the classrooms are slightly lower in comparison with the internal gains. The reason for this could be the low window-to-wall ratio (around 22%). These buildings were designed with high ceilings (around 4.5m) and high windows (around 2.5m) to allow more daylight into the spaces, but the glazing area is significantly less in comparison with the buildings from the 1950s and onwards. These characteristics, summed with thick walls that provide high thermal mass, allow natural ventilation working effectively and significantly reducing overheating.



(a) (b)

Figure 79: Comparison of cumulative frequencies of heat gains in classrooms: (a) Building of Group A; (b) Buildings of Group C.

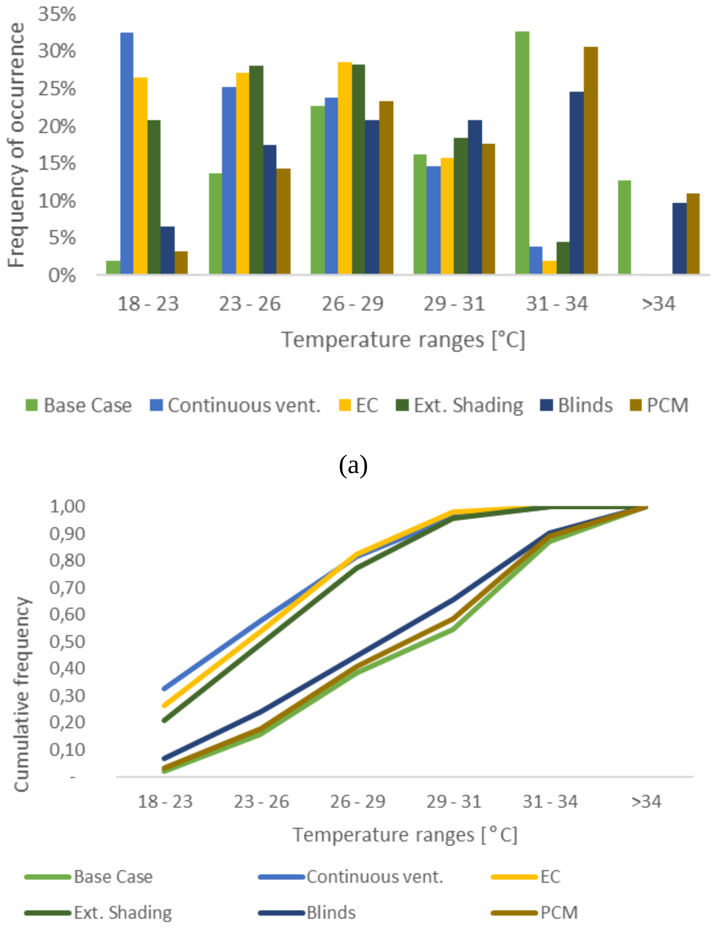
The buildings dated from the 1960s and 1970s tend to have larger glazing areas and, thus, the amount of heat gained from the sun is quite similar to the internal heat gains. In these buildings the heights of the ceilings and windows are lower, around 3.6 m and 1.6 m respectively, as is the thermal mass, due to thinner walls. Consequently, natural ventilation by itself is not able to release all the heat from the room and more measures are required.

In a similar process as in the sensitivity analysis, the measures resulting from the multi-objective optimization process were simulated to scrutinize their effect in the indoor temperatures. The selected measures for this purpose were: continuous ventilation, electrochromic glazing, louvres of one metre in length, PCMs in the internal partitions, and blinds. Figure 80 to Figure 82 show the distribution of the internal temperatures that are reached as an effect of each of the measures in the different building types. The distribution is shown through absolute and cumulative frequencies.

At first glance, electrochromic glazing seems to be the measure that contributes the most to reducing the overheating in all the different types of buildings. In Group A, however, three measures have a very similar individual performance: electrochromic glazing, continuous ventilation, and external shading in the form of louvres one metre in length. We can deduce that, despite the very similar effect between the electrochromic glazing and continuous ventilation, the optimization process prioritized the latter, due to its lower costs. In this group, it can be seen that the PCMs have no effect: the number of discomfort hours due to overheating is almost the same as in the base-case scenario. The steeper slope of the cumulative frequencies of the measures with a higher effect in Group A, in comparison with the slopes of the other groups, also shows how such measures allow lower temperature ranges to be reached, thus reducing further the number of discomfort hours due to overheating.

In Group B, the impacts of all the measures are more differentiated between one another, where electrochromic glazing achieves a major reduction of overheating, followed by continuous ventilation then external shading, blinds, and the use of PCMs. In this group, only the electrochromic glazing allows indoor temperatures above 34°C to be avoided, and although the occurrence of indoor temperatures in the higher ranges decreases significantly in comparison to the base-case scenario, the shift is less marked than it is in Group A. In Groups C and D, the effect of both external shading and electrochromic glazing is very similar and delivers the greatest overheating reduction. In these cases, the PCMs show a better performance; however, their contribution to reducing temperatures above 31°C is still low.

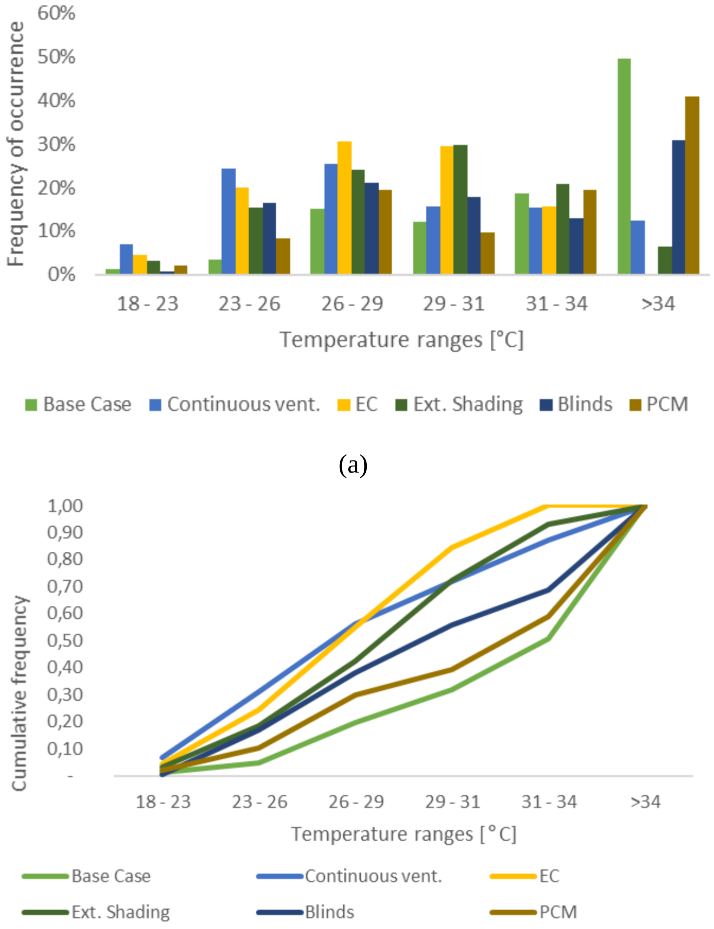
Regarding blinds, it can be observed that for all the groups, this measure is ranked as only fourth in achieving the highest reduction in overheating. However, the effect is not insignificant: in the buildings from Group B for instance, the number of hours with temperatures above the 30°C is reduced by one third. Since this is an existing measure, the recommendation would be to use them from the middle of the morning (approximately 10:30) on the hottest days.



(a)

(b)

Figure 80: Distribution of indoor temperatures by passive measures – Buildings in Group A: (a) absolute frequency; (b) cumulative frequency.



(a)

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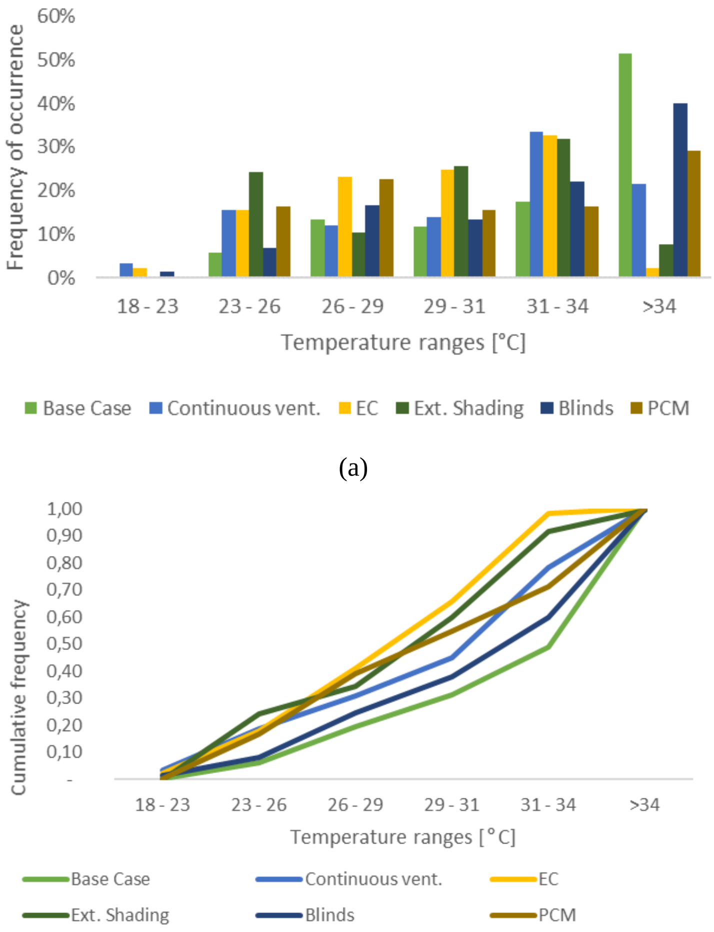
Figure 81: Distribution of indoor temperatures by passive measures – Buildings in Group B: (a) absolute frequency; (b) cumulative frequency.



(a)

(b)

Figure 82: Distribution of indoor temperatures by passive measure – Buildings in Groups C and D: (a) absolute frequency; (b) cumulative frequency.

8.2 Trade-offs

8.2.1 Natural ventilation

The results in this study have shown that a good natural ventilation strategy can significantly reduce the number of discomfort hours due to overheating in the analysed classrooms. Such a strategy would also improve the air quality, which in fact, according to the indoor CO_2 measurements recorded to calibrate the models, these levels could rise up to 2180 ppm. However, when using natural ventilation, further aspects should be considered:

- Adequate outside air quality (odours, pollutants, particulate matter):

When looking into indoor air quality, the point of reference is usually the CO_2 concentration level. Although these levels are generally considered a useful indicator for controlling a broad range of indoor pollutants, such as bio-effluents, they do not provide information on other types of pollutants, especially those from external sources, such as nitrogen dioxide (NO_2) and particulate matter (PM) from traffic (Chatzidiakou et al., 2015). Therefore, before selecting natural ventilation as the main strategy to guarantee good indoor air quality and thermal comfort, the schools' surroundings should be investigated.

Fortunately, the outdoor air quality in the city of Karlsruhe is considered acceptable. According to the Institute for the Environment, Measurements and Nature Conservation of the Baden-Württemberg State (LUBW), the highest concern in this matter regards particulate matter, where the value of the daily emission limit (50 micrograms per cubic metre) is allowed to be exceeded 35 times in one year. Karlsruhe exceeded this value only seven times in 2017. In terms of outdoor CO_2 levels, the city has recorded on average below 400 ppm and in terms of NO_2, the annual mean has not exceeded the reference value of 40 micrograms per cubic metre (LUBW, 2018).

This overview suggests that there should not be any significant concerns in terms of outdoor quality, but this does not mean that each case should not be evaluated individually. It is recommended to check, for instance, whether a school is located near a highway, a factory, or an establishment such as a sewer system or a waste or water treatment plant that could emit strong odours or chemicals. Furthermore, it could be required that windows remain closed during the arrival of the pupils, since cars idling, even for just a few minutes, has proved to be an important source of contamination (USGBC, 2017).

- Burglary protection and safety requirements:

Leaving the windows opened at night may not be a welcome measure on many occasions, as it raises concerns about potential burglary or the entry of animals. These risks can be avoided, or at least reduced, with additional locks that guarantee that the tilted windows cannot be further opened from the outside. It is important to remember, however, not to lock windows that are part of the escape routes or that should be available to open if the fire plan of the building requires it. In such cases, it could be better to turn to automatic windows, since it is possible to get smoke sensors connected to the controls of the windows to close or open them as required (Velux, 2019).

- Weather changes:

Cooling through natural ventilation has specific weather requirements. On one hand, effective air exchange occurs only when the room air is warmer than the outside air or the wind generates a pressure difference. Ideally, air exchange rates of over 10 ACH should be achieved (Cook et al, 2011). On the other hand, people might be dissuaded from using this strategy if they think it may rain during the night. Therefore, as before, it is recommended to use automatic windows with sensors, to make the strategy more effective. Various companies in Germany offer the controls and a set of sensors, which measure CO_2 levels, humidity, temperature, and rainfall. As mentioned in Chapter 6, the current costs for those packages are estimated at about 1000 euros. However, the purchase of the control technology is a one-time investment.

The effect of warm nights was analysed in section 7.5, but it is also interesting to scrutinize the potential of natural ventilation. For this purpose, the number of hours where the outdoor temperature is lower than the indoor temperature was quantified. It was found, for example, that in the schools of Group A, there were, on average, about 310 hours in the analysed month in which the outdoor temperature was lower than the indoor temperature, which accounts for approximately 56% of the time. In the schools of Group C, this number of hours is approximately 420, which accounts for 72% of the time (according to the base cases, the schools in Group A have less risk of overheating, which is why this number is lower). This is why the potential of natural ventilation is so high.

To understand this data better, Figure 83 is shown with a resolution of 24 hours. In this graph, it can be seen that, during a hot day, the external temperature begins to be higher than the internal temperature at around 07:00 in a school of Group A, and around 08:00 in a school of Group C. However, during a hot day like this, under normal summer conditions, there are about 7 hours in which natural ventilation releases heat from the buildings. On the other hand, on a normal summer day, schools can take advantage of lower outside temperatures during the morning in the schools of Group A and during almost the complete day’s class-time in Group C. In this way, it is possible to understand better why natural ventilation has such a significant effect, as long as the buildings have enough thermal mass to absorb heat during the day and release it at night, and there are sufficient opening areas to allow enough fresh air to fulfil this purpose.

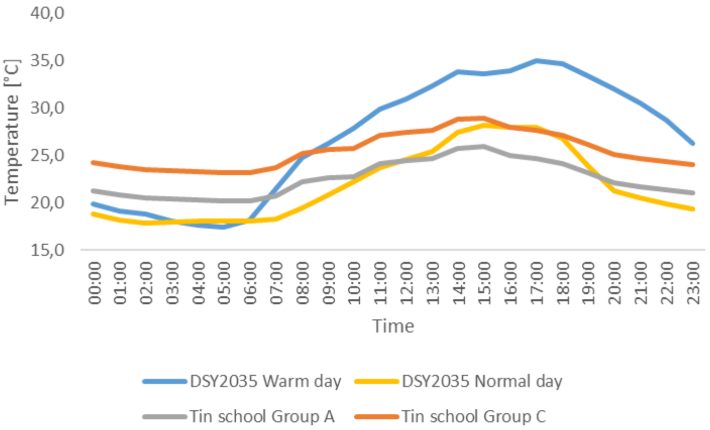


Figure 83: Comparison of outdoor and indoor temperatures during one summer day.

- ➢ Noise protection and acoustics:

According to the World Health Organization, to be able to hear and understand spoken messages in classrooms, the background sound pressure level should not exceed 35 dB LAeq during teaching sessions, which is, in general, a relatively low level, close to the levels of a residential zone during the night (WHO, 2019). The Standard EN15215 also suggests 35 dBA as a reference value. This means that in classrooms, for example, one should strive for as low background noise levels as possible.

The simulated schools are not directly located on a highway or main street; however, some schools in the city are, and in such cases, natural ventilation would be limited during the daytime. The City of Karlsruhe has available noise maps, where it is possible to identify the general external noise, as well as the noise related to traffic and trains, during the day and during the night (City of Karlsruhe, 2019). Although the minimum threshold is 55 dB(A), it is possible to perceive in Figure 84, that, in general, within the main streets, the level of external noise is bearable, and the more challenging locations are close to the railway lines. Naturally, each case should be analysed individually to confirm which ventilation strategy is suitable for each school, and perhaps in each façade and each classroom.

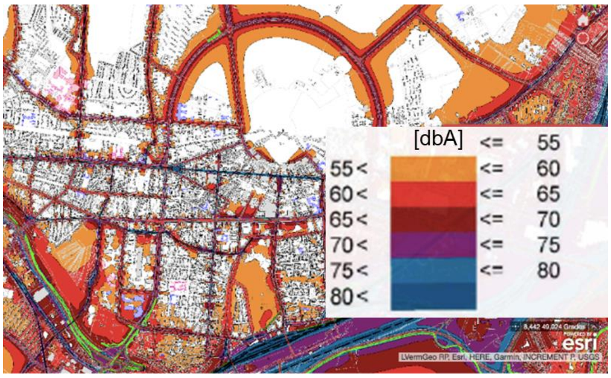


Figure 84: The noise map of the City of Karlsruhe shows that, during the day, noise levels below 55 dB(A) are reached only near green areas and away from railways and main streets. (City of Karlsruhe, 2019a).

8.2.2 Electrochromic glazing

The parametric overview suggested that electrochromic glazing has a strong effect on reducing overheating in the classrooms, especially in lightweight buildings. Therefore, in a similar exercise to that reported in section 8.2.1, this effect was analysed and compared with the effect of natural ventilation in a 24-hour resolution graph, as shown in Figure 85. It can be seen that the effect of the electrochromic glazing starts at the time of the occupancy and helps to maintain lower indoor temperatures during the day-time in the school buildings from both Group A and Group C. In the school building from Group C, the indoor temperature during the day achieved by the use of electrochromic glazing is significantly lower than that achieved by continuous natural ventilation, while in the Group A building the continuous ventilation, first ensures lower temperatures than in the other buildings, and, moreover, the effect is greater than that with electrochromic glazing.

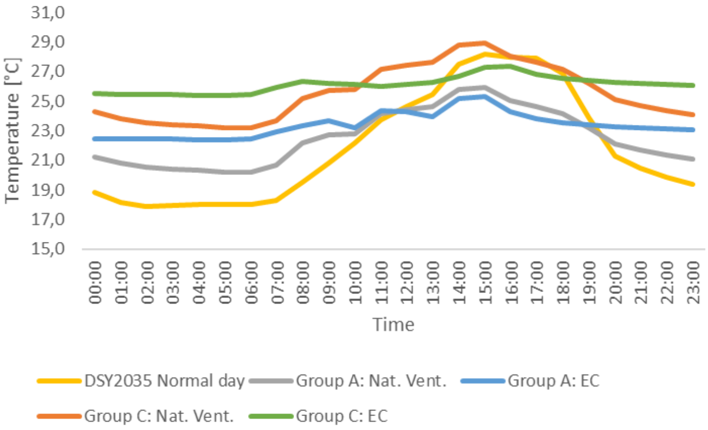


Figure 85: Comparison of indoor temperatures as effect of natural ventilation and electrochromic glazing in a school of Group A and a school of Group B.

Various studies have shown that electrochromic glazing has a good capacity or a good potential to reduce HVAC loads. For example, in the early 2000s Lee et al. (2002) estimated a reduction in the peak electrical loads by 20 to 30% in buildings in Washington, USA. While Syrrakou et al. (2006) concluded that, theoretically, electrochromic windows could reduce cooling requirements by approximately 50%. More recent studies have confirmed these estimates; for instance, a recent pilot assessment project in Denver, USA, found that chromogenic windows (electrochromic and thermochromic windows) contributed little in controlling heat losses compared with double pane, low-emissivity windows, but they were very effective in limiting heat gains, due to the material's ability to dynamically regulate solar radiation. In the Denver test case, electrochromic windows reduced window heat gain by 46% over the baseline low-e window, resulting in reductions of 9% in the annual cooling load (GSA, 2014). Similarly, Ali et al. (2018) suggested that double electrochromic windows could save 8% of the electrical power required for cooling in a refurbishment project in Pakistan. These results also reflect the drop in prices as the technology has improved and expanded, from approximately 6000 €/m² in 2000 to less than 1000 €/m² in 2018 (Baunetz, 2017). However, there are still concerns around the periods for the return of the investment and other possible effects on the quality of the indoor environment.

In terms of payback periods, an early study by Syrrakou et al. (2004) calculated this as approximately 3 years, but more recent studies have estimated longer periods. For instance, Tavares et al. (2014) compared three glazing types in buildings located in Mediterranean climates and calculated a simple payback of 10 years. This is evidence of the lack of data and the need for more case studies with records of energy consumption and bills. At the same, it raises concerns about the acceptability of these types of new technologies, since, depending on the class of building ownership, acceptable payback periods vary between two to seven years. Moreover, there might be some other drawbacks to consider: for instance, the transformation between transparent and dark takes several up to 30 minutes until the transformation that begins on the outer edges moves its way towards the centre.

Another concern around electrochromic glazing regards the colour rendering index (CRI), which is the indicator that measures how well the colours of an object are reproduced under a condition (such as under an artificial light source), in comparison with a natural light source. For classrooms and offices, this value should not be less than 80%, which means that the reproduction of colours can be trusted (Hunt, 2004). Mardaljevic (2014) showed in a white paper that a natural spectrum of daylight illumination could be achieved by zoning the glass panes and keeping some of them in a clear state. In his measurements, a CRI of above 87% was achieved by keeping approximately 10-15% of the glass area in the clear state whilst the other panes were tinted appropriately to provide the required level of heat gain control. The lighting simulation programs do not calculate the CRI. However, it was considered interesting to estimate the effect on the overheating reduction when implementing zoned glass panes. The simulations of combined panes suggested that such arrangements delivered in average 2% more discomfort hours, in comparison with a full EC glazing, as summarized in Table 21. In this way, the overheating reduction is still significant, while an indoor natural colouring can still be achieved.

The daylight simulations were undertaken, as previously mentioned, with Radiance, at a working plane height of 0.85m, under overcast day conditions, and with a grid size of 0.05m. The German regulation for daylighting, DIN 5034, suggests measuring brightness at this height but in half room depth and at a distance of 1 m from the two sidewalls. Unfortunately, the software does not give precise values for specific points. For this reason and since daylight simulations are not the focus of this study, it was decided to use the traditional distribution method and the reference values from 2% to 5% for adequate average Daylight Factor, as recommended by The Commission Internationale d' Eclairage – CIE (SLL, 2012).

Table 21: Comparison of illuminance between clear, combined and full electrochromic glazing. The combination of electrochromic with clear glazing provides a significant overheating reduction and allows good levels of indoor daylight and a natural spectrum.

School Group	Daylight Factor Average (%)	Discomfort hours [#]	Discomfort hours [%]
Group A (average)			
Clear	5.15	39	26%
Combined	3.75	19	13%
Full EC	2.93	15	10%
Group B (average)			
Clear	3.47	47	31%
Combined	2.82	25	16%
Full EC	1.78	22	14%
Group C&D (average)			
Clear	2.53	55	36%
Combined	2.14	26	17%
Full EC	1.51	22	14%

Looking at these features from the electrochromic glazing, it is worth mentioning (as explained in section 6.3) that liquid crystal windows react much faster than electrochromic windows: in just a few seconds, and the CRI is around 95%, depending on the mixture (Merck, 2018). Although the current prices could be about twice as much as those of electrochromic windows (Fenseterversand, 2019), it might be worth evaluating this technology more closely in the forthcoming years.

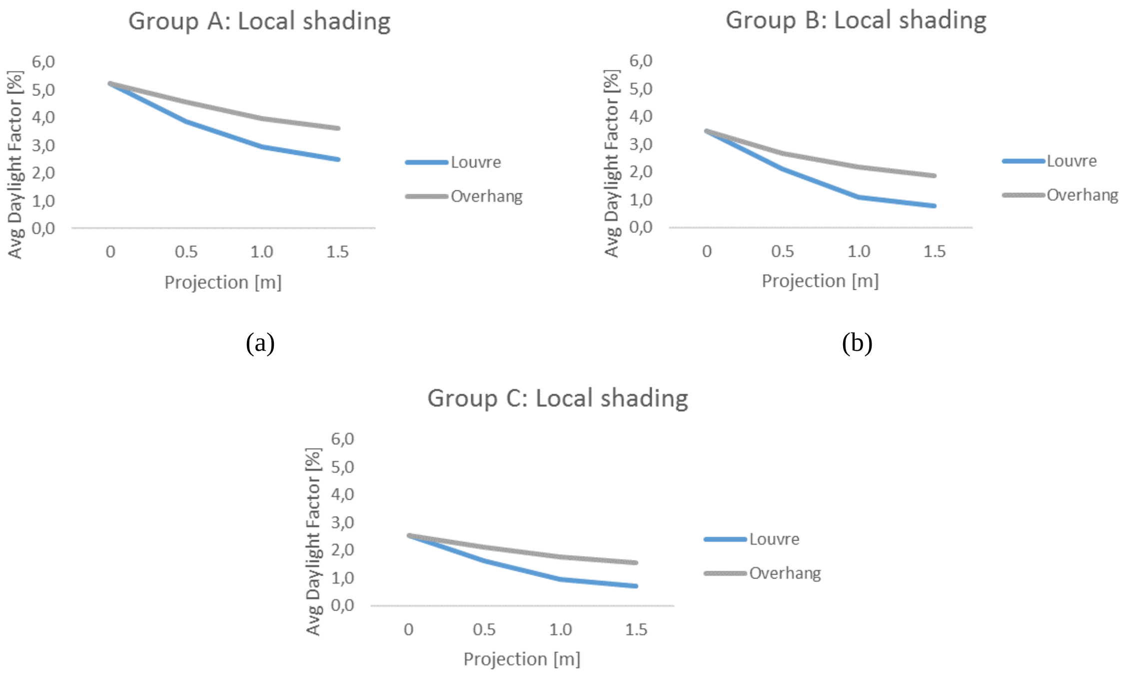
Table 21 also draws our attention to the average levels of natural lighting that can be achieved. Under clear glazing, the average Daylight Factor of the buildings in Group A is above 5%, in Group B around 3.5% and in Group C and D around 2.3%. This means that without shading or tinted glazing, the buildings of Groups C and D are below the recommended value of 3% for classrooms, which implies that visual comfort should be further evaluated.

The change of colour has another unstudied effect, at least specifically in buildings with electrochromic glazing. Most of the electrochromic glasses change their opacity from transparent to blue. The blue portion of the visible spectrum is where the sensitivities of circadian photoentrainment take place. Some studies suggest that there are potential health risks at excessive exposure to blue environments, which include sleep deprivation, metabolic dysfunction, aging, and these are thought to be involved in depression, diabetes, hypertension, and obesity, as well. Hatori et al. (2016) for instance, studied the effects of LEDs on human health and suggested that the extensive use of this lighting exposes people to relatively higher amounts of blue light throughout the day, which potentially affects health, cognition, and aging, especially in infants and juveniles. Although they recognize that further and long-term studies are required, they first, recommend raising public awareness about the appropriate use of light-emitting devices that are blue rich, and the potentially harmful impact of LED screens, especially in the youngest age groups. Secondly, they call on architects and designers to maximize the availability of natural daylight during daytime hours, in balance with reduced glare and increased energy efficiency. In this case, they do not see electrochromic glazing as a potential hazard, but as a technology that could increase wellbeing and potentially decrease health negative impacts through the possibility of having more glazing (which increases the external views), with smart windows that adjust according to the needs for lighting and thermal comfort.

Another aspect to consider regards occupant satisfaction. Hedge et al. (2018) conducted occupant surveys in office buildings with electrochromic and low-e windows. Their results showed that results from subjective reports of eyestrain, headaches, lighting quality satisfaction, and alertness were significantly better for the electrochromic glass buildings, but no significant differences between building types were found for daylight quality, mood, health and well-being, self-rated productivity, and work quality. Other studies claim that electrochromic windows improve wellbeing by allowing occupants more access to external views (Fernandes et al., 2013; Sadeka & Mahrousb, 2018; Kell et al., n.d.), but additional recorded data on user satisfaction and productivity is still missing. Furthermore, no studies were found about school environments.

8.2.3 External shading devices

As with the use of the tinted windows, the implementation of external shading devices might raise concerns about visual comfort. Therefore, daylight simulations were undertaken, and it was found that for the school buildings of Group A, which have higher windows, overhangs, and louvres with a projection of up to 1.5 metres could be acceptable without reducing the Daylight Factor below 3%. However, for the rest of the buildings, since this value is already low (around 3%), additional fixed external devices could decrease the uniformity and amount of daylight. Figure 86 compares the average daylight factors of the different school groups. Although the average Daylight Factor is not reduced so much in Group A, it is important to bear in mind that several of them are considered to be historic buildings and the fixed shading elements could be considered invasive if they were installed on their facades.



(a) (b)

(c)

Figure 86: Reduction of average Daylight Factor by increasing the projection of overhangs and louvres. Comparison of school buildings: (a) Group A; (b) Group B; (c) Groups C and D

On the other hand, fixed external devices might also raise concerns about the potential increase in heat consumption during the winter, due to a reduction of solar gains. Although the sun in the northern hemisphere has a lower angle during winter than during the summer, and therefore the external shading should not have much effect on solar gain, nevertheless, simulations for the heating season were carried out, to quantify this effect. The simulations summarized in Table 22 suggest that overhangs of 1.5 meters could increase the heating consumption by up to 2% and louvres of the same projection up to 4%. For these results, there is not much differentiation amongst the different school types.

Table 22: Comparison of estimated heating consumption of the school buildings with the use of overhangs and louvres as external shading devices.

School ID	No Shading	1m Overhang	1m Louvre	∆ Overhang	∆ Louvre
	Heating consumption [kWh/m2]				
A1	100,36	101,4	104,4	1%	4%
A2	89,99	91,8	91,8	2%	2%
B1	105,54	108,7	109,8	3%	4%
B2	171	174,4	179,6	2%	5%
C1	176,77	178,5	182,1	1%	3%
C2	114,68	118,1	119,3	3%	4%
D1	92,95	94,8	95,7	2%	3%

8.3 Increasing ventilation and air movement

The results presented in previous sections show that air movement and air temperature contribute significantly to releasing heat from indoor spaces and with it, reduce the risk of overheating. Therefore, it was sought to find out whether the buoyancy effect could be induced to enhance the natural ventilation strategy, without considerably modifying the structure of the buildings, that is, through a different arrangement of the windows. The Fraunhofer Institute for Building Physics studied different window opening arrangements to find more appropriate flow rates. They found that oscillating and tilt windows placed in two or three rows, in combination with automatic controls, proved to be very effective in guaranteeing air quality and thermal comfort. Two separate windows for supply and exhaust air generate a stable air volume flow in the room, which can be controlled via the opening width (BINE, 2015).

Considering those results, the effect of new windows openings was tested, as illustrated in Figure 87, where the windows are totally replaced, keeping the same area, but adding more openings, which increases the stack effect.

(a) (b)

Figure 87: (a) Usual arrangement of windows in school buildings. (b) Suggested modification if windows were to be completely replaced. The increase of window opening options in the same vertical row promotes the exchange of air.

Choosing one of the Pareto Fronts of each school building, dynamic thermal simulations were carried out using these new opening arrangements and evaluated to discover if the number of discomfort hours could be reduced further. The simulations show that, with at least two different openings in the vertical row, the indoor temperature, especially during the morning hours, drops by around 2°C, which has a significant impact during the rest of the day.

The continuous ventilation option significantly increases the air change rate in all buildings, in comparison with the base case scenario of opening the windows only during the breaks. Most importantly, it is possible to achieve 10 air changes per hour, which has been shown to be a useful target air change rate when sizing openings for natural ventilation (Cook et al., 2011). However, as can be seen in Figure 88, windows with two or more vertical openings allow higher flow rates, which leads to less than 5% discomfort hours for most of the schools, complying with the recommendation of the standard EN 15251.

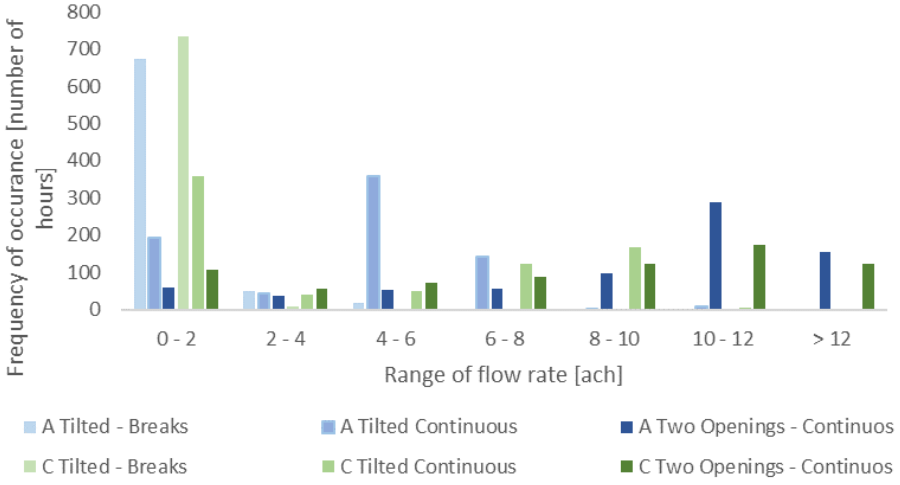


Figure 88: Frequency distribution of flow rate achieved by different window opening options. Comparison between school groups A and C. Flow rates above 10 ACH can only be achieved with continuous ventilation. Two vertical openings allow higher flow rates that prevent overheating.

Summer thermal comfort may be also improved by increasing the air velocity. Therefore, the number of discomfort hours was calculated for the previous scenarios but adding fans. According to the standard EN 15251, if such fans can be controlled directly by the occupants, the upper limits of the acceptable indoor temperatures can be increased by a few degrees. Ceiling fans generate non-uniform velocity profiles, and therefore relatively non-uniform thermal environments, which leads to more thermally comfortable environments, as research on alliesthesia suggests (Babich et al., 2017)

Table 23 summarizes the effect on the overheating reduction when increasing the air movement by adding openings in the windows and by adding ceiling fans that could deliver an air velocity of 0.5 m/s. With these measures, overheating could be avoided in most of the school building types and reach acceptable conditions in lightweight buildings.

Table 23: Comparison of discomfort hours due to overheating in classrooms at different solutions: optimum, new opening arrangements and ceiling fans.

ID	External window opening strategy	Glazing type	Optimum: Discomfort hours [#]	Optimum: Discomfort hours [%]	New openings: Discomfort hours [#]	New openings: Discom-fort hours [%]	Adding ceiling fans: Discomfort hours [#]	Adding ceiling fans: Discomfort hours [%]
A1	Continuous ventilation	Clear glazing (ST=0.7)	12	8%	5	3%	0	0%
A2	Continuous ventilation	Clear glazing (ST=0.7)	9	6%	4	3%	0	0%
A3	Continuous ventilation	Clear glazing (ST=0.7)	7	5%	1	1%	0	0%
B1	Continuous ventilation	Sun prot. glazing classic (ST=0.47)	13	8%	7	5%	0	0%
B2	Continuous ventilation	Sun prot. glazing silver (ST=0.32)	11	7%	5	3%	0	0%
C1	Breaks and night	Sun prot. glazing silver (ST=0.32)	16	10%	9	6%	3	2%
C2	Continuous ventilation	Sun prot. glazing classic (ST=0.47)	17	11%	12	8%	6	4%
D1	Breaks and night	Electrochromic	26	17%	20	13%	10	6%

9 Discussion and Recommendations

9.1 Further discussion

The indoor environmental quality of classrooms plays an important role in students' lives, as it influences health, cognitive performance, and well-being. The traditional building designs have cared for the creation of safe environments where teaching activities can take place under essential functional requirements, but the features related to the indoor environment have remained in the background. These traditional requirements included the appropriate sizes of the indoor and outdoor spaces, access to daylight and ventilation, the specific design of spaces for the different learning activities (including libraries, laboratories, sports halls, etc.) and, of course, the provision of mechanical systems to provide services such as water, electricity and heating.

Building design as a function of structural safety and functionality can be clearly seen in the history of architecture from the end of the 19th Century until the decade of the seventies. What is quite interesting in this timeline is that the wartime periods made possible to see a marked difference between the advances and requirements of the previous and subsequent epochs. As was shown in the characterization of the schools, the buildings constructed before 1918 are more robust and with higher floor-to-ceiling distances. The massive walls responded to the need for ensuring safety (in terms of structural stability) and to keep occupants apart, as much as possible, from the strong winter conditions. Such dimensions were lower in the buildings constructed after the war periods, as a response of two main factors: first, during the wars several advances in terms of structural efficiency took place, and second, the rapid reconstruction of cities after the wars was required. The structural efficiency was due to the need to build civil and military infrastructure with lower costs, which led to research on how to make buildings and structures thinner (with less amount of material) but equally safe. The need for rapid reconstruction improved the processes of mass production of construction materials such as bricks, cement blocks and subsequently prefabricated cement slabs (Coetzer, 2010).

The indoor environmental requirements were then satisfied differently in each epoch. In the 19th Century, the building design sought to maximize daylight, as artificial lighting was still not available, and thermal comfort was achieved by the thick walls and hot water central heating systems. The buildings from the 1950s and onwards could take advantage of electricity and more advanced heating systems.

Those differences in design determined to a large extent the building's performance. However, the current plans for energy efficiency and adaptation to climate change tend to seek and advise on general measures that are applicable to more contexts, leaving aside such characterization. Such guidelines have great value when making a first approach towards screening potential sustainability measures, but they are not sufficient for the authorities or the designers when looking for quantitative tools that allow them to make decisions about the most appropriate building refurbishment strategies. It is for this reason that this study selected buildings that represented the typical characteristics of each period and the evaluation of the models was based on the differences or similarities that were found between them.

The hypotheses raised at the beginning of this research included the premise that overheating conditions are already occurring in the school buildings of Karlsruhe and that older buildings had better performance (in terms of indoor comfort), due to their greater thermal mass. The first hypothesis was partly confirmed with the temperature measurements taken during the summer of 2017. These data showed that various rooms had indoor temperatures even above 32°C, which at first glance seems to be an uncomfortable environment. However, in order to determine if this was an acceptable condition according to the standard EN15251, it would be required to calculate the time when the indoor temperatures exceed the comfort zone of Category II (as the reference used in this study). Since the temperature was recorded only for two weeks and only three days had temperatures above 28°C, it was decided to calculate the allowed daily exceedance in minutes, which in this case is 24 minutes (approximately 5% of the occupied time).

To explain this procedure, the case shown in Figure 60 was taken as an example. In this classroom at 07:30 hours, when the first class takes place, the indoor temperature is 29.5°C and remains stable until 10:00 hours, at which point it begins to rise again. At 07:30 hours the outdoor temperature is 22°C, at 09:00 hours it is 23°C and rises to 24°C at 10:00 hours, which means that the upper acceptable limits for these hours would be 29.06°C, 29.39°C and 29.72°C respectively, calculated following Equation 3. This would mean that there would be at least one hour of overheating. This situation occurs in four out of the six classrooms measured. However, it is a very specific situation and the investment in measures to reduce overheating cannot be justified just based on the conditions of several minutes per day.

The second hypothesis was also partially confirmed. The temperatures in the school building of Group B were slightly higher than in the building of Group A, but the CO_2 measurements suggested that the rooms were not occupied during the complete day. Therefore, it is not possible to claim that the differences in the indoor temperatures responded to the building construction types.

However, once the models were calibrated and some profiles were standardized (in terms of internal heat gains, and occupancy and window opening schedules), the simulations supported the first two hypotheses. The effects of the building design and construction details typical of each epoch can be observed comparing the results of the base case scenarios. The first results suggested that overheating in the school buildings of Group A was approximately 5% less than in the buildings of Group B and almost 10% less than in the building of Group C. Under the current weather conditions, characterized by the DSY2010, as a statistical representation of the warm conditions of the last 10 years, the simulations show that if the classrooms are occupied during the eight hours of class time, the indoor thermal conditions are not acceptable, and the number of discomfort hours due to overheating will exceed the recommended threshold of 5%. Furthermore, under the prognoses of the future weather conditions, if the schools remain as they are now, the indoor environment would be counterproductive for learning activities and the students' cognitive performance could be severely affected. Although it is true that eight-hour classes are not a common practice for pupils, all-day schools are becoming more popular and sometimes school premises are also used by other groups; either by students of the same school at extracurricular activities or even by adults. On the other hand, it should be also considered that internal heat gains might tend to increase as Internet and Communications Technologies (ICT) are wide spreading. Despite the fact that electronic devices tend to be more energy efficient with time, the trend is to use them more, adding heat to the indoor spaces.

The studies on climate change have suggested that the average temperature in Southern Germany will increase by approximately 2.5°C in the near future, and this is reflected in the DSY2035 weather file. Comparing the temperatures from May to September, the number of hours with temperatures above 26°C rises from 431 in the DSY2010 to 737 in the DSY2035, which is an increase of about 8%. Therefore, under these conditions, the simulations suggest an increase of indoor overheating in the range of 9% to 13% in the near future, in comparison with the data from 2010, reaching discomfort periods up to 40% of the occupied time. Considering the results of recent studies, the cognitive performance of pupils could be significantly reduced.

When studying educational premises, to enhance cognitive performance should be one of the starting points to design indoor environments, and this leads to the question of how to define overheating. For this study, it was decided to use the standard EN15251 as it is the most used European reference, but Chapter 2 showed that several gaps remain when linking indoor environmental quality with the cognitive performance. Starting with how to normalize the test procedures to judge the performance of students; because different students may perform better in different tasks depending upon their interest and motivation, but also considering the temperature preferences between the different age groups. Because of this situation, there is no consensus among the standards or the guidelines on what the comfort ranges for classrooms should be or how overheating should be defined. The Building Bulletin 101 - Ventilation of School Buildings[6] (BB101, 2006), guideline reference for the United Kingdom, recommends for instance no more than 120 hours with indoor air temperatures above 28°C in classrooms, average indoor temperatures of no more than 5°C above the outdoor temperatures, and no indoor temperatures above 32°C. Meanwhile, as it was explained in section 7.2, the standard EN15251 has three categories, where Category I, is recommended for buildings with sensible subjects and Category III is in general recommended for existing buildings. It was decided to use Category II as a reference due to the fact that some of the investigated buildings are more than 100 years old and, it was thought, that to refurbish such schools to meet the highest performance guidelines would require high, and perhaps unjustified costs.

In view of this situation, three aspects should be highlighted. First, various authors agreed that in general pupils prefer lower temperatures. Although many of them do not suggest specific comfort ranges, Chatzidiakou et al. for instance recommended temperatures around 22–24°C, while Wargocki and Wyon mentioned better performances even at 20°C. Second, the standard EN15251 states that the temperature limits of the three categories are based on comfort studies in offices,

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[6] With recommendations of the Approved Document Part L2 – Conservation of fuel and power in existing buildings of the United Kingdom.

which did not take peoples´ work performance into account. In this sense, even if there are no established comfort ranges for pupils yet, it could be agreed that the indoor temperatures during the warm days (with day temperatures above 25°C) should be kept as low as possible, that would mean to try as possible to meet the requirements of Category I.

Third, the results of this study showed that with a better ventilation strategy, i.e. continuous ventilation trough windows with at least two vertical openings, it is possible to reduce the number of discomfort hours due to overheating, according to the EN15251 Category II, below 10% in all except the lightweight building. The simulation results of Table 23 were quantified to establish overheating under the Category I, and it was found that in general the number of discomfort hours would rise around 3 to 5%. However, with the support of ceiling fans, these percentages would still be within the recommended threshold. Therefore, one of the main recommendations of this study is to improve the natural ventilation study in all types of school buildings and maximize the airflow movement as much as possible in order to create more comfortable learning environments for children.

It is important to keep in mind that indoor environmental quality does not only involve thermal comfort but also air quality, acoustics, interior lighting, daylight, quality of views, and occupant satisfaction, and although these last factors were not the primary focus of this study, the impacts of the potential measures on them were analysed to raise awareness regarding trade-offs.

One of the first main concerns regarded the indoor air quality. As mentioned above, both, the school visits and the CO_2 measurements, suggested that windows are mostly kept closed during classes and are just opened during the breaks, which are very short: from 10 to 15 minutes. This practice not only affects the indoor temperatures but also air quality. With this opening window profile, the flow rate is below two air changes per hour, which is far lower than the recommended values, from six to ten. The consequences are clearly visible, since the indoor CO_2 levels reached values even above 2000 ppm, showing the need to change the ventilation strategy.

It was also mentioned that, although there were some sporadic concerns about noise that promoted this practice, the main concern regarded children’s safety, as the pupils could fall off of the windows or hit their foreheads on the projecting edges of the windows. In the presence of intense outdoor noise there are no strategies to support the natural ventilation through window opening, but various options could solve the second issue, guaranteeing safety but also allowing more fresh air to the classrooms through larger opening areas. It was mentioned that to avoid burglary, locked windows would be a solution, but also side opening windows or opening elements between windows, such as dampers could be considered.

This last solution implies the complete replacement of windows, which invites us to reflect on two further aspects. The first one is a reminder that, when possible, each building should be evaluated by spaces (i.e. use and location of each room). Naturally, all spaces require good indoor air quality and thermal comfort, but, depending on the location, a good natural ventilation strategy through window opening might not be appropriate. In such cases then the recommendation would be to avoid the allocation of classrooms there, when possible, and place offices or storage spaces there instead, because they have fewer occupants, and therefore a lower requirement for fresh air. Such analyses would avoid the costs of replacing windows unnecessarily.

Similarly, each façade should be also analysed separately. As shown in section 7.1, due to the sun pattern, the temperature difference between a room in the south façade and a room in the north façade could be around 3°C. This implies that the appropriate refurbishment measurements are different for each façade, and, such specific analyses will reduce investment costs. Other possibilities could be also considered before deciding on additional measures. For instance, in both measured schools, the computer rooms were located in the south and southeast facades. Knowing that these two facades are subjected to higher sun gains, these rooms should be located on the north façade.

The second aspect that should be considered is the feasibility of potential refurbishment measures. In the case of windows replacement, structural aspects should be evaluated before deciding on the options that could be used; some types of windows might be heavier and wider, and therefore their implementation may not be possible at all.

In addition to the selection of the appropriate measures to improve thermal comfort, the indoor air quality requires further attention. Therefore, another recommendation of this study is that all classrooms should be provided with CO_2 sensors and, when possible, with alarms to inform the teachers when unacceptable values are about to be reached. Although there is not a clear consensus on what exactly these ranges should be, it has been suggested that, for learning environments, levels above 1200 ppm should be avoided (Camacho-Montano et al., 2018)

The sensitivity and parametric analyses, together with the optimization process suggested that an adequate natural ventilation strategy has great potential for reducing overheating, even under the near future weather conditions. However, it was also mentioned that for some school buildings this strategy alone might not be sufficient to provide good indoor thermal comfort, and even though other passive measures were suggested as potential solutions, the evaluation of each specific case might conclude that non-passive strategies are more suitable, especially taking into account the need to guarantee indoor air quality. To support that decision, some references can be used. For instance, the CIBSE Applications Manual AM10 (2015a) provides a roadmap to select an appropriate ventilation strategy. As shown in Figure 89, the natural ventilation strategy is recommended only when the minimum requirements of the aspects mentioned before are met. Additionally, they suggest verifying whether the occupants are able to adapt to weather changes. Since in Germany is rare to find schools that require uniforms, it can be claimed that clothing is not a concern. However, for conditions such as certain building layouts, or spaces with high internal heat gains, mechanical ventilation might be a more appropriate measure. From Figure 89 it is also interesting to see that only extreme conditions would require the implementation of full air conditioning.

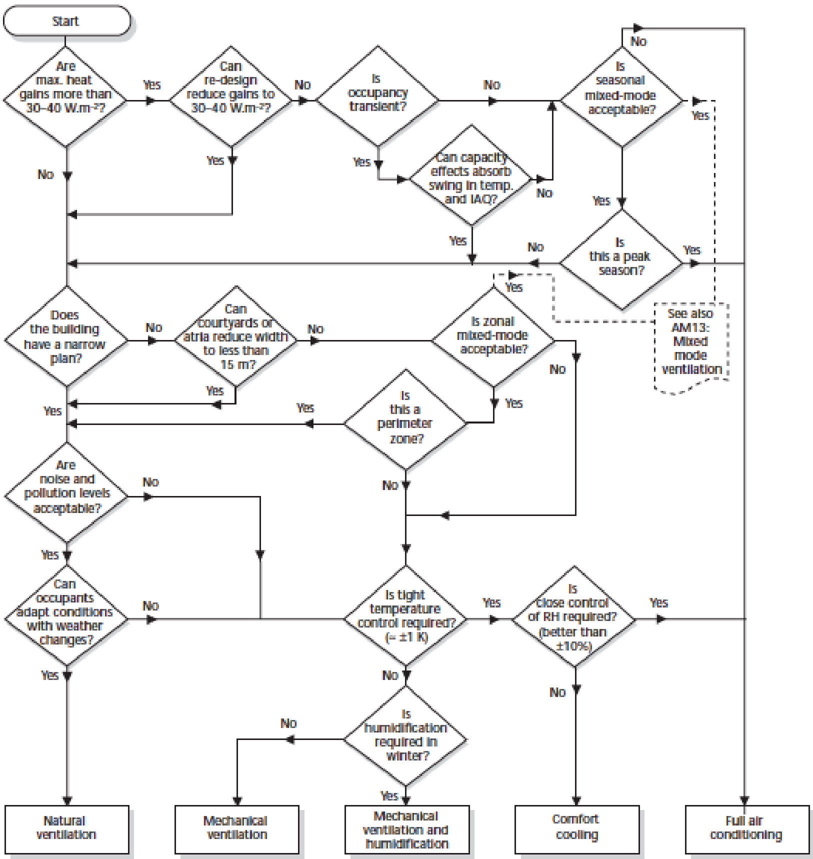

Figure 89: Guidance on how to select a ventilation strategy.
Source: CIBSE Applications Manual AM10

Chapter 8 also showed that a new arrangement of the window openings would improve the indoor conditions even more. The reason for this is that such an arrangement allows using the wind driving force and promotes the stack effect. It was mentioned in Chapter 3 that during the summer, the wind speeds in Karlsruhe are around 3 m/s to 3.5 m/s, which are good rates to help drive natural ventilation. Therefore, the initial parametric and optimization results showed how the buildings should take advantage of such a strategy. Furthermore, it is important to consider that stack effects do not occur just over the whole height of a building. Stack pressures will be exerted over any vertically spaced openings that are inter-connected. The air will always tend to flow in at the bottom and out at the top (when the indoor temperature is higher and with a reverse flow when the outdoor temperature is higher), which creates an air exchange mechanism in the room, even if it is isolated from the rest of the building.

The stack effect induces higher flow rates with the vertical separation of the openings than with just only one. The double opening also increases the depth of penetration of the fresh air into the space: as a rule of thumb, the depth for effective ventilation is about 2.5 times the floor-to-ceiling height (CIBSE, 2015a), which is an appropriate range of about 9 m to 10 m for the studied school buildings. Such a strategy can be improved naturally by separating the inlet from the outlet to be further apart, but this would entail higher costs when refurbishing existing buildings, as it would require intervening in the facades. If required, it might be more appropriate to also look into cross-ventilation, which would increase the effective depth to 5 times the floor-to-ceiling height. This strategy could then be implemented in spaces such as auditoria.

The simulation results of implementing more vertical openings suggested that the number of discomfort hours due to overheating was significantly reduced, allowing most of the buildings to comply with the recommended thresholds. Such results were possible because it was assumed that continuous ventilation is feasible and/or the solar heat gains could also be reduced. The main implication of continuous ventilation is the possibility to take advantage of the free night cooling. Because of the lower night-time temperatures, the inside versus the outside temperature differences will be greater, and this will enhance both the stack-driven flow rates and the cooling capacity of the outside air. By cooling the fabric of the building by night ventilation, there is a reduction in the mean radiant temperature of the space, which improves the occupants' perception of thermal comfort during the following day.

This strategy implies, of course, that the night-time temperature is low enough to 'pre-cool' the building, but that might be not always the case. As discussed in Chapter 3, the city of Karlsruhe is already experiencing some hot days directly followed by warm nights, and although official heat waves in the region have not been registered since 2003, every year of the past four has reached new records of high temperatures (German Weather Service, 2019). It was noted that the DSY2035 does not reflect this situation and that the weather files of the French city of Marseille were used to exemplify the effect that heat waves could have on the refurbished school buildings. The simulations suggested that the number of discomfort hours would then be between 20% and 33% of the occupied time because the potential free night cooling is significantly reduced. The recommended measures cannot be based on heat wave conditions either, because they are not representative and would result in high costs. However, if temperatures continue rising and heat waves become more common, then mechanical ventilation could be considered. With such a measure, the potential of the few hours when the outdoor temperatures are lower than the indoor temperatures could be enhanced. One of the drawbacks would be the increase in energy consumption.

From this analysis, it can be concluded that the potential of natural ventilation should not be neglected, because its effect is significant, it can prevent high investment and maintenance costs, and the associated emissions will be low. However, the appropriate strategy should be analysed individually (by buildings and single spaces) and considering security risks, the thermal mass of the building, and the selection of the appropriate control strategy: manual or automated. If the decision is that the strategy is manually controlled, it must be clear who are the people involved and the tools that would be required to support the strategy, such as sensors of indoor and outdoor temperatures and indoor CO_2 levels.

The cumulative effects can also be observed in the combination of natural ventilation and shading from either electrochromic windows, blinds or external shading devices. When the solar radiation falls on the envelope of a building, the surfaces will warm up and the heat is transferred through the building fabric to the inside spaces. Solar radiation on windows will enter immediately and quickly warm up the air and surfaces of the room, whereas the radiation falling on the opaque building fabric such as walls and windows, takes a longer time to come through and warm the space up.

The solar heat gain to a room from solar radiation falling on a window in summer could be around 500 W/m^2 for a south-facing window in the city of Karlsruhe (PVGIS, 2009). Furthermore, if the outside air is warmer than inside, there will be also a heat gain through the building fabric, due to the air temperature difference, in addition to the solar gain. Windows are therefore a key source of external heat gains. The immediate measure to reduce solar heat gains is the use of blinds, since they are always available. Internal blinds can provide shading and help to reflect solar heat, when they are provided with a solar reflecting coating or a metallized finish on the reverse, but are less effective than external devices in reducing the solar gain, as much of the solar energy has already come through the window. This solar gain coming through the window can be absorbed by the shading device and still be transmitted to the room. Furthermore, blinds reduce the effect of natural ventilation and could reduce daylight significantly. A further option that could be implemented includes solar control films that can be added to the glazing, usually on the internal surface of the glass. Although it is a quite simple retrofit strategy, they can be damaged easily. Electrochromic glazing and external shading devices are thus the most appropriate options to reduce solar heat gains entering into the rooms; therefore, when these strategies can be implemented together with natural ventilation, the number of discomfort hours due to overheating can be reduced to comply with the recommended thresholds.

The optimization and the parametric analysis showed that the PCMs had a significant performance only at the lightweight buildings. As it was expected, the PCMs increase the thermal mass capacity of these rather thin walls constructed with light materials but there is another issue regarding thermal mass that has not been discussed yet. Because the main energy consumption is heating, the first set of refurbishment measures include the window replacement (with lower u-values) but also, the implementation of insulation; usually at upper roofs but also at walls when possible. Such a measure would significantly change the building heat storage capacity. In this regard, several studies have been made, but no consensus has been found about the potential increase in the risk of overheating. Mavrogianni et al. (2012) for instance studied dwellings in the United Kingdom and concluded that under certain cases, adding or increasing internal solid wall insulation could increase indoor temperatures. In a similar study, Mulville & Stravoravdis (2016) suggested that improving building fabric (increased insulation and reduced airtightness) increases the risk of overheating. However, Fosas et al. (2018) stated that despite the extensive research, the literature has failed to resolve the controversy of insulation performance and its potential risk of exacerbating overheating, primarily due to varied scope and limited comparability of results. Fosas and colleagues studied this problem through constructed pairwise comparisons designed to isolate the effect of insulation on overheating, considering a broad range of thermal influencing variables: latitude, climate, insulation, thermal mass, glazing ratio, shading, occupancy, infiltration, ventilation, orientation, and thermal comfort models. They suggested that insulation has been seen to both decrease and increase overheating, depending on the influence of other parameters. Their parameter ranking showed that insulation only accounts for up to 5% of overall overheating response. They claimed that in cases with acceptable overheating levels (below 3.7%), the use of improved insulation levels is not only sensible, but also helps deliver better indoor thermal environments. As it was discussed by these researchers, the simulations do not yield conclusive results either; while in general adding insulation reduces the thermal mass of the envelope, it is difficult to quantify their effect in the risk of overheating given the large amount of materials available in the market with very different properties. In any case, if historic buildings are insulated, the positive effect of the continuous ventilation would be significantly lower and additional measures to natural ventilation would be required.

9.2 Recommendations

Once the optimization process and the parametric analyses had evaluated the advantages and consequences of the potential low invasive solutions, the similarities between building types were gathered to propose some recommendations. The simulations suggested that the heavyweight buildings could take great advantages of their mass to prevent overheating by means of good ventilation. If a good strategy can be implemented, it would not be necessary to take other measures, such as windows with sun protection or external shading. However, as continuous ventilation might not always be feasible, ceiling fans would be recommended to increase thermal comfort.

The buildings with light partitions can still take advantage of an improved ventilation strategy, but an additional measure would be required to achieve thermal comfort. In these cases, depending on how the windows could be upgraded, a further measure such as ceiling fans or external shading should be evaluated according to the costs. The lightweight buildings, however, require more sun protection to prevent overheating. Therefore, it would be recommended to install electrochromic glazing or combine two other passive measures. The previous recommendations are summarized in the roadmaps in Figure 90 to Figure 92.

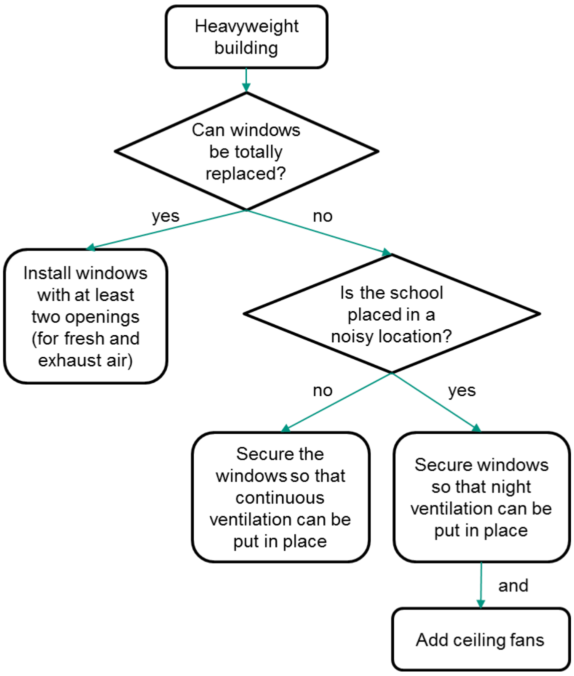

Figure 90: Roadmap of recommended refurbishments for school buildings like those in Group A

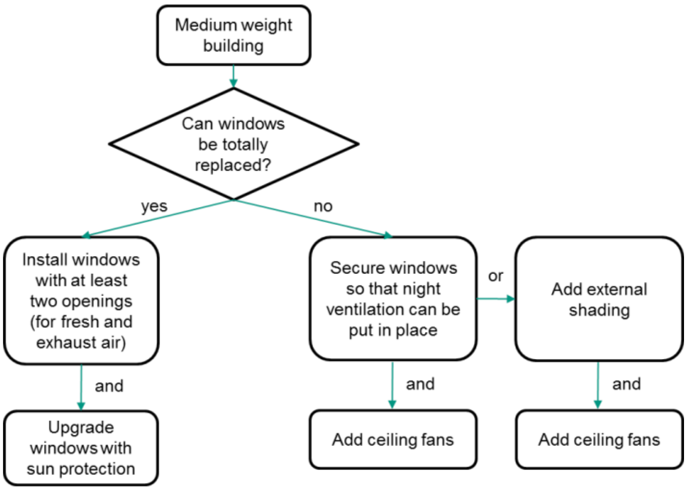

Figure 91: Roadmap of recommended refurbishments for school buildings like those in Group B

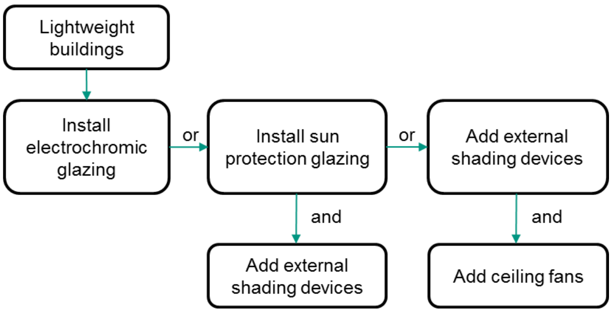

Figure 92: Roadmap of recommended refurbishments for school buildings like those in Groups C & D

10 Other passive measures

This study focused on low-invasive measures that could be evaluated by means of Dynamic Thermal Simulations. However, other technologies and solutions are emerging and even though they could not be evaluated in this study, and for some, there is still not enough information about their performance, it may be interesting to inquire about them in the near future. This section briefly explores some of them

10.1 Green roofs

It was discussed in the previous chapter that isolating buildings to improve their performance during the winter might increase their risk of overheating. For historic buildings, the most common and relatively easy practice is to insulate the pitched roof, in fact, as it was shown in Chapter 4, this measure has already been put in place in some school buildings. In existing buildings with flat roofs, the refurbishment is more complex, where the overlay is one of the most common practices. In the overlay, the existing waterproof membrane is converted in a vapour check layer and insulation is added with a new waterproof membrane over, creating a warm roof (Greenspec, 2019). However, there is another type of insulation that has proved to deliver high performance in winter as well as in summer; green roofs. The heat insulating properties of plants are based on various factors. The transmission losses are reduced by the enclosed air volume, acting as an insulation layer, and the emitted amount of longwave radiation is reduced by absorption and reflection of the plants. The plant layer also protects against the wind; the thick layer of plants reduces air movement at the exterior surface of the structure and hence reduces the convective heat loss. But green roofs also reduce overheating in the summer, as the plant layer absorbs and reflects the short wave radiation from the sun. The absorbed energy is then used through evaporative processes and photosynthesis and adds therefore not to the heating of the building (University of Siegen, 2019).

10.2 Reverse windows

The main issue of existing low emissivity windows is that the coatings are either placed on the outer (maximum solar gain, desirable in winter) or the inner side (minimum solar gain, desirable in summer) of the glazed unit. But there have been some prototypes of reversible windows where the users can rotate the sash 180 degrees from a winter to summer position and vice versa to change the position of low-e coating to select the right configuration. However, not many applications have been found. The Company *Bergamo Tecnologie* has one of them. According to their simulation results shows conducted in five cities: Bilbao, Ankara, Malmö, Oslo, and Zagreb, it was possible to reduce up to 6 kWh/m^2 in the energy consumption in comparison with a fixed window in solar protection position (A2PBEER, 2019). The idea, however, is not new. Feuermann and Novoplansk investigated in 1997 through computer simulations the energy savings achievable by reversing equator-facing windows for the duration of the cold season as opposed to leaving them in the ‘‘summer position’’. They suggested that the magnitude of the effect is climate dependent with colder and clearer climates being the best candidates to achieve higher energy consumption reductions. They recognized however that their study was non-exhaustive and that more cost-benefit studies with pilot projects should be conducted.

10.3 Films on windows

Spectral-selective coatings tints, films, and coatings on the glass are able to reduce solar gains without unduly reducing visible light transmittance. Window films are cost-effective solutions to reduce overheating, are easy to install and cause little disruption. However, various authors have discussed various disadvantages. While films block unwanted solar energy, they also block desirable visible light; in some cases, highly reflective window films with metalized heat-reflective coatings also block as much as 85% of the visible light outside from entering the inside of a building (Mylona, 2016). Additionally, they cause in the external appearance of windows, which can have a negative impact on property values. The durability of window films depends on varied factors such as climate and solar exposure; if they are correctly installed, their life span could be from five to ten years (Bahadori et al., 2017). Therefore, before opting for such a solution, it should be analyse if other measures have a better cost-effective performance during the life cycle.

10.4 Double-skin façade ventilation

A double-skin façade is a special form of the solar chimney where the whole façade acts as an air duct. The aim is to trap the solar gain in a cavity between inner and outer skins, and then ventilate the heat away to outside before it heats up in excess the adjoining occupied space. Usually, the cavity is naturally ventilated but in some applications, mechanical systems are involved. Careful design should be made in order to consider the thermal and lighting performance of the façade, together with the regulations on fire protection. This application is naturally more common at new buildings, where the complete designed can be controlled, but there are several successful in refurbishment applications. The most common application in existing facades are at glazed buildings, where adding a properly designed second skin can result in energy savings (heating and cooling) and improved thermal and visual comfort, improved sound attenuation and exterior solar shading, which is protected being covered by the second skin. However, the double skin facades are often more expensive than single skin facades. For a building, which is not highly glazed and with a high level of thermal insulation, the energy use for heating and cooling is likely to be lower, than for a highly glazed building with a double skin façade (Wardner et al., 2007). Therefore, each case should be evaluated with the specific whole building performance simulations and a complete life-cycle cost analysis. Furthermore, skin facades should be designed to perform according to the season. Some application may include a shading device to allow or avoid solar gains passing through the cavity. Figure 93 shows an example of a double façade at a glazed building and Figure 94 explains the operation principle of a double skin façade application in in summer and winter.

Figure 93: Glazed building with double skin façade.
Source: Wardner et al. (2007)

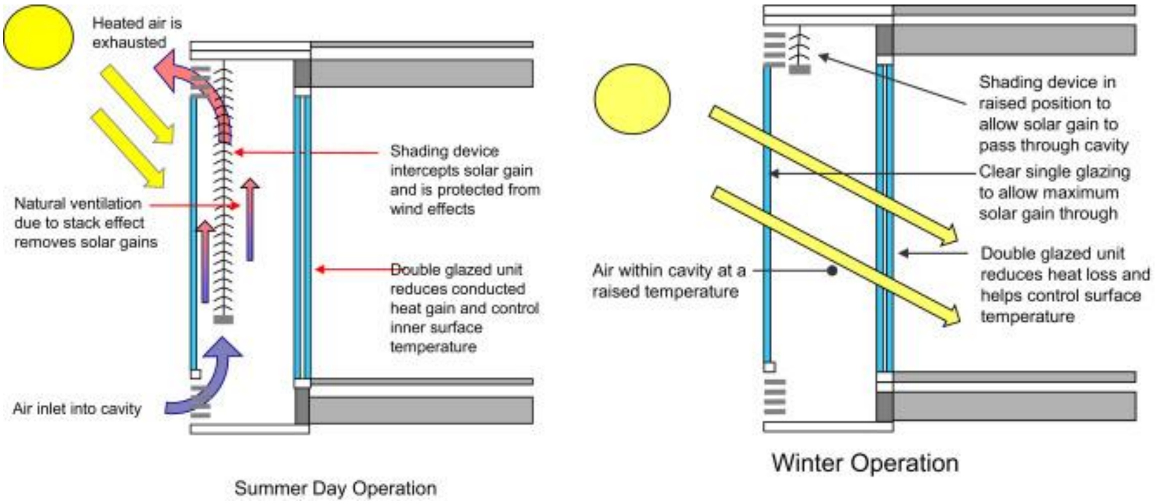

Figure 94: Operation principle of double skin facades in summer and in winter.
Source: Kilaire, Stacey (2017)

10.5 Phase Change materials in air-handling units

Phase change materials (PCMs) can be used in both passive and active applications. This study analysed PCMs as panels in partitions to increase the thermal mass of lightweight buildings, but nowadays there are several more applications. For instance, PCMs can be integrated into air handling units and act as a storage system in order to shift the loads from on-peak to off-peak mode. Rahdar et al. (2016) investigated one of these applications and showed that the power consumption could be reduced by approximately 8% in comparison with a conventional system. Figure 95 shows the South Bank University in London, UK, where a top floor of an existing building was converted to have a dynamic passive cooling using PCM containers forming an Air Handling Unit (AHU) with circulation fans. The PCMs are set up with an air circulation freeze cycle at 22°C. Once the PCMs are frozen during office hours, this stored energy is used to handle the sensible loads of the space as free energy.

Figure 95: Example of PCMs integrated into an Air Handling Unit.
South Bank University. London, K. Source: author.

11 Conclusions

This study presented the assessment of low-invasive measures to improve thermal comfort in classrooms during the summer. Such evaluation was made by means of Dynamic Thermal Simulations (DTS) executed with the software DesignBuilder. The first phases included an extensive literature review to establish the state of the art, an analysis of the current and future climate conditions of the city, and the analysis of the building stock in the city to select an appropriate sample to investigate with the simulations. The subsequent stages involve the creation and calibration of the models. The evaluation of the measures was undertaken though sensitivity analyses and a multi-objective optimization process minimizing the number of discomfort hours and the investment costs. Finally, parametric analyses were undertaken to scrutinize the results, and consider side effects of the measures. With the similarities found between the most appropriate solutions for the different classifications of the buildings, recommendations were made prioritizing the most feasible measures in terms of costs and practicability.

The analysis of the building stock of the existing schools in Karlsruhe allowed classified them into four main groups: Group A with heavyweight buildings constructed before 1918; Group B with buildings with heavyweight envelopes but lighter partitions constructed in the 1950s and 1960s; Group C with medium weight constructions also from the 1950s and 1960s; and Group D with lightweight construction as typical from the 1970s. It was shown that no clear relationship was found between the buildings´ age of characteristics such as the surface-area-to-volume ratio and the window-to-wall ratio and the energy consumption. Although it is not clear why, it was considered that this could be attributed to the management of the buildings of the participation of some schools in the energy savings programs. As this analysis did not provide a path to select the sample for the study, the school buildings were ranked according to their heating and electricity consumption, and the highest consumers from each group were chosen, considering as well that the require information to undertake the simulations was available as far as possible. Eight school buildings were considered an appropriate sample, as they represented well the typical construction details found in the literature and the layouts of the school buildings of the city. Naturally, it is acknowledged that a greater number of schools would strengthen the results by increasing the size of the sample. However, it was considered that the constructive details would not have been very different, since they were chosen especially based on the literature, in the absence of finding this information in the database and the impossibility of conducting tests that would allow more exact data to be provided.

The climate analysis showed that although it was considered that the city enjoyed mild conditions, in the last years there has been an increase in the number of warm days (T>25°C, hot days (T>30°C) and warm nights (T>20°C). In addition, the prognosis of climate in the near future foresees an increase in the average temperature of the region of approximately 2.5°C. This situation showed that classrooms are currently experiencing overheating and it will exacerbate if no measures are undertaken. The simulations of the base-case scenarios suggest that the number of discomfort hours due to overheating under the current conditions are around 18% of the occupied time in the heavyweight buildings, 22% in the medium weight buildings and 25% in the lightweight buildings. By 2035, the percentage of overheating could rise to approximately 27%, 31%, and 37% respectively, which means a rise in overheating of about 10%.

The sensitivity analyses allowed analysing the effect of individual passive measures while the optimization process showed which measures are more suitable for each building type reducing at the same time overheating and costs. These results together with the deeper study of the measures made through the parametric analyses, allowed proposing recommendations for the potential refurbishments. The heavyweight buildings, for example, could significantly benefit from the natural ventilation, while the lightweight buildings would require the combination of two or more options. In any case, the ventilation strategy should be improved to guarantee good air quality, as the direct measures showed that the CO_2 levels in some classrooms are well above the recommended limit of 1500ppm.

Acknowledging the effect of higher flow rates on the improvement of adaptive thermal comfort, it was also recommended, when possible, to add openings in the windows or the use fans. According to the simulations, with these measures, it would possible to avoid overheating or reducing it in less than 5% in all types of school buildings.

With the identified common patterns, flowcharts were created to guide the developers. Such roadmaps firstly suggest the measures that are less invasive such as increased ventilation and glazing with lower solar transmittance. Each case, however, should be studied individually, as the trade-offs between thermal comfort and other aspects such as visual and hearing comfort.

11.1 Contribution to knowledge

This research has focused on evaluating the performance of combined low-invasive strategies in representative school buildings within a real-life context. This study integrates for the first time the characteristics of the different building construction types, the forecasts of climate change, the specific requirements for educational environments, and the individual and combined effects of the measures to reduce overheating, together with their investment costs. The methodology implemented was developed by the author in the search of quantitative methods to be followed in each of its phases, in order to guarantee robust results.

Exploring the effects of the measures under different climatic conditions as well as in individual and combined contexts, helped understanding the results for the different building types. Even though the study focused on one classroom per school building, often, working with specific examples provides better understanding of the whole. The simulations were based on several assumptions of parameters (heat gains, openings operation, thermal mass, obstacles etc.) that were kept consistent through the study.

By following sensitivity analysis, optimization processes and parametric runs critical conditions of classrooms, valuable guidance for future refurbishment projects could be identified. The buildings under investigation are representative of more than 80% of the school buildings of the city, and although it is always recommended to analyse each case individually, it is considered that the evaluated measures are applicable to buildings with similar characteristics, significantly improving the environmental indoor quality of the classrooms.

The low-invasive evaluated measures have been shown to have potential in reducing overheating without a significant increase on the energy consumption. This is important because it will reduce costs and also contribute significantly to the battle against climate change.

List of Figures

List of Tables

List of abbreviations

BREAM® - Building Research Establishment Environmental Assessment Methodology.

DSY – Design Summer Year.

EnEV -German Energy Saving Ordinance.

HGW – Amt für Hochbau und Gebäudewirtschaft – Office of Construction and Building Industry.

HVAC - Heating, Ventilation and Air Conditioning.

IAQ - Indoor Air Quality.

IEQ - Indoor Environmental Quality.

LEED® - Leadership in Energy and Environmental Design.

LENB – Leitlinie Energieeffizienz und Nachhaltiges Bauen – Guideline on energy efficiency and sustainable buildings.

SEAP - Sustainable Energy Action Plan.

TRY – Test Reference Year.

USGBC – United States Green Building Council

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Appendices

Appendix A: Buildings´ construction details

- Bismarck-Gymnasium

External walls	Massive. U≈1,5 [W/m^{2}K] 10mm Mortar, 100mm Sandstone, 240 Brickwork, 10mm Mortar
Internal partition	Massive. U≈1,2 [W/m^{2}K] 13mm Gyps, 320mm Brickwork, 13mm Gyps
Ceiling/ Floor	U≈0,9 [W/m^{2}K] 6mm Linoleum, 30mm Screed, 300mm Cast concrete, 15mm Acoustic panel
Glazing	Double U≈2,7 [W/m^{2}K]

- Kant Gymnasium

External walls	Massive. U≈1,4 [W/m^{2}K] 320mm Brickwork, 10mm Plaster
Internal partition	Massive. U≈1,2 [W/m^{2}K] 10mm Gyps, 320mm Brickwork, 10mm Gyps
Ceiling/ Floor	U≈0,7 [W/m^{2}K] 6mm Linoleum, 50mm Screed, 300mm Cast concrete, 15mm Fiber board
Glazing	Double U≈2,7 [W/m^{2}K]

- Pestalozzischule

External walls	Massive. U≈1,5 [W/m^{2}K] 10mm Mortar, 100mm Sandstone, 240 Brickwork, 10mm Mortar
Internal partition	Massive. U≈1,2 [W/m^{2}K] 13mm Gyps, 300mm Brickwork, 13mm Gyps
Ceiling/ Floor	U≈1 [W/m^{2}K] 6mm Linoleum, 50mm Screed, 250mm Cast concrete, 15mm Acoustic panel
Glazing	Double U≈2,7 [W/m^{2}K]

- Schloβschule

External walls	Massive. U≈1,1 [W/m^{2}K] 13mm Ceramic tiles, 75mm Brickwork, 5mm Air gap, 200mm Concrete Block, 13mm Plaster
Internal partition	Light. U≈1,9 [W/m^{2}K] 13mm Gyps, 240 Air gap, 13mm Gyps
Ceiling/ Floor	U≈0,7 [W/m^{2}K] 6mm Linoleum, 50mm Screed, 300mm Cast concrete, 10mm Gyps, 5mm Air gap, 15mm Acoustic panel
Glazing	Double U≈2,7 [W/m^{2}K]

- Adam Remmele Schule

External walls	Massive. U≈1,1 [W/m^{2}K] 15mm Mortar, 180mm Brickwork, 25mm Air gap, 280 Brickwork, 15mm Mortar
Internal partition	Light U≈1,9 [W/m^{2}K] 13mm Gyps, 240 Air gap, 13mm Gyps
Ceiling/ Floor	U≈0,9 [W/m^{2}K] 6mm Linoleum, 30mm Screed, 330mm Cast concrete, 30mm Air gap, 15mm Fiber board
Glazing	Double U≈2,7 [W/m^{2}K]

- Grundschule Bulach

External walls	Light. U≈0,6 [W/m^{2}K] 100mm Brickwork, 50mm Air gap, 240 Concrete Block, 13mm Plaster
Internal partition	Light. U≈1,6 [W/m^{2}K] 13mm Gyps, 250 Air gap, 13mm Gyps
Ceiling/ Floor	U≈1.2 [W/m^{2}K] 6mm Linoleum, 25 Wood board, 250mm Air gap, 15mm Acoustic panel
Glazing	Double U≈2,7 [W/m^{2}K]

- Max-Planck-Gymnasium

External walls	Light. U≈0,7 [W/m^{2}K] 100mm Brickwork, 50mm Air gap, 180 Concrete Block, 13mm Plaster
Internal partition	Light. U≈1,6 [W/m^{2}K] 13mm Gyps, 250 Air gap, 13mm Gyps
Ceiling/ Floor	U≈1,0 [W/m^{2}K] 6mm Linoleum, 2omm Screed, 300mm Cast concrete, 200mm Air gap, 15mm Acoustic panel
Glazing	Double U≈2,7 [W/m^{2}K]

- Sophie Realschule (Schulzentrum Südwest)

External walls	Light. U≈0,6 [W/m^{2}K] 105mm Brickwork, 50mm Air gap, 200mm Concrete block, 13mm Plaster
Internal part.	Light. U≈1,7 [W/m^{2}K] 13mm Gyps, 1000 Air gap, 13mm Gyps
Ceiling/ Floor	Light U≈2,2 [W/m^{2}K] 6mm Linoleum, 200mm Cast concrete, 13mm Plaster
Glazing	Double U≈2,7 [W/m^{2}K]