DIPLOMARBEIT

PHASE CHANGE MATERIALS AS A THERMAL RETROFIT OPTION FOR BUILDINGS IN THE CITY OF VIENNA

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KURZFASSUNG

Steigende Temperaturen im Sommer in Folge des Klimawandels und des Urban-Heat-Island Effektes sind große Herausforderungen für die Gebäudeplanung. Um die Innenräume auf eine nachhaltige Art und Weise innerhalb des thermischen Komfortbereichs zu halten, gibt es verschiedene Ansätze. Einer dieser Ansätze beruht auf dem Einsatz von Phase-Change-Materials (PCMs). Diese Materialien nutzen ein aus der Thermodynamik bekanntes Prinzip aus, nämlich die zusätzlich erforderliche Energie für Phasenwechsel (Schmelzen und/oder Verdampfen). Diese zusätzlich erforderliche Energie kann als Speicher für überschüssige Wärmeenergie in Innenräumen dienen. Es zeigt sich, dass die Anwendung solcher neuartiger Materialien für Zwecke des Einsatzes im Hochbau noch relativ wenig beforscht ist. Diese Arbeit befasst sich daher mit möglichen Anwendungsfeldern solcher Materialien. Dabei wird der Effekt des Einsatzes solcher Materialien anhand von Case Study Bauwerken bzw. Räumlichkeiten in Case-Study Bauwerken im Wiener Kontext untersucht. Wesentlich Annahmen in dieser Masterthese sind, dass beim Einsatz der Materialien dem Gebäudenutzer nicht die Möglichkeit genommen wird, das Fenster zu öffnen, bzw. keine zusätzlichen Verschattungseinrichtungen montiert bzw. konstruiert werden.

Im Detail wird in dieser Arbeit ein Phase-Change-Material mit variierender Schichtdicke, Anzahl der Elemente und unter unterschiedlichen Belüftungsszenarien untersucht und zwar anhand zweier Zimmer eines Wiener Altbaus. Methodisch kommt hier numerische thermische Simulation zum Einsatz. Die Hauptforschungsfrage ist, ob die Anwendung von Bauteilschichten aus Phase-Change-Materials zu signifikanten Verbesserungen des thermischen Komforts in den Räumlichkeiten führt (im Vergleich zu Fällen ohne diese PCMs). Zusätzlich wird untersucht, welche weiteren Parameter die Wirksamkeit dieser Maßnahme beeifnlussen. Die Resultate dieser Bemühungen zeigen, dass PC-Materialien bei angemessener Applikation zu signifikanten Verbesserungen des thermischen Komforts führen können.

Unterschiedliche Parameter wie Belüftung, Materialpositionierung, Materialdicke sowie Anwendungsumgang wurden via Simulation getestet. Eine Erkenntnis aus diesen Bemühungen ist, dass eine dünnere Schicht verteilt über eine größere Oberfläche eine bessere Performance zeigt, als eine dickere Schicht verteilt über eine kleinere Oberfläche. Zudem hat sich bezüglich der Positionierung herausgestellt, dass eine Deckenmontage die beste Leistung erbringt. Der Parameter Belüftung war die Variable mit dem höchsten Einfluss auf die Performance des Systems.

Abschließend kann festgehalten werden, dass Phase-Change-Materials bei angemessener Belüftung in Räumlichkeiten eine Verbesserung hinsichtlich des thermischen Komforts

darstellen können. Im Kontext der Wiener Klimadaten kann festgehalten werden, dass hier genug Abende mit ausreichender Temperaturabsenkung vorliegen um eine Wiederverfestigung in den Materialien auszulösen – dabei ist ein entsprechendes Lüftungsregime vorzusehen.

ABSTRACT

With rising summer temperatures, so rises the challenge of keeping rooms thermally comfortable by using little to no energy. Phase change materials can store excess heat from a space by using it to change their phase. Still being new and relatively unexplored as building materials, this work targets the possibility of such a material to bring typical Viennese rooms into thermally comfortable region without using active cooling systems, all while giving occupants the freedom to open windows or avoid shading devices.

In this work, one specific phase change material was simulated with various layer thicknesses, quantities and ventilation schedules for two Viennese rooms, one of which represented a normal overheating prone and the other a critical space. Main research questions ask whether implementing a layer of phase change material in the room can bring significant improvements to thermal comfort. Additionally, an effort is made to understand and explain influencing factors for incorporation of phase change materials.

Results showed that a typical Viennese room could be significantly improved from a thermal comfort perspective, when a phase change material layer was properly introduced and ventilated. Critical rooms could also be notably improved, however adding high quantities of phase change material to the rooms could defeat the purpose.

Behaviour of phase change materials was better understood by testing various cases of ventilation and materials' positioning, layer thickness and area coverage. Simulations showed that when the same quantity of phase change material was tested, a thinner layer spread across a larger surface behaves better than a thicker one spread across a smaller surface. Additionally, best positioning in the room performance wise is found to be the ceiling. Ventilation proved to be the variable with most influence on performance.

Conclusions were drawn that, assuming the room is properly ventilated, phase change materials alone could guide a room into thermally comfortable region, more or less depending on rooms' and environments' conditions. From a weather perspective, Vienna has evenings that have low enough temperatures to cool the phase change material to the solidifying point, it is only important to ventilate the room enough during evening hours.

Keywords

PCM, passive cooling, natural ventilation, energy efficiency, thermal comfort, historical buildings retrofit.

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CONTENTS

1 INTRODUCTION

1.1 Overview

As summer temperatures are steadily increasing from one year to the next (EEA, 2017), we are starting to realise the impact of overheating and the issues that come along. According to the European Commission (EC, 2016), half of the produced energy in Europe is consumed on heating and cooling purposes. Cooling has a minor share on the yearly energy consumption, however the trend is increasing due to climate change and temperature rise.

Overheating can be tackled by means of active, passive cooling and both combined. Active cooling systems use energy in order to lower temperatures and are generally inefficient. To go along, refrigeration emits heat back into the atmosphere, thereby contributing to the increase of urban heat island effect. On the other hand, passive systems do not require any energy input, but generally have limited performance and are highly influenced by user behaviour.

New buildings are often being designed with various precautionary measures against overheating, from incorporation of thermal mass, sophisticated shading devices, highly efficient appliances, heat exchangers to green roofs, etc. However, already existing buildings have limitations on the application of retrofit measures. Some, like shading devices or efficient appliances, are easily implemented, whilst other measures are challenging or even impossible to apply. Thermal energy storage (TES) is one of the commonly used passive cooling methods. It is achievable by using sensible, latent or thermochemical heat storage. Sensible and latent heat storage are more suitable for building implementation. Often, buildings are equipped with a great deal of thermal mass, that is, sensible heat storage of materials used in the building construction. Rarely, but more increasingly, latent heat storage systems are used. Sensible heat storage depends on the specific heat capacity of a certain material. Latent heat is the function of the material's phase change enthalpy. During the phase transition, heat is stored in the material within a narrow temperature span. Phase change materials (PCMs) have gained increasing attention over the last decade, with the emergence of organic compounds which did not have the drawbacks of inorganic PCMs. Soares N. et al. (2012), have found that prior to 2003, only two review articles on PCM integration into buildings for increasing thermal efficiency were published, while just during the last years, more than 20 articles on that topic were published.

PCMs can help regulate indoor temperatures by absorbing excessive heat from a room and using in for the phase transition, substantially decreasing average and peak room temperatures. However, the performance of such materials highly depends on various factors, such as internal and external gains, occupancy, room usage, weather conditions, ventilation, etc. Therefore, in order to deeply understand the behaviour, influencing factors and possible issues with PCM incorporation, extensive simulations have to be made. PCMs can be used in active and passive systems. Active system implies that the PCM is paired with other smart technology in order to maximize efficiency. Passive systems rely on the natural change of weather through the day and year, with no additional inputs. This study will simulate and analyse the impact of one specific PCM for retrofit of historical buildings in Vienna. The study will focus on passive implementation. However, the framework created for this study will be applicable on any PCM, both in a passive or active system. In order to simulate PCM incorporation in Vienna, two typical rooms were chosen. Both located in an antique building, one on the 3rd floor and the other in the attic. Rooms will be simulated under different scenarios. The complete procedure will be furtherly explained in the method section.

Based on simulation results and scientific background knowledge, key influencing factors will be pointed out, and it is investigated if PCMs are suitable as a retrofit option for passive cooling in the city of Vienna.

1.2 Motivation

Several factors act as main motivators for this study; energy efficiency, sustainability and thermal comfort.

Energy efficiency is no longer a topic reserved only for the ones with an academic background. More and more people are now getting aware of its importance. However, in central European climate, where strong winters are expected every year, the challenge of being thermally energy efficient is perceived through the winter season. Lately, there is a growing need for summer overheating solutions. Newly designed and constructed buildings can be equipped with many passive and/or active solutions like shading devices, thermal mass, ground-coupled heat exchanger, AC unit, etc. Retrofitting existing buildings poses a different challenge due to various regulations and limitations. Shading and minimizing internal gains could be an efficient strategy to achieve a good level of thermal comfort. However one of key motivating factors in this study is to assess a solution which could allow occupants to enjoy daylight, while being in a thermally comfortable and energy efficient environment. PCMs might be the bridge that will make the aforementioned possible. They are yet to be fully explored as building materials, nonetheless, enough researches imply that they could bring significant benefits for the building sector. Only 16% of energy consumed for heating and cooling purposes in Europe is derived from renewable resources. Since passive cooling mechanisms are not consuming energy, they are financially feasible, as well as environmentally friendly, not contributing to UHI nor air pollution. It is substantial to test how well those solutions incorporate into retrofit scenarios.

Lastly, studies have shown that occupants perceive an overall better level of thermal comfort in naturally cooled rooms. PCMs give an opportunity for the occupant to control the indoor conditions by means of natural ventilation. As claimed by Hellwig, Brasche and Bischof (2006), 85% of people wish to have control over the indoor climate, and in naturally ventilated offices 87% do feel to have control.

PCM incorporation as a retrofit option for existing historical buildings could, therefore, be beneficial from an economic, environmental and thermal comfort standpoint.

1.3 Background

1.3.1 Overview

Increasing awareness on the importance of energy efficiency has brought up innovative ways to maximize efficiency, or decrease consumption. As aforementioned, the building sector accounts for around 50% of total Energy consumption in Europe. Therefore, in recent years, many new studies have appeared, exploring and validating various methods for lowering energy usage in the building sector. One particularly interesting method is TES. In the building sector, TES can function in two ways, by means of sensible or latent heat storage. As already mentioned, PCMs absorb heat in order to transition the phase, thereby using their latent heat storage capacity. By doing so, PCMs are materials that have high thermal capacity in comparison to their mass, making them suitable for lightweight constructions, therefore as well retrofit scenarios. Other than an Igloo, the first documented usage of PCMs for a residential building was an experiment conducted by Dr. Maria Telkes in 1947 (Telkes, M., 1978). Telkes incorporated 4m^3 of Glauber's salts in a house constructed in Dover, Massachusetts, USA. The system was designed for passive solar heating, however it was observed that PCM thermal storage was able to cool surrounding rooms in the summer. The, otherwise successful, experiment was terminated after two and a half seasons, when Glauber's salts disintegrated and lost their phase change transition capabilities. This experiment brought attention to the possibilities offered by PCMs and its drawbacks.

Phase change most suitable for thermal energy storage is the solid-liquid transition. In this group of PCMs, there are three different kinds; organic compounds, inorganic compounds and eutectics. At first, inorganic salt hydrates were used due to their high latent heat of fusion and general accessibility. Before realising the drawbacks of inorganic compounds, there was no need to experiment with organic PCMs, as they were more expensive and had lower heat of fusion. Only when it was realised that inorganic compounds have drawbacks, organic compounds were furtherly developed.

1.3.2 PCM incorporation possibilities

Two distinct groups of PCM incorporation are micro and macro encapsulation. Micro encapsulation showed up recently, when organic, non-abrasive, PCM compounds were discovered, that could be encapsulated into tiny containers and then mixed with other materials. Some examples are micro encapsulated PCM gypsum wallboards, PCM plaster, or more sophisticated microencapsulation ways, like furniture with micro encapsulated PCM, which leads to the clear advantages of micro encapsulation: They are easy to mount, whether in form of plaster, wallboard or a couch, it makes them easily implementable for retrofit scenarios. However, due to the limited quantity, performance is limited as well.

On the other hand, macro encapsulation is a more straightforward approach, where a body of PCM mass is placed in a container of any shape and placed in the space. More sophisticated ways of macro encapsulation are PCM panels – being thin and covering a large surface, they expose a lot of PCM volume to the temperature change. That leads to the advantages of macro encapsulation: They have bigger heat capacity limit, due to larger quantities that can be installed. Easy implementation for floors and ceilings, as well as attic spaces. However not the ideal solution for walls, because the panels could be damaged by drilling or piercing, etc. Which would create eventual leakage and ineffectiveness of the PCM panel. Another disadvantage of PCM macro encapsulation is that due to the thicker layer, incomplete melting might occur, as well as sub cooling. With regard to simulating the performance of PCMs, it is possible to represent both incorporation methods in EnergyPlus (the building energy simulation tool used in this study), although micro encapsulation would have to be simplified. As EnergyPlus works in layers, the micro encapsulated part would have to be divided in a volume-proportional layer. In order to avoid unnecessary simplification and loss of simulation accuracy as well as having larger heat storage capacity, the chosen incorporation method for this work is macro encapsulation. More precisely, macro encapsulated PCM panels will be tested, with different thicknesses. Further explanation will follow in the method section.

1.3.3 PCM selection

In order to consider a PCM for building applications, it first must fulfil certain requirements concerning thermodynamic, kinetic, chemical and economic properties. Materials used for phase change thermal energy storage must have a large latent heat and high thermal conductivity. Their melting temperature should be within thermal comfort range. To go along, they should melt congruently with minimum sub cooling, while being chemically stable, nontoxic and non-corrosive. Economically, of course, they should have a low production cost (Farid, M.M., et al., 2003).

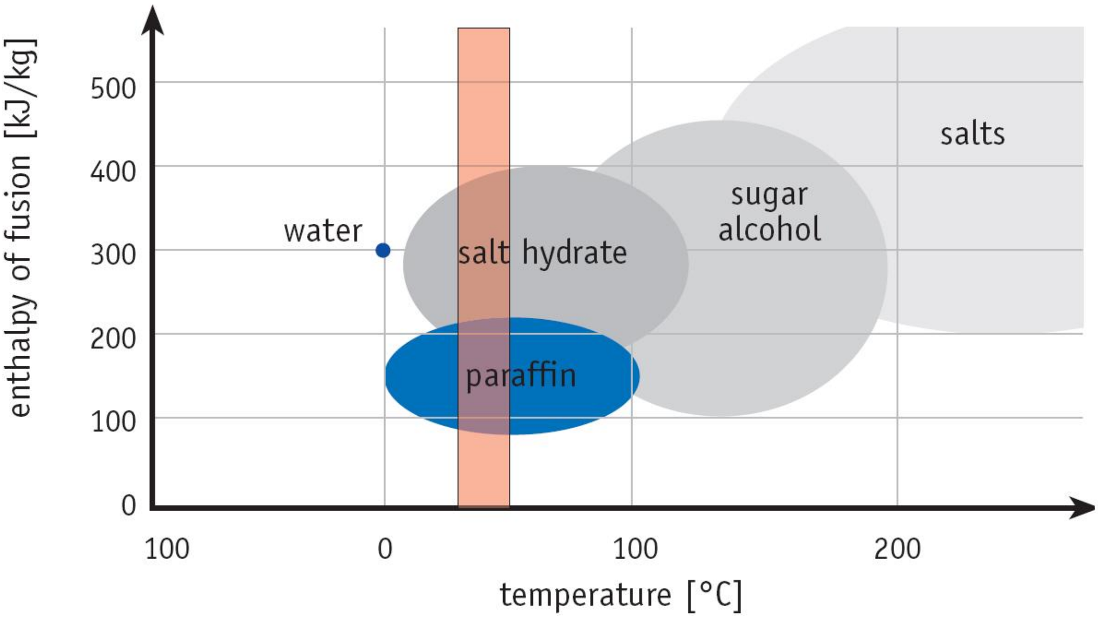

Figure 1: Temperature ranges and corresponding enthalpy of fusion of several PCMs. Red zone indicates the acceptable temperature ranges for residential usage.

According to Zhou et al. (2011), PCMs used in buildings must have the phase change temperature within thermal comfort criteria (18°C to 30°C). Khudhair, A.M. and Farid, M.M. (2002), have concluded that the optimal diurnal heat storage occurs with a melting temperature of 1-3°C above average room temperature. They claimed that PCM wallboards could save up to 20% on residential house conditioning costs. Many other articles have concluded that PCM implementation reduces energy consumption and/or that it can serve as a passive cooling mechanism (Lee, K.O. et al., 2014; Kenisarin, M. et al., 2015; Tyagi, V.V. et al., 2010; Sharma, R.K. et al., 2015). However, none of those studies were done for the city of Vienna.

Having in mind all aforementioned criteria for PCM selection, the chosen material for this study is a product of the company Entropy Solutions LLC based in Plymouth, Minnesota. The company developed the world's first completely renewable PCM. Recently, Entropy Solutions LLC created a PCM that has its melting point in the desired range for building usage, under the name PureTemp 25. It is an organic PCM, produced from agricultural resources. The material was tested over a 2-year period for 10.000 thermal cycles, where it proved to be stable, maintaining the melting temperature within ±1.1°C. That test period translates into more than 27 years of daily usage. If an assumption is made that, due to the Viennese climate, such a material would be used half of the days per year, the lifetime of the material extends to over 50 years, which makes it a very reasonable choice for a building material. Technical data sheet of the material follows in *Table 1*. Melting and solidification heat capacity graphs are shown in *Figure 2* and *Figure 3*.

As shown in the table and graphs, PureTemp PCM has been tested for separate melting and freezing curves, making it suitable for a more accurate EnergyPlus simulation, which will be furtherly discussed in the section about simulation engine validation.

Table 1: PureTemp 25 Technical Information

PureTemp 25 is a USDA Certified Biobased product	
Appearance	Clear liquid, waxy solid
Melting point	25 °C
Heat storage capacity	187 J/g
Thermal conductivity (liquid)	0.15 W/m°C
Thermal conductivity (solid)	0.25 W/m°C
Density (liquid)	0.86 g/ml
Density (solid)	0.95 g/ml
Specific heat (liquid)	2.29 J/g°C
Specific heat (solid)	1.99 J/g°C

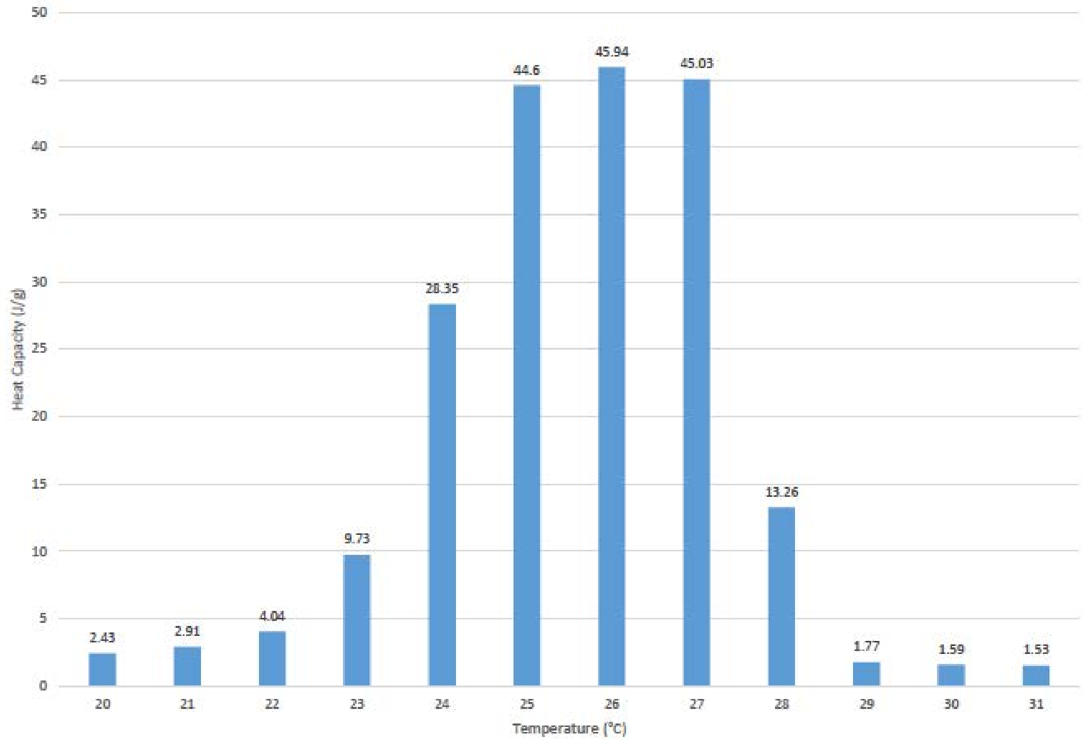

Figure 2: PureTemp 25 Heat Capacity Melt Histogram

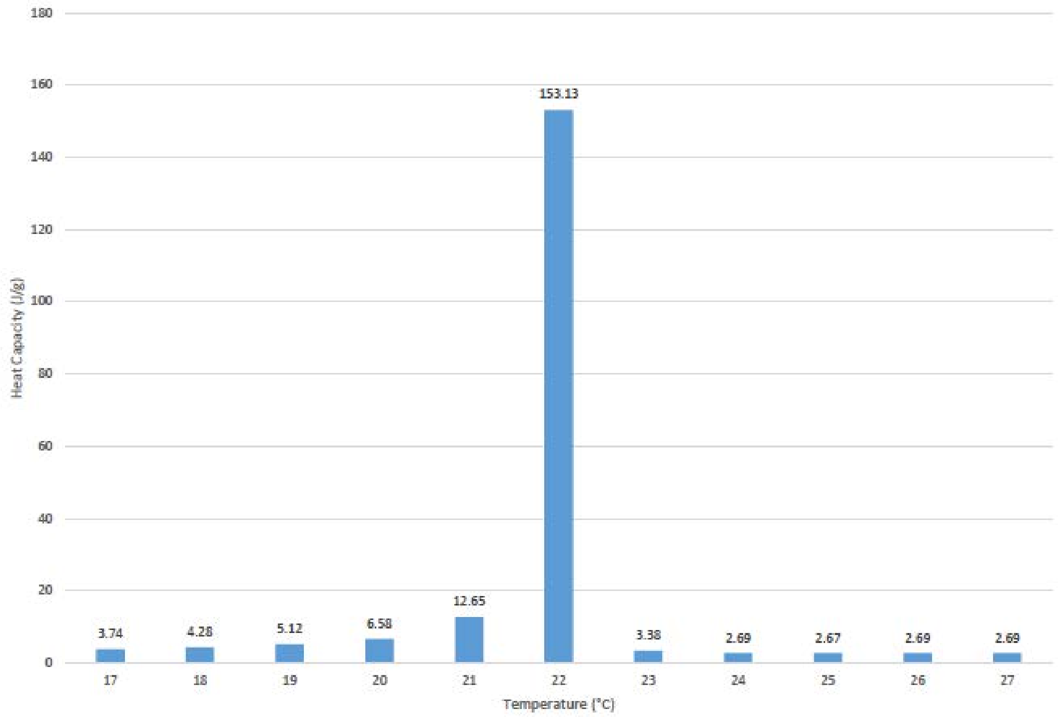

Figure 3: PureTemp 25 Heat Capacity Solidification Histogram

1.3.4 Simulation engine validation

To do a simulation work without an empirical study, one needs to be certain the simulation tool is accurate. Several authors tested the accuracy of EnergyPlus as a simulation tool for phase change materials and came to the conclusion that, given the accurate input assumptions and weather file, EnergyPlus is able to correctly predict PCM behaviour.

Tardieu, A. et al. (2011), have concluded that when EnergyPlus software was used to predict the thermal performance of office size test rooms in New Zealand, long term measurements conducted for the test rooms showed a good agreement with simulation results.

Tabares-Velasco, P.C. et al. (2012), verified and validated EnergyPlus phase change material model for opaque wall assemblies. The study identified key limitations of, and guidelines for using the EnergyPlus PCM model:

1. Time steps equal to or shorter than three minutes should be used
2. Accuracy issues can arise when modelling PCMs with strong hysteresis
3. Default CondFD can be used with acceptable monthly and annual results. However, if accurate hourly performance and analysis is required, smaller node space (1/3 of the default value in EnergyPlus) should be used at the expense of longer run times.

Point 2 was stated because the PCM model in EnergyPlus had only one input for temperature-enthalpy. A very common occurrence in PCMs is that the enthalpy graphs for melting and solidification are not the same. Therefore in the model they studied, subcooling was neglected. If a specific PCM does not have a strong hysteresis, accuracy is rather good, otherwise it can pose a problem. However, their conclusion came before EnergyPlus released the update (EnergyPlus and IDD version number: 8.9.0) and new material property object with phase change hysteresis. This model has not been validated yet, nevertheless it is safe to assume it will be accurate, having in mind that it is an extension to a previously validated model.

This study will use the updated Phase Change Hysteresis EnergyPlus model because PureTemp 25, PCM selected for this study, has been tested separately for melting and solidification, making it suitable for the Phase Change Hysteresis model, which will, ultimately, provide more accurate results. To go along, aforementioned points 1 and 3 will be applied to the study.

1.4 Research Questions

As stated in the motivation, driving factors for this study are energy efficiency, sustainability and thermal comfort. Research questions will target those topics.

Can PCM incorporation in a typical Viennese building provide enough latent heat storage to increase energy efficiency (by removing active cooling mechanisms) and thermal comfort? What are the most influencing factors when incorporating PCMs in a historical Viennese building?

2 METHOD

2.1 Overview

This thesis aims to provide a framework which will help test PCM retrofit scenarios for the city of Vienna in the cooling season, hence pointing at possible advantages and disadvantages as well as help determine some key incorporation factors such as PCM positioning, ventilation schedule and layer thickness for a specific PCM.

2.1.1 Environment selection

In order to determine key influencing factors, the general environment of the study must be clearly specified.

The study will revolve around one PCM and two rooms that are chosen to represent the majority of antique Viennese rooms. Both rooms are situated in the same building. Test room 1 (TR1) is considered to be a typical overheating prone space, located on the 3rd floor of the residential building, with two windows on the outside facing walls. Second test room (TR2) is considered potentially critical, being an attic space with little thermal mass and plenty outside facing surface area (*Figure 4*). This study will observe a five month period, where overheating is likely to happen, specifically from 1st of May until 30th of September. Transition periods are included in this timeframe, which could point to possible benefits of PCM to lower temperature fluctuations in such days where day temperatures are above and night temperatures below thermal comfort. All simulations will run for the entire year, and results will be output for the study period. Test rooms are located in a building located in the Viennese 4th district, built in 1829. Building plans of importance for this study can be found in the appendix. Input parameters for the simulation model will be discussed in the latter part of the text, however it is important to note that the building's constructions (Helmut, S. et al. 2012) and respective U-Values will be assumed based on Austrian standards and not from the plans. This decision was made in order for the test rooms to represent typical Viennese rooms more closely.

2.1.2 PCM Incorporation

As explained in the background, PCMs come with different incorporation methods. The PCM that is examined in this study will be simulated in form of a macro encapsulated panel with varying thicknesses (depending on the case of the sensitivity analysis). Panels were chosen amongst other incorporation methods for several reasons. First, they provide an easily applicable retrofit option. From insulation to aesthetics, panels are widely used in the building sector and already have a number of mounting techniques and possibilities. Even though some authors lean towards micro encapsulation as the better solution, a PCM that features macro encapsulation was chosen because it can be simulated very accurately with EnergyPlus. Simulating micro encapsulation would require a different data set and a slight simplification in the EnergyPlus software, where micro encapsulated PCM and the panel material would be divided in two (volume-related) layers. Other than that, a macro encapsulated PCM allows for the sensitivity analysis to test different thickness scenarios with ease.

Incorporation will be primarily focused on the ceiling because, along with the floor, as it is the least disruptive surface to place panels which should not be pierced. Placing them on walls could lead to usage issues, where occupants are not able to fully modify their living space. Nonetheless, it will be tested whether or not PCM positioning on walls can bring benefits, ignoring the aspect of space comfort, in an architectural sense.

2.1.3 Modelling and software

Test rooms were modelled using SketchUp 2016 software and OpenStudio plugin (version 1.13.0). All geometry information was taken from building plans and Google Earth was used as a reference for the creation of shading objects affecting the test rooms. OpenStudio is a plugin that acts as a bridge between the SketchUp and EnergyPlus model, translating geometry in the format EnergyPlus needs, also allowing to change construction names, boundary conditions, create windows, thermal zones, etc. That way OpenStudio plugin largely facilitates the transition of geometry to EnergyPlus. Upon completion, the model was exported into an IDF file using OpenStudio plugin and furtherly adjusted and simulated with EnergyPlus simulation software (IDD version number: 8.9.0).

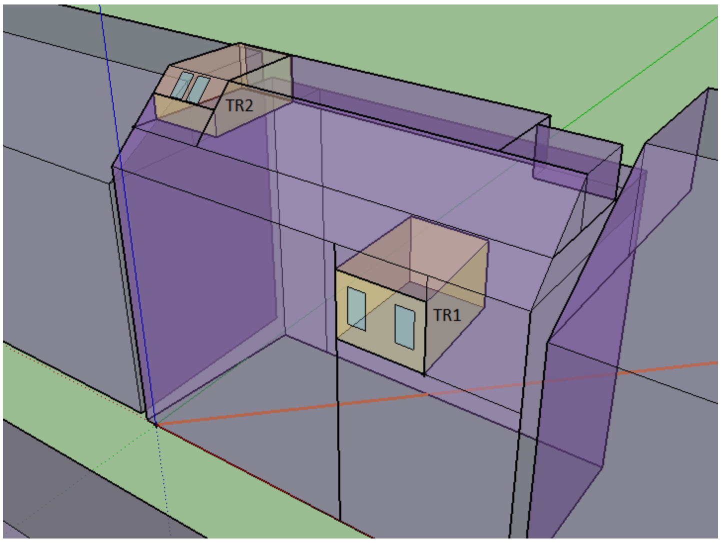

Figure 4: OpenStudio model of the test rooms

2.2 Input parameters

Simulating the impact of PCMs is not trivial. Many factors can influence simulation outcomes and in order to derive a scientifically valid conclusion, various cases need to be simulated. In order to do so, a starting point needs to be defined as well as which input parameters are prone to change and which are not. The baseline case was modelled following standards and guidelines as well as on-site information.

2.2.1 Baseline case

Base case model will serve as a benchmark for PCM simulations. Its input parameters are defined largely by Austrian standards and actual building conditions. Geometry was taken from building plans, however, constructions and consequential U-Values were taken from the Austrian guideline (OIB-RL 6, 2015), as shown in *Figure 5*. This decision has been made in order for these test rooms to represent the vast majority of Viennese rooms, which are prone to overheating.

Operable shades were not modelled in two test rooms because the goal of this study is to assess PCM performance and not techniques to minimize internal gains. Ventilation is required for PCM operation, hence testing ventilation strategies will follow. Every change that does not directly affect PCM performance was, therefore, left out of the sensitivity analysis.

Epoche / Gebäudetyp	KD	OD	AW	DF	FE	g	AT
vor 1900 EFH	1,25	0,75	1,55	1,30	2,50	0,67	2,50
vor 1900 MFH	1,25	0,75	1,55	1,30	2,50	0,67	2,50
ab 1900 EFH	1,20	1,20	2,00	1,00	2,50	0,67	2,50
ab 1900 MFH	1,20	1,20	1,50	1,00	2,50	0,67	2,50
ab 1945 EFH	1,95	1,35	1,75	1,30	2,50	0,67	2,50
ab 1945 MFH	1,10	1,35	1,30	1,30	2,50	0,67	2,50
ab 1960 EFH	1,35	0,65	1,20	0,55	3,00	0,67	2,50
ab 1960 MFH	1,35	0,65	1,20	0,55	3,00	0,67	2,50
Systembauweise	1,10	1,05	1,15	0,45	2,50	0,67	2,50
Montagebauweise	0,85	1,00	0,70	0,45	3,00	0,67	2,50

Bei den angegebenen Werten handelt es sich grundsätzlich um Mittelwerte aus der Erfahrung und nicht um schlechtest denkbare Werte.

Legende:

- KD ... Kellerdecke
- OD ... Oberste Geschoßdecke
- AW ... Außenwand
- DF ... Dachfläche
- FE ... Fenster
- g ... Gesamtenergiedurchlass-grad
- AT ... Außentüren
- EFH ... Einfamilienhaus
- MFH ... Mehrfamilienhaus

Systembauweise ... Bauweise basierend auf systemisierter Mauerwerksbauweise o.ä.

Montagebauweise ... Bauweise basierend auf Fertigteilen aus Beton mit zwischenliegender Wärmedämmung

Für alle nicht erwähnten Bauteile wie z.B. Kniestockmauer-werk, Abseitenwände, Abseitendecken sind grundsätzlich die entsprechenden Werte für Außenbauteile zu verwen-den.

Figure 5: OIB-RL 6 2015 Historical U-Values

Following simulations used a weather file provided by EnergyPlus, sourced to ASHRAE IWEC. The ASHRAE IWEC 1.1 database contains "typical" weather files for 227 locations outside the USA and Canada. The International Weather for Energy Calculation (IWEC) files are derived from up to 18 years of DATSAV3 hourly weather data originally archived at the National Climatic Data Centre (EQUA, 2018).

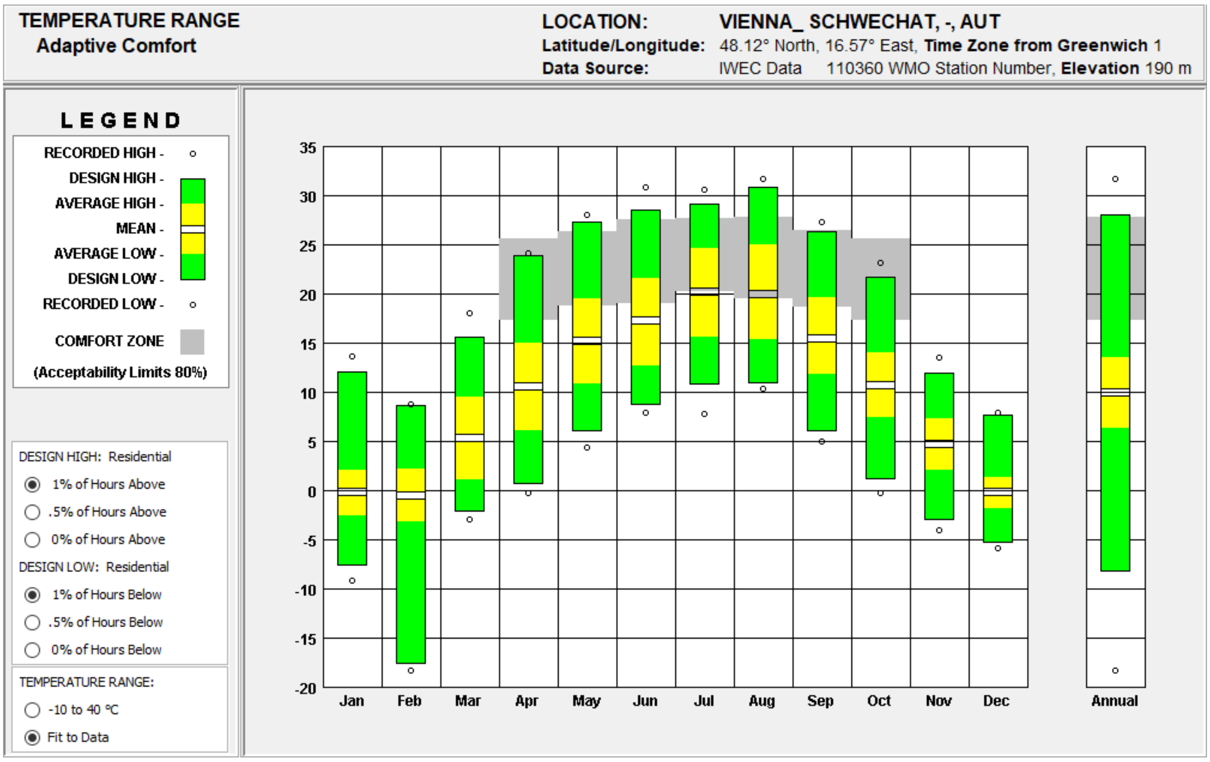

Figure 6: Overview of the IWEC standard weather file

This weather file is, arguably, underestimating peak summer temperatures. According to weather databases in Vienna (TAD, 2018), peak high temperature in July 2017 was 34°C and in August 2017 was 38°C. However, the IWEC weather file gives maximum temperatures of 30,5°C and 31,5°C in July and August respectively (*Figure 6*). Average monthly and peak low temperatures, however, match rather well. This weather file will be used in the upcoming simulations as it is the standard weather file for the city of Vienna. For the sake of having a representation on how would test rooms behave under more severe weather conditions, scenarios thought to be best performing for both test rooms will be simulated with a weather file measured on the TU Vienna weather station through year 2012. Pictured below (*Figure 7*), this weather file has considerably higher peak high values than the standard weather file, therefore it will show the behaviour of test rooms under extreme heat waves. Peak temperatures of the TU Vienna weather file match relatively well with the aforementioned historic weather database for year 2012.

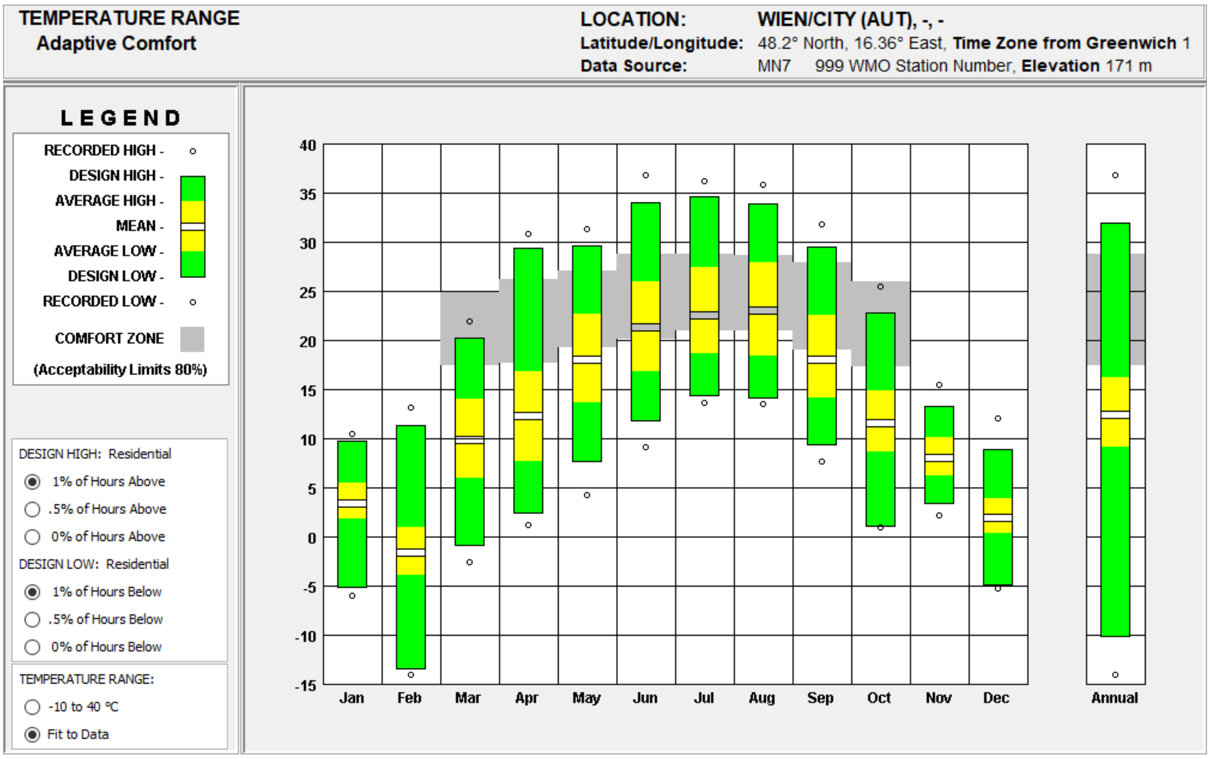

Figure 7: Overview of the TU Vienna weather file

Schedules and values for internal gains from occupants and equipment as well as minimum required ventilation are taken from the standard ÖNORM B 8110-3-2012-3-15, as shown in *Table 2*.

Table 2: Residential schedules for people and appliances from ÖNORM B 8110-3-2012-3-15

Residential				
Time of day	Appliances	People		Ventilation
	Specific heat output	Specific heat output	Specific hygienic airflow	Specific airflow
h	W/m²	W/m²	m³/m²h	m³/m²h
00:00 until 01:00	1,76	3,76	1,411	1,411
01:00 until 02:00	1,67	3,76	1,411	1,411
02:00 until 03:00	1,8	3,76	1,411	1,411
03:00 until 04:00	1,8	3,76	1,411	1,411
04:00 until 05:00	2,61	3,76	1,411	1,411
05:00 until 06:00	5,76	3,76	1,411	1,411
06:00 until 07:00	5,09	3,76	1,411	1,411
07:00 until 08:00	8,06	0,94	1,411	1,411
08:00 until 09:00	6,84	0,94	0,353	1,411

09:00 until 10:00	6,3	0,94	0,353	1,411
10:00 until 11:00	5,67	0,94	0,353	1,411
11:00 until 12:00	4,1	0,94	0,353	1,411
12:00 until 13:00	3,47	0,94	0,353	1,411
13:00 until 14:00	3,33	2,82	0,353	1,411
14:00 until 15:00	5,36	2,82	1,058	1,411
15:00 until 16:00	6,3	2,82	1,058	1,411
16:00 until 17:00	7,7	2,82	1,058	1,411
17:00 until 18:00	6,71	3,76	1,058	1,411
18:00 until 19:00	6,26	3,76	1,411	1,411
19:00 until 20:00	5,36	3,76	1,411	1,411
20:00 until 21:00	4,32	3,76	1,411	1,411
21:00 until 22:00	3,11	3,76	1,411	1,411
22:00 until 23:00	2,7	3,76	1,411	1,411
23:00 until 24:00	1,98	3,76	1,411	1,411

Infiltration values are assumed to be 0.2 air changes per hour for both TR1 and TR2. TR1 has windows only on one wall, while TR2 has windows on two sides, therefore air change rates will be defined for one and two sided ventilation. Natural ventilation will, by schedule, be active only for the study period. Starting values for natural ventilation are tilted windows during daytime and open windows during the night (values and schedules explained in *Table 3*).

As aforementioned, the study period starts in May and ends with September but the simulation runs for the entire year. Duration of study equals to 3672 hours. A basic HVAC system is set up to run in the period that will not be presented in the results, in order to maintain the temperature at 22°C before the study period. Test rooms will be occupied only during the study period, for the reason that EnergyPlus' adaptive comfort model outputs the time criteria was not met during occupied hours, that way the results can be filtered only for that period.

2.2.2 Variables & Nomenclature

In order to easily distinguish between different simulation cases and to provide crucial information on the case through the name itself, a naming system must be established.

2.2.2.1. Distinction between test rooms

TR1 – Defined in the method overview, represents test room 1, the "standard" Viennese room

TR2 – Represents the "critical" Viennese room

2.2.2.2. Distinction between cases

PCM – This will stand for simulation cases that include phase change materials.

CTRL – Abbreviated from control, these simulations will represent cases without PCMs

2.2.2.3. Variables

Ventilation – Only variables in the ventilation object are air change rate and operational schedule. Four air change patterns will be defined, as seen in *Table 3*.

Table 3: Natural ventilation assumptions

Window aperture		Air change rate (h^{-1})
Windows tilted	One-sided	0.5
	Two-sided	1.0
Windows open	One-sided	2.0
	Two-sided	4.0

To go along, 2 ventilation schedules will be designated: Daytime ventilation (DV) from 7:00 to 19:00 and Night ventilation (NV) from 19:00 to 7:00. Baseline case will feature a ventilation schedule as follows: tilted windows during daytime and open windows during the evening. This ventilation schedule is thought to be, intuitively, a realistic and efficient starting point.

PCM positioning – Each test room has 3 distinct surface types; ceiling/roof, floor and walls (those divided into outside, adjacent and partition walls). Abbreviations are as follows: ceiling (C), roof (R), tilted roof (RT), outside wall (OW), adjacent wall (AW) and partition wall (PW). *Figure 8* shows the surfaces. *Table 4* links surfaces to respective areas.

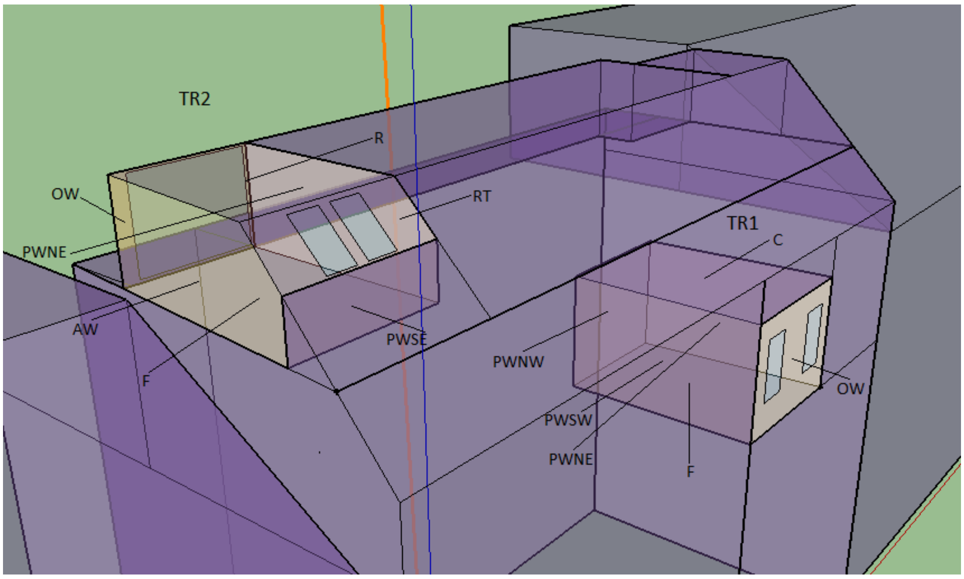

Figure 8: Test rooms and respective surfaces

Table 4: Surface areas & abbreviations

Test room	Surface name	Abbreviation	Area [m^2]
TR1	Ceiling	TR1_C	25.97
	Floor	TR1_F	25.97
	Outside wall	TR1_OW	12.74
	Partition wall Southwest	TR1_SW	21.28
	Partition wall Northwest	TR1_NW	14.76
	Partition wall Northeast	TR1_NE	21.34
TR2	Roof	TR2_R	17.79
	Tilted roof	TR2_RT	4.22
	Floor	TR2_F	22.32
	Adjacent wall	TR2_AW	14.18
	Partition wall Southeast	TR2_SE	5.68
	Partition wall Northeast	TR2_NE	14.12
	Outside wall	TR2_OW	1.72

<u>PCM layer thickness</u> – Third variable throughout cases is the layer thickness of the PCM panel. Multiple values will be tested, 3cm, 5cm and 7cm layers. This range of thicknesses is commonly seen on the market.

2.2.2.4. Sensitivity analysis

Sensitivity analysis will consist of various alterations of the aforementioned variables. Ventilation scenarios will be tested through different PCM thicknesses and positioning and results will be compared in the following sections. Some ventilation scenarios are presented in *Table 5*, respective air change rates in *Table 3*.

Table 5: Ventilation scenarios

	Window aperture						
Daytime ventilation	Tilted	Tilted	Open	None	None	None	Open (VC*)
Night ventilation	Open	Tilted	Open	Tilted	Open	None	Open (VC)

** VC refers to special case of ventilation control*

For a special case of ventilation control, two conditions will be applied to the natural ventilation schedules. First, ventilation will be active if outside temperature is lower than inside ($T_{in}>T_{out}$) and secondly, ventilation will be functioning if the first condition is fulfilled and as long as room temperature is above 18°C. This is done to represent natural ventilation conditions in a realistic manner, where window opening is a more dynamic activity, depending not only on inside conditions and not easily representable with a fixed schedule. Additionally, this limit should reduce overcooling of the rooms. These values were assumed with guidance from the study by Marais, J.M. and Teichmann, C., 2014. Special case conditions will be applied only to one ventilation scenario. Possible benefits of this scenario will be discussed in the latter part of the text. After ventilation strategies, best performing cases will be tested with varying PCM layer thickness and positioning. Possible implementation surfaces are shown in *Table 4*. Three thicknesses will be tested; 3, 5 and 7cm layers.

Finally, best performing scenarios will be simulated with the aforementioned weather file, measured at the TU Vienna tower, to test PCM performance under heat waves.

2.2.2.5. Nomenclature

Names of cases will have the following format:

(TEST ROOM)_CASE_(PCM POSITIONING)(PCM LAYER THICKNESS)_(VENTILATION SCHEDULE)(VENTILATION AIR CHANGE RATE)

Example:

TR1_PCM_C5_DV05_NV2 – Meaning: Test room 1 with a 5cm PCM layer on the ceiling, daytime ventilation windows tilted one-sided (0.5h^{-1}), night ventilation windows open one-sided (2h^{-1}).

** If the same numerical value applies to two abbreviations, they will be written together; for instance a 3cm PCM layer on the roof and tilted roof will be abbreviated as RRT3, or ventilation of 1 air change per hour both during day and night will be abbreviated as DVNV1.*

If no PCM is present, fields for PCM layer thickness and positioning will simply be left out.

Example:

TR2_CTRL_DV1_NV4 – Meaning: Test room 2 control simulation, daytime ventilation windows tilted two-sided ($1h^{-1}$), night ventilation windows open two-sided ($4h^{-1}$).

2.3 Statistical Analysis

EnergyPlus outputs results in form of .cvs files, which are analysed easily using Microsoft Excel. Important outputs for the sake of determining efficiency of PCMs are hourly operative indoor and hourly mean outdoor temperatures. Operative temperature, often used in thermal comfort analysis, takes into account not only the temperature of the indoor air, but also the temperature of the surrounding surfaces. Those values will be the base of results discussion. However, other parameters will be derived from the simulation. Thermal comfort will be assessed by an adaptive indicator, specifically Adaptive Comfort Model Based on European Standard EN15251-2007, which is included in EnergyPlus. As explained in EnergyPlus' InputOutput reference, the model is intended for use in naturally ventilated buildings, and it determines the acceptability of indoor conditions given the 7-day weighted mean outdoor air temperature and the indoor operative temperature. It also relates indoor temperatures to the outdoor climate to account for people's clothing, hence there is no need to define clothing values in the simulation.

The model defines three comfort regions, as shown in *Table 6*: Category I (90%) Acceptability, Category II (80%) Acceptability, and Category III (65%).

EnergyPlus outputs results of this adaptive thermal comfort model as a number of hours temperature values were out of range for each comfort region. For this study, category II will be used to compare simulation cases. According to the categories description given by the standard, Category II is a normal level of expectation for renovations and new buildings (see *Table 6*).

Table 6: Adaptive Thermal Comfort Categories for European Standard EN15251-2007

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations

III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

Temperature values for outdoor environment and both test rooms are output as mean hourly values. From hourly temperature values, a range of statistical data will be extracted, as follows:

Mean operative temperature, maximum operative temperature, minimum operative temperature, number of hours where temperature exceeds 27°C (with the percentage of occurrences for the simulation range) and number of hours where thermal comfort criteria was not met.

Results will be compared and discussed largely through the perspective of temperature differences, especially the number of hours above 27°C (as that temperature is the overheating limit according to ÖNORM B8110-3:2012) and the adaptive thermal comfort model results. Along with the numerical comparison, simulation cases will be compared through a series of graphs. All data that has one value as an output (number of hours certain criteria were not met) will be easily compared from case to case in a single graph. In order to compare cases with outputs that have a large amount of values (like hourly operative temperature), cumulative distribution function graphs will be plotted.

Additionally, two 10-day spans will be examined more closely. Those spans will be adjusted according to the baseline simulation, in order to include most critical (highest) temperatures.

For those spans, again, mean temperature and number of hours above 27°C (with the percentage of coverage for the entire range) will be analysed.

While presenting data for the entire range will give a good overall picture, having additional spans will give the opportunity to inspect temperature fluctuations more closely and give the possibility to reach conclusions which are not obvious from the entire range.

3 RESULTS

Except for some general information, results will be presented per test room, where relevant simulation scenarios will be aggregated in a graph or a table to clearly show differences between them.

3.1 Overview on the scenarios

In order to have a better perspective over results, some general information on the test rooms is presented in the following table.

Table 7: General information on test rooms

	TR1	TR2
Room floor area [m^2]	25.97	22.32
Outside-facing surface area* [m^2]	16.35	33.15
Window area [m^2]	3.61	9.42
Windows Total Transmitted Solar Radiation** [GJ]	2.38	6.42

** Including windows*

*** Total value during the study period, acquired through baseline case simulation*

Aforementioned 10-day spans for deeper analysis were selected according to the baseline simulation, such that the vast majority of peak temperatures is contained within those two spans. Labelled as 10-day period A and 10-day period B, they cover dates from 30.6. to 10.7. and 10.8. to 20.8., respectively. These two time spans contain 100 highest temperature values for TR1 and 95 out of the 100 highest values for TR2.

As mentioned in the method section, results presentation consists of three stages. Firstly, ventilation scenarios (*presented in Table 5*) will be tested with a starting PCM layer positioned on the ceiling of both test rooms, with thickness that varies between 3, 5 and 7cm. Upon implication of ventilation scenarios, best performing ones will be tested with combined PCM layer thicknesses and positioning. After implications of PCM position and quantity, best performing cases of both test rooms will undergo a simulation with the TU Vienna weather file.

3.2 Implications of ventilation strategies

First set of simulations was focused on ventilation and PCM layer thickness scenarios, that is, changing ventilation patterns and later PCM layer thickness, while keeping the same PCM positioning in the room. The starting PCM position is ceiling for TR1 and roof plus tilted roof for TR2. Initial positioning was decided intuitively and based on conclusions from some aforementioned studies (e.g. Farid, M.M. et al., 2003). Following graphs will picture only certain outputs for the purpose of clearer presentation, however details will be further explored discussed in the discussion section.

3.2.1 TR1 results

Following tables and graphs are shown with the same PCM layer thickness for all ventilation scenarios. Upon that, when necessary, different thicknesses will be compared.

Table 8: General TR1 ventilation strategies scenarios simulation results

Simulation scenario	TR1_CTRL_DV05_NV2	TR1_PCM_C5_DV05_NV2	TR1_PCM_C5_DVNV05	TR1_PCM_C5_DVNV2	TR1_PCM_C5_NV05	TR1_PCM_C5_NV2	TR1_PCM_C5_DVNV0	TR1_PCM_C5_DVNV2_VC
Temperature above 27°C [Hours]	482	154	719	105	1107	192	1575	84
Temperature above 27°C [%]*	13.13%	4.19%	19.58%	2.86%	30.15%	5.23%	42.89%	2.29%
Mean temperature [°C]	23.21	23.11	24.77	22.51	25.47	23.42	26.84	22.54
Maximum temperature [°C]	30.79	28.54	31.20	28.46	32.37	28.71	34.22	28.22
Minimum temperature [°C]	16.17	18.11	19.97	17.40	20.37	18.36	21.44	18.67
EN15251 Category II Acceptability Limits** [Hours]	1180.67	723.63	169	1297.3	521.93	547.1	1365.73	1281.17
EN15251 Category II Acceptability Limits [%]	31.38%	19.24%	4.49%	34.48%	13.87%	14.54%	36.30%	34.06%

** Percentages apply to the study period (tot. 3762 hours)*

*** Acceptability limits – Time not meeting the adaptive comfort model during occupied hours of the study period.*

In the coming figure, cumulative distribution functions for some TR1 simulation scenarios are shown. The benefit of CDF graphs is that more scenarios can be pictured together clearly. A CDF graph will show the frequency of peak (or any) temperatures, which will facilitate the discussion and results analysis as well as comparison to other scenarios.

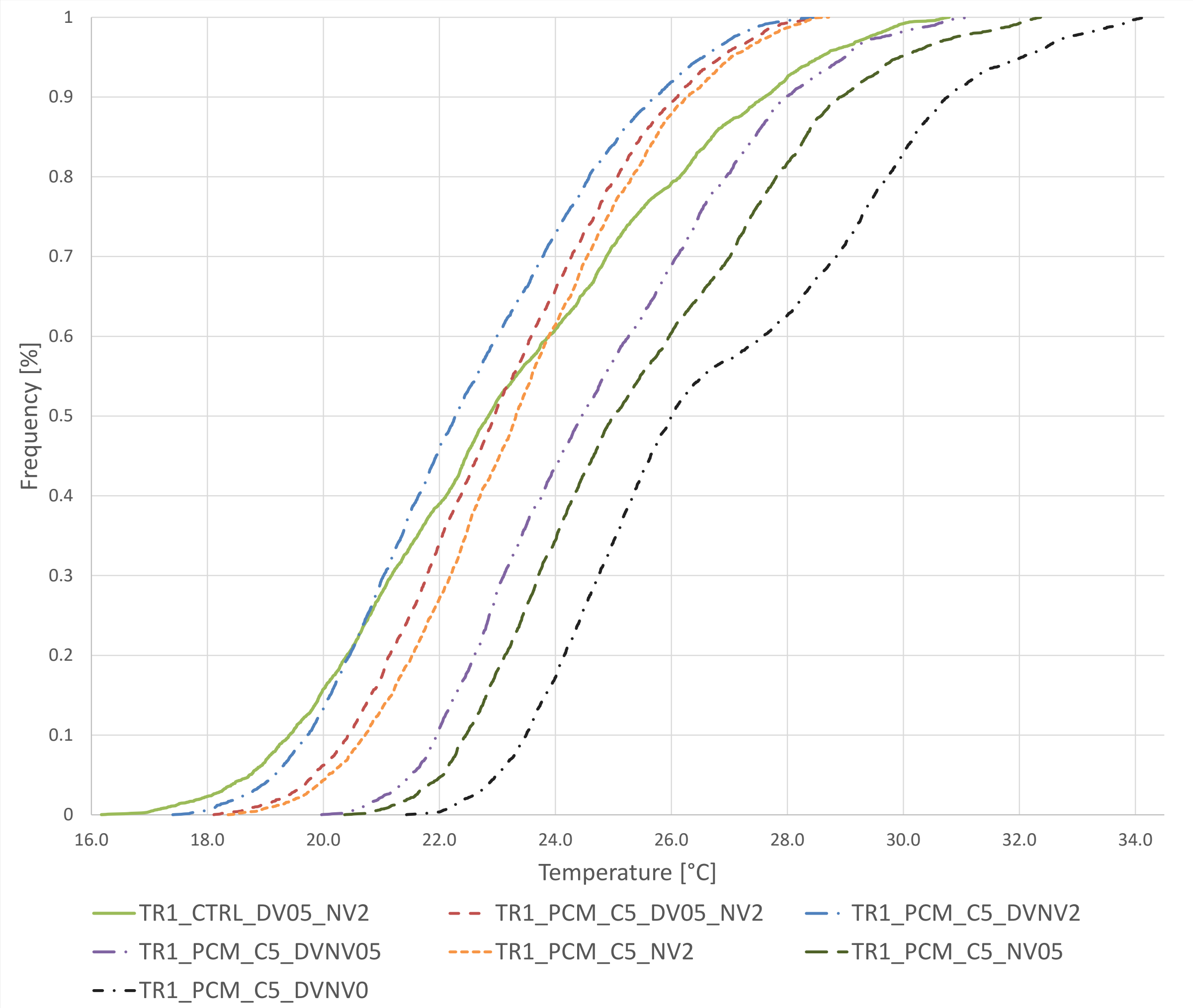

Figure 9: Cumulative distribution functions for TR1 implications of ventilation strategies scenarios

Figure 9 shows that, if improperly ventilated, a PCM layer cannot keep up with the temperature raise. Increasing the PCM layer thickness, or quantity in that matter, makes sense only if proper discharge is possible. In the latter part of results presentation, only scenarios with open windows during night time will be shown with different layer thicknesses, as those showed to have enough ventilation for solidifying PCMs.

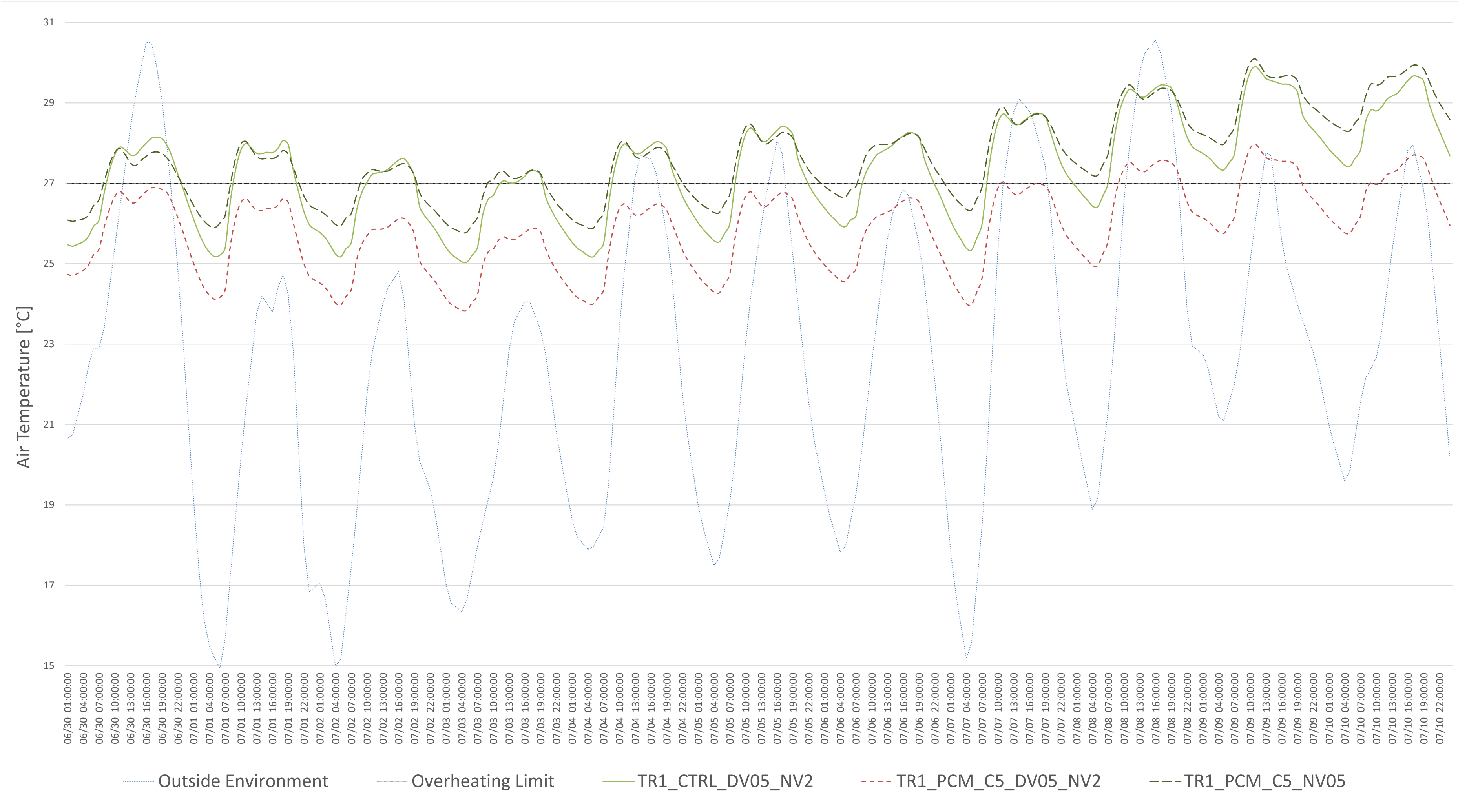

Figure 10: 10-day temperature chart A for TR1 ventilation strategies relevant scenarios

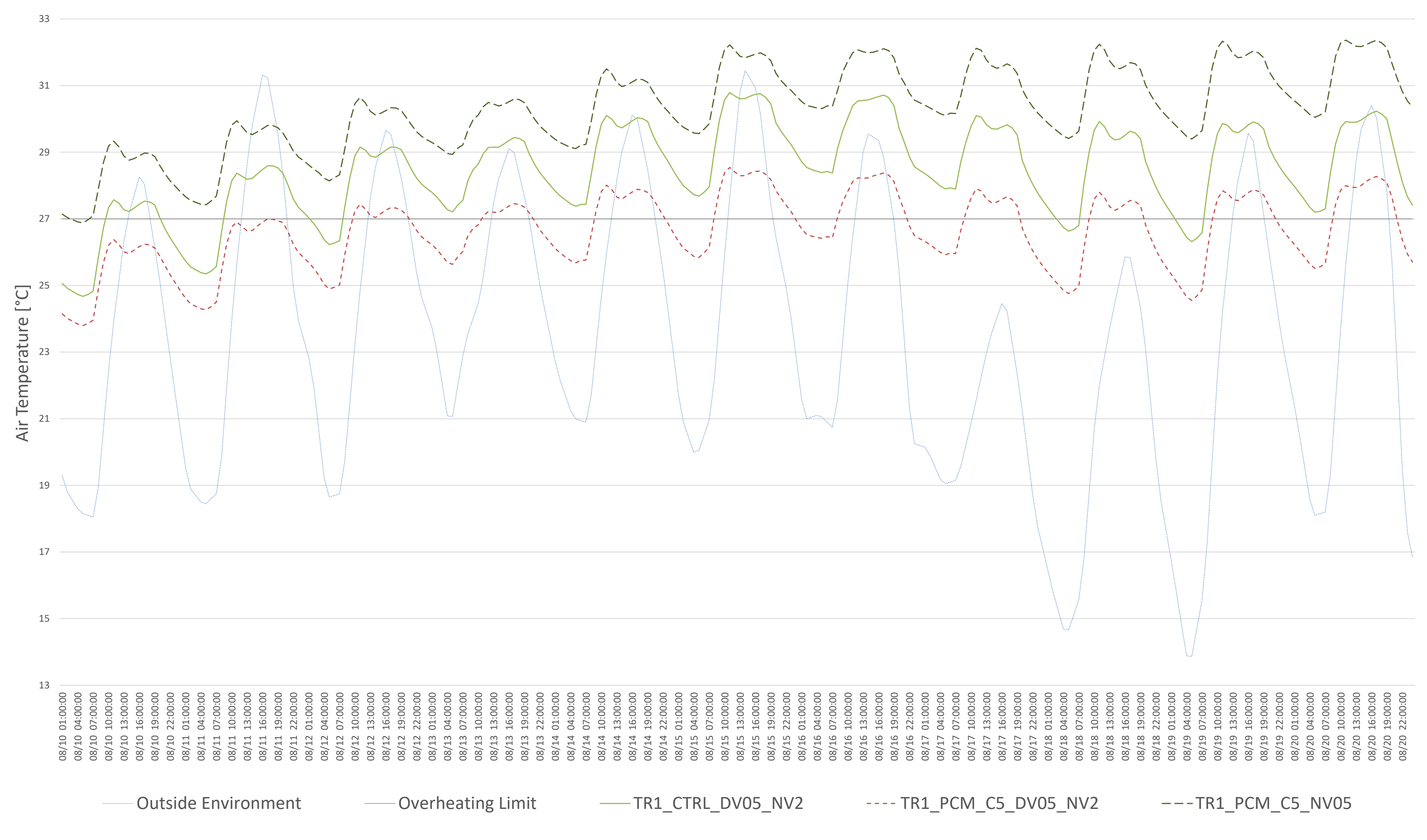

Figure 11: 10-day temperature chart B for TR1 ventilation strategies relevant scenarios

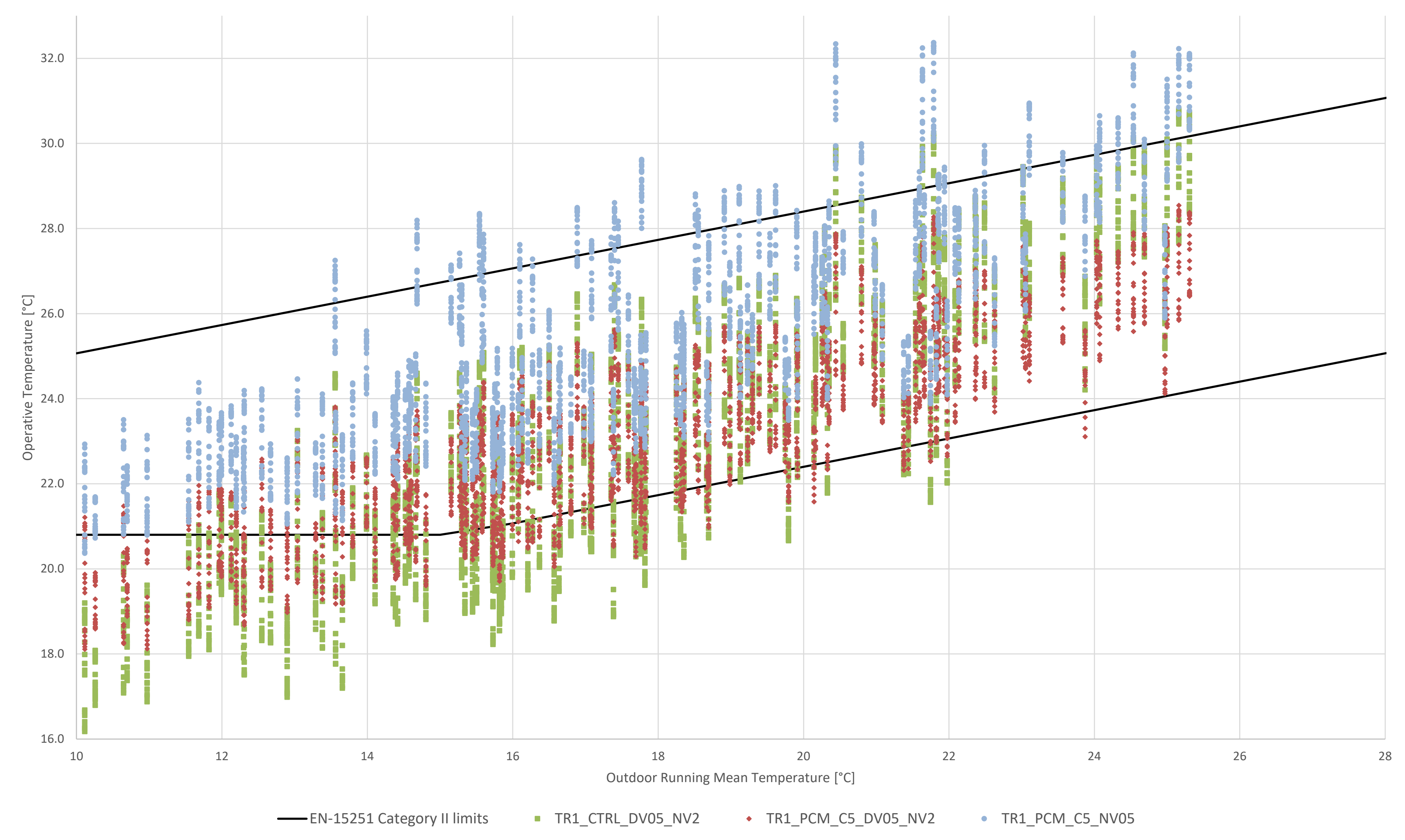

Figure 12: EN-15251 Adaptive comfort category II acceptability limits for TR1 ventilation strategies relevant scenarios

TR1, as already mentioned, is not a critical space, which means solar gains are not as high as in TR2 for instance. That being said, performance differences of various layer thicknesses for TR1 are minimal, when observed on a large scale. Therefore, different layer thicknesses will be shown on a graph that has 60 hours of values and includes one of the warmest days in the simulation period. That way, the separation in temperature curves and possible benefits/drawbacks of a thicker PCM layer during peak temperatures will be easily visible.

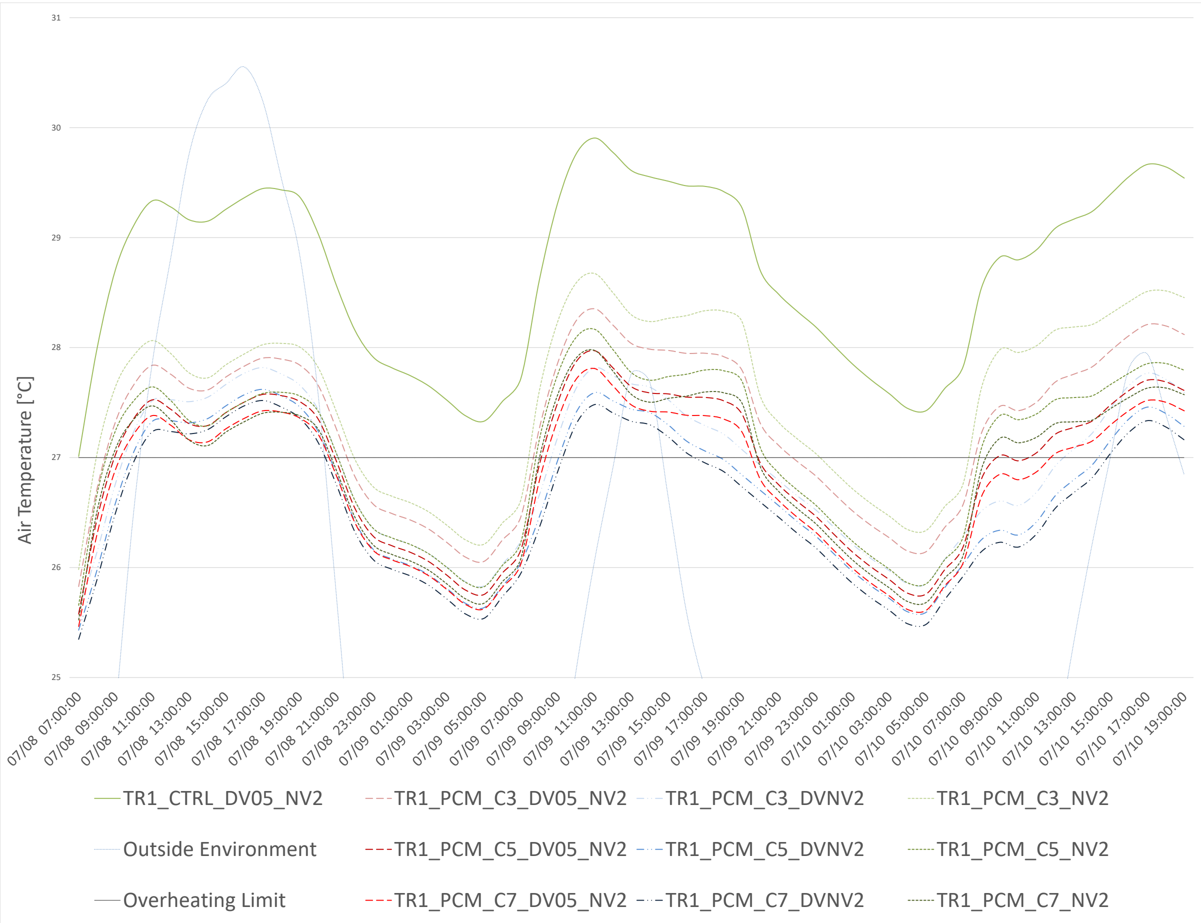

Figure 13: TR1 ventilation strategies scenarios with differing thicknesses; each ventilation scenario is represented with one line type, each thickness with different colour

Table 9: Comparison of different PCM layer thicknesses for TR1 ventilation strategies scenarios

Metrics	PCM layer thickness [cm]	Ventilation scenario		
		DV05_NV2	DVNV2	NV2
Temperature above 27°C [Hours]	3	218	152	282
	5	154	105	192
	7	136	89	158
Temperature above 27°C [%]	3	5.94%	4.14%	7.68%
	5	4.19%	2.86%	5.23%
	7	3.70%	2.42%	4.30%
Mean temperature [°C]	3	23.19	22.52	23.53
	5	23.11	22.51	23.42
	7	23.07	22.50	23.36
Maximum temperature [°C]	3	28.99	28.86	29.27
	5	28.54	28.46	28.71
	7	28.40	28.36	28.55
Minimum temperature [°C]	3	18.03	17.10	18.33
	5	18.11	17.40	18.36
	7	18.13	17.45	18.36
EN15251 Category II Acceptability Limits [Hours]	3	738.47	1347.77	572.07
	5	723.63	1297.30	547.10
	7	721.57	1289.40	547.33
EN15251 Category II Acceptability Limits [%]	3	19.63%	35.83%	15.21%
	5	19.24%	34.48%	14.54%
	7	19.18%	34.27%	14.55%

** PCM layer positioning – Ceiling*

3.2.2 TR2 results

The following tables and graphs show results for test room 2.

Table 10: General TR2 ventilation strategies scenarios simulation results

Simulation scenario	TR2_CTRL_DV1_NV4	TR2_PCM_RRT5_DV1_NV4	TR2_PCM_RRT5_DVNV4	TR2_PCM_RRT5_DVNV1	TR2_PCM_RRT5_NV4	TR2_PCM_RRT5_NV1	TR2_PCM_RRT5_DVNV0	TR2_PCM_RRT5_DVNV4_VC
Temperature above 27°C [Hours]	1222	871	635	1368	1008	1684	2060	637
Temperature above 27°C [%]	33.28%	23.72%	17.29%	37.25%	27.45%	45.86%	56.10%	17.35%
Mean temperature [°C]	24.98	24.64	23.66	26.49	25.20	27.48	29.10	23.75
Maximum temperature [°C]	36.93	35.95	33.90	38.14	37.36	39.94	41.47	33.90
Minimum temperature [°C]	13.37	16.52	16.01	19.02	16.77	19.37	20.76	18.51
EN15251 Category II Acceptability Limits [Hours]	1682.83	1111.23	1252.43	1137.03	1152.9	1522.03	2031.4	1224.8
EN15251 Category II Acceptability Limits [%]	44.73%	29.54%	33.29%	30.22%	30.65%	40.46%	54.00%	32.56%

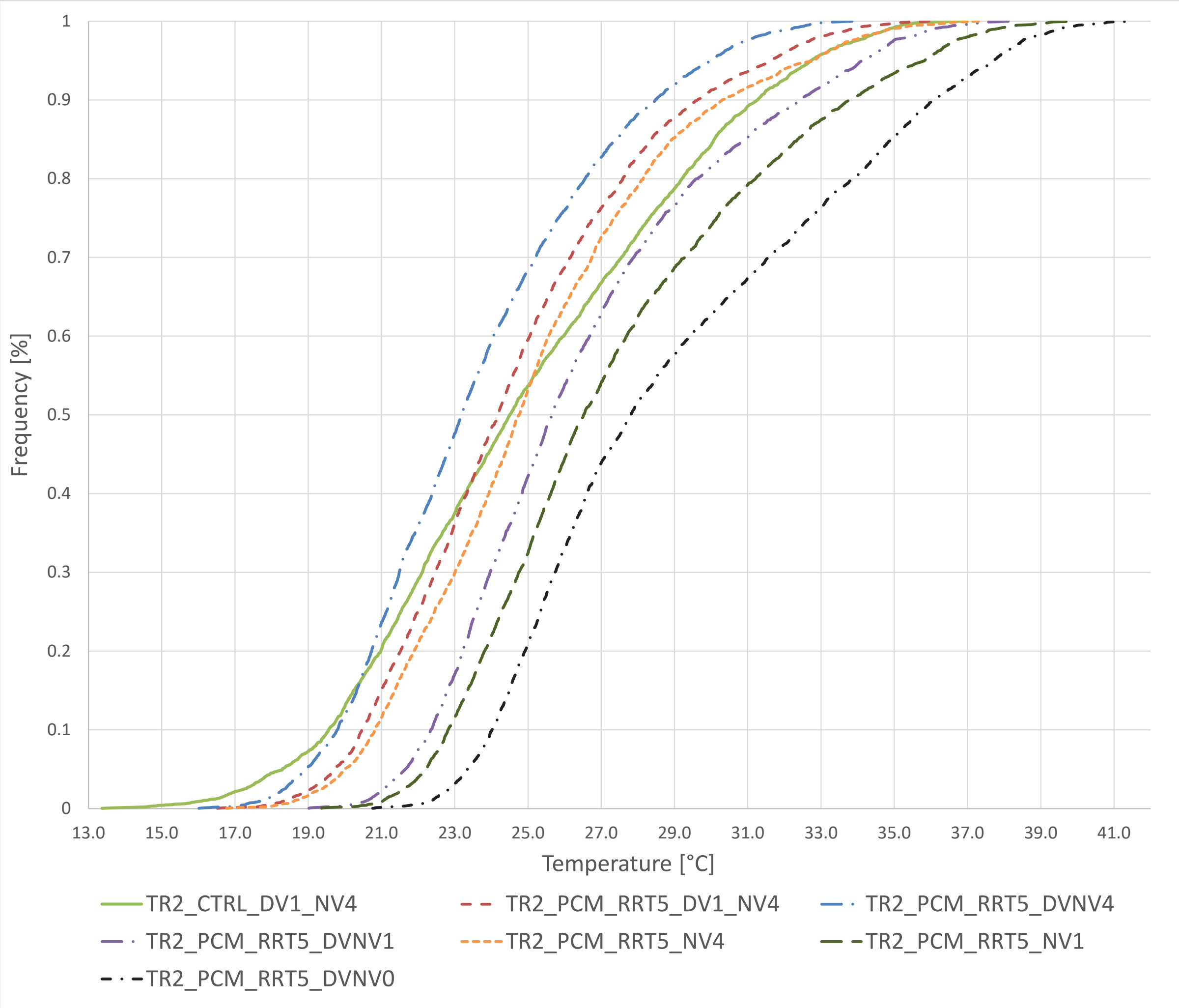

Figure 14: Cumulative distribution functions for TR2 implications of ventilation strategies scenarios

Similar to TR1s cumulative distribution function, one for TR2 (*Figure 14*) also shows that it is more important to properly ventilate a space rather than adding PCMs. This graph will determine which ventilation patterns are going to be further explored.

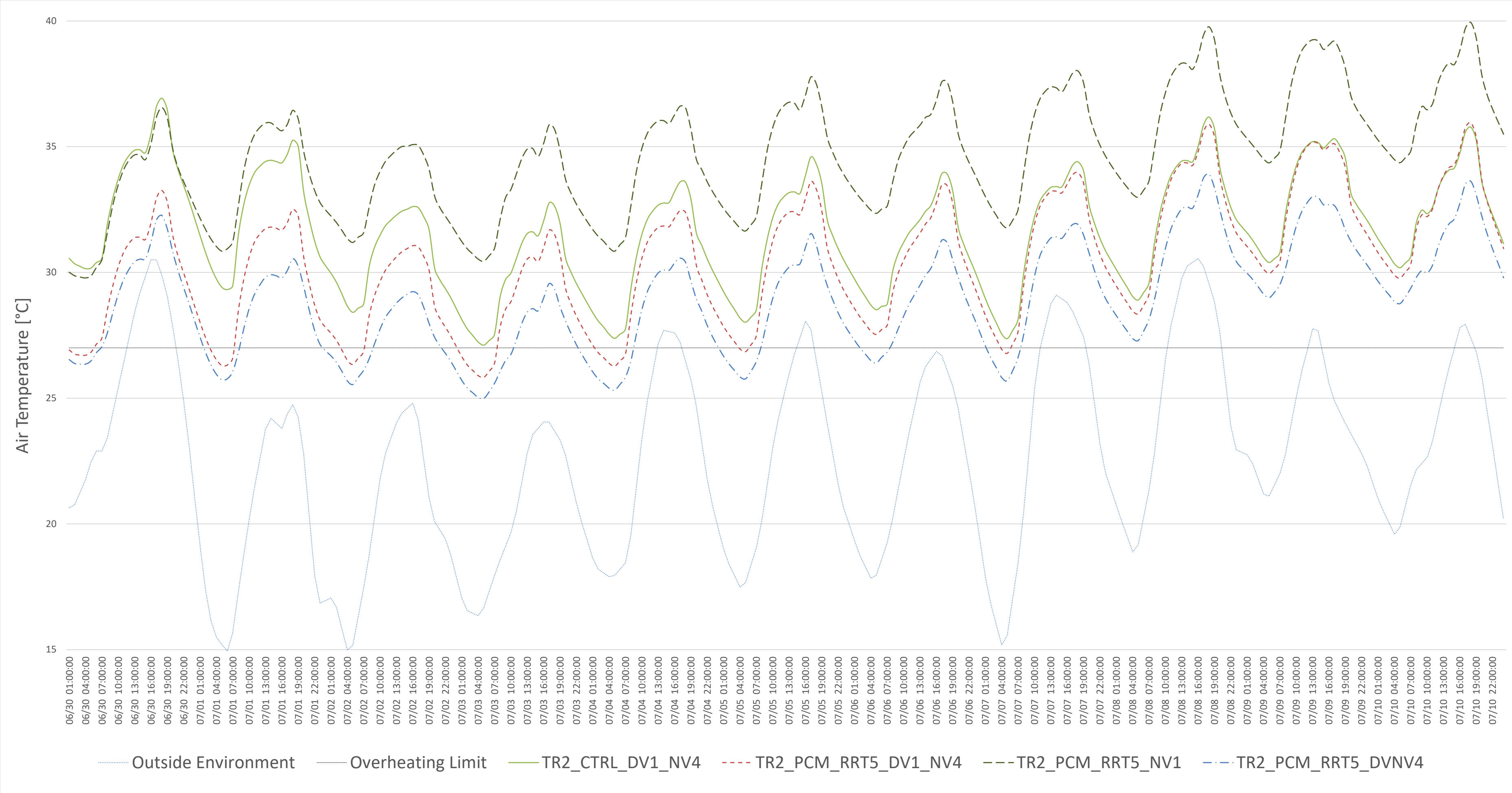

Figure 15: 10-day temperature chart A for TR2 ventilation strategies relevant scenarios

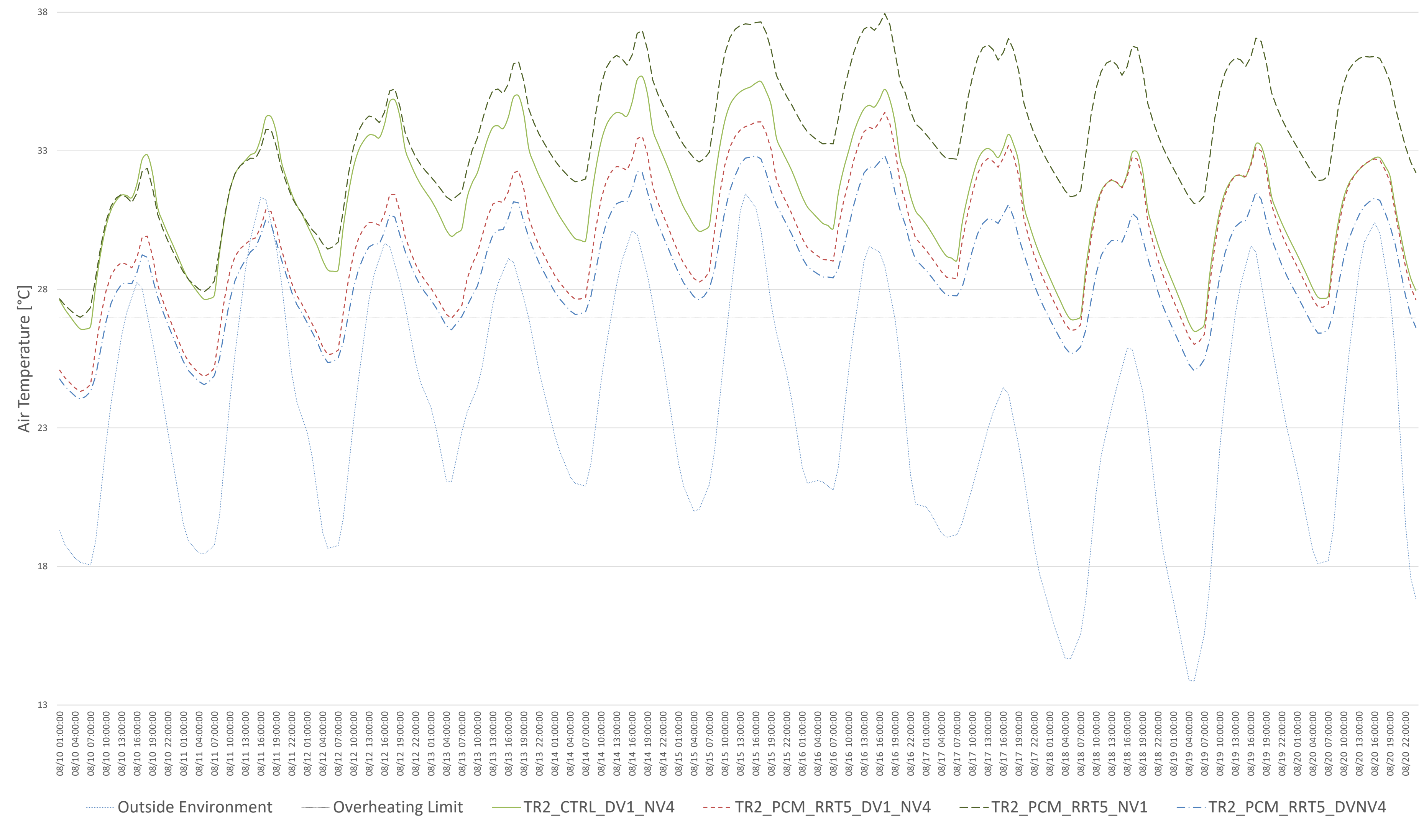

Figure 16: 10-day temperature chart B for TR2 ventilation strategies relevant scenarios

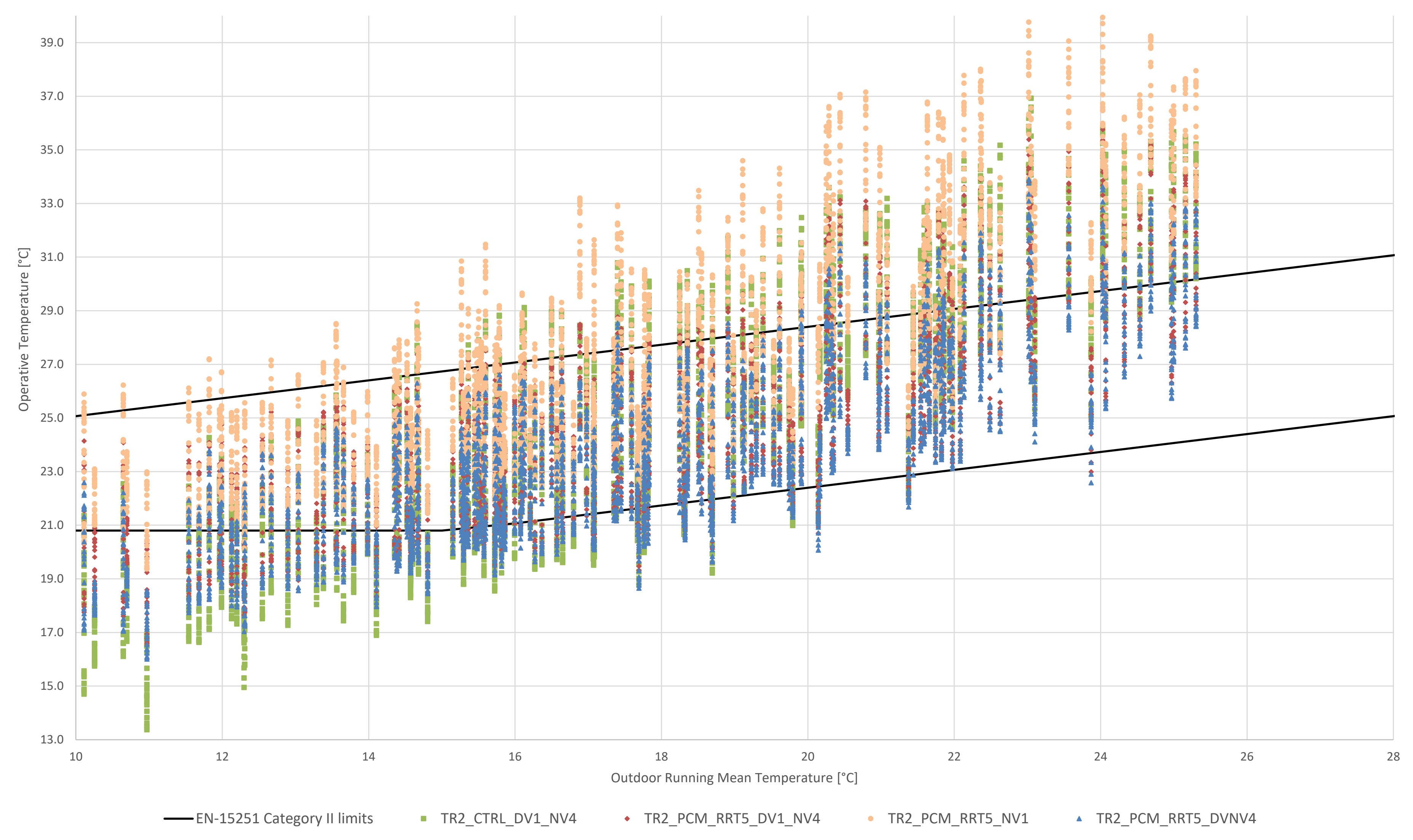

Figure 17: EN-15251 Adaptive comfort category II acceptability limits for TR2 ventilation strategies relevant scenarios

Similarly like TR1, TR2 performs clearly better with a higher ventilation rate scenario. With the internal solar gains that TR2 has, ventilation is even more important than for TR1. Not only during the evening, but as well during the day. Due to the lack of thermal mass and high internal solar gains, it is of crucial importance to ventilate such spaces as TR2 during the day as well in order to use every moment where outside temperature is lower than the inside. Therefore, only scenarios with open windows during the evening and open/tilted during daytime will be tested for varying thicknesses.

Figure 18: CDF graph for TR2 ventilation strategies scenarios with varying thickness

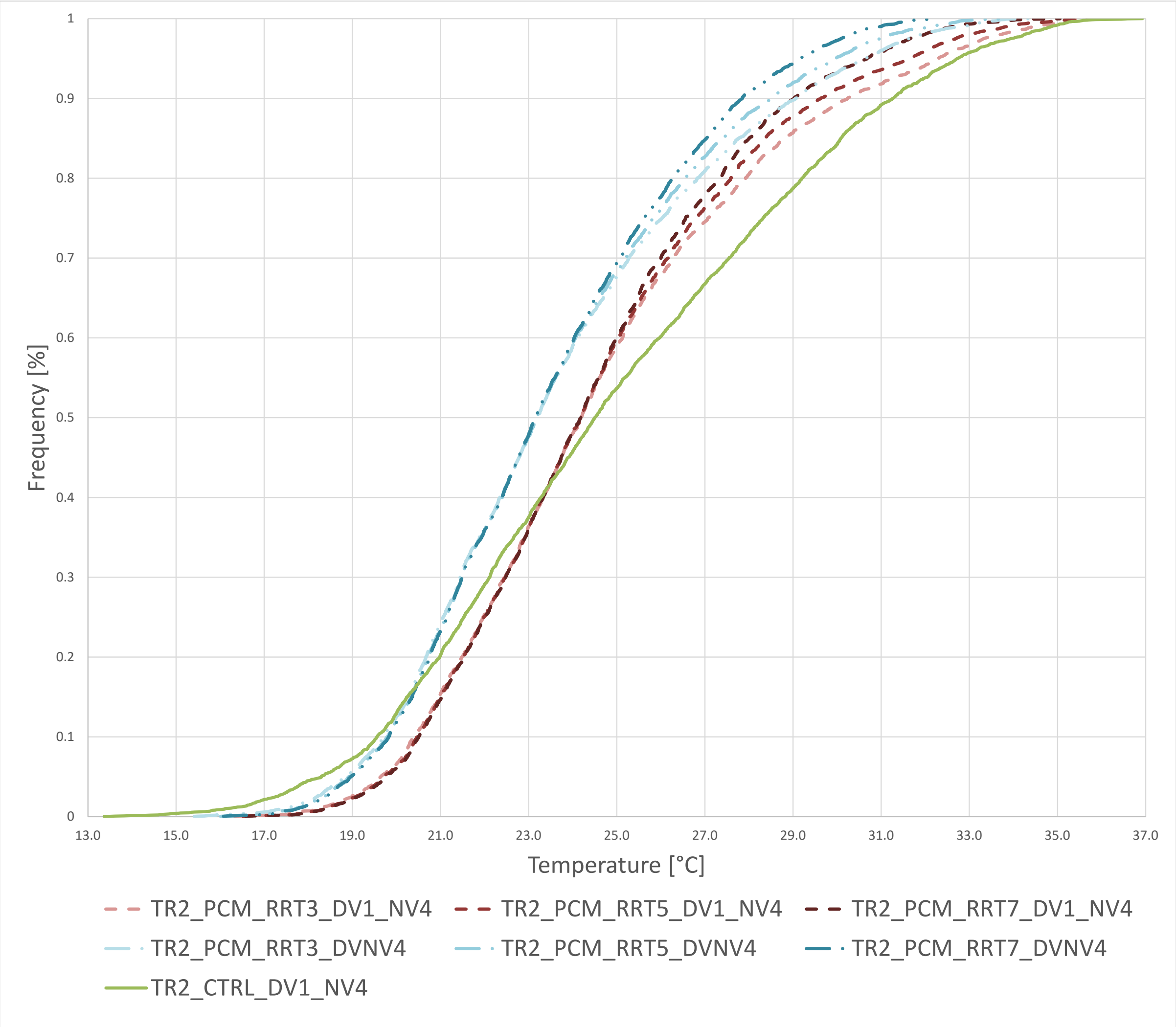

Table 11: Comparison of different PCM layer thicknesses for TR2 ventilation strategies scenarios

Metrics	PCM layer thickness [cm]	Ventilation scenario	
		DV1_NV4	DVNV4
Temperature above 27°C [Hours]	3	935	700
	5	871	635
	7	816	558
Temperature above 27°C [%]	3	25.46%	19.06%
	5	23.72%	17.29%
	7	22.22%	15.20%
Mean temperature [°C]	3	24.77	23.76
	5	24.64	23.66
	7	24.48	23.51
Maximum temperature [°C]	3	36.18	34.34
	5	35.95	33.90
	7	35.06	32.32
Minimum temperature [°C]	3	16.33	15.41
	5	16.52	16.01
	7	16.58	16.07
EN15251 Category II Acceptability Limits [Hours]	3	1197.87	1343.43
	5	1111.23	1252.43
	7	1020.3	1154.57
EN15251 Category II Acceptability Limits [%]	3	31.84%	35.71%
	5	29.54%	33.29%
	7	27.12%	30.69%

** PCM positioning – Roof & tilted roof*

3.3 Implications of position and quantity

Upon implication of ventilation simulation scenarios, patterns and their effect on PCM performance became clear. Second set of simulations is focused on PCM positioning and quantity. Intuitively, ceiling/roof was selected as a starting point because it makes sense both from an energy and thermal comfort perspective. Still, it is important to understand the impact of PCMs, when positioned on partition walls or in a combination (ceiling and partition wall), etc. A PCM layer can be also seen as a thermal mass layer, therefore, when applied to a surface other than the ceiling, it would make the most sense to apply a PCM layer on a surface with the least amount of thermal mass. Following scenarios will explore combined PCM positioning, with varying thicknesses, with a focus on total quantity. Results are expected to show whether a thinner layer spread across a larger surface can outperform a thicker layer on less surface, even if total PCM quantity remains similar and will the same amount of PCM behave in another fashion when placed on different surfaces.

3.3.1 TR1 results

Following simulations will be done under only one ventilation scenario because, based on results from ventilation strategies simulation scenarios, tilted windows during daytime and open windows during the evening are arguably producing the best results. More explanation on this premise will follow in the discussion, however the main point is that all scenarios with open windows during night time performed well. When daytime ventilation was high, the room had a tendency to overcool (due to the early morning and late afternoon hours), therefore decreasing thermal comfort, while the scenario without day ventilation had a slightly worse performance but not such a prominent overcooling issue. Even the special ventilation control case, that reduced overcooling impact, had lower thermal comfort in comparison to the case with tilted windows during daytime. Although simulation results pointed to the case without day ventilation as the best performing thermal comfort wise, from a realistic point of view, in a naturally ventilated building occupants should have the possibility to open the windows during daytime. Because of that, the scenario with tilted windows during daytime and open windows during night time was chosen to be worked with for position and quantity simulation scenarios.

Four additional scenarios were simulated. Firstly one scenario had the PCM layer installed on the floor surface in order to compare the performance to the ceiling based simulation. Both have the exact same PCM quantity, distributed equally. Secondly, the notion that a 3cm layer distributed across a larger surface will perform better than a 5cm layer with similar total PCM volume has been put to the test. One simulation features a 3cm layer on the ceiling and northeast partition wall, and the other on the ceiling and northwest partition wall (difference in partition wall surface area, therefore total PCM quantity). The last variation of position and quantity scenarios is a combined case where a 5cm layer is placed on the wall and a 3cm layer on the northeast partition wall.

Table 12: TR1 position and quantity scenarios simulation results compared to ventilation strategies scenarios with the same ventilation pattern

Simulation scenario	TR1_CTRL_DV05_NV2	TR1_PCM_C3_DV05_NV2	TR1_PCM_C5_DV05_NV2	TR1_PCM_F5_DV05_NV2	TR1_PCM_CNE3_DV05_NV2	TR1_PCM_CNW3_DV05_NV2	TR1_PCM_C5_NE3_DV05_NV2
PCM quantity [m^3]	0	0.78	1.29	1.29	1.42	1.22	1.94
Temperature above 27°C [Hours]	482	218	154	217	84	115	48
Temperature above 27°C [%]	13.13%	5.94%	4.19%	5.91%	2.29%	3.13%	1.31%
Mean temperature [°C]	23.21	23.19	23.11	23.11	23.11	23.13	23.07
Maximum temperature [°C]	30.79	28.99	28.54	28.98	28.09	28.28	27.84
Minimum temperature [°C]	16.17	18.03	18.11	17.63	18.75	18.48	18.77
EN15251 Category II Acceptability Limits [Hours]	1180.67	738.47	723.63	819.87	565.4	614.4	567.07
EN15251 Category II Acceptability Limits [%]	31.38%	19.63%	19.24%	21.79%	15.03%	16.33%	15.07%

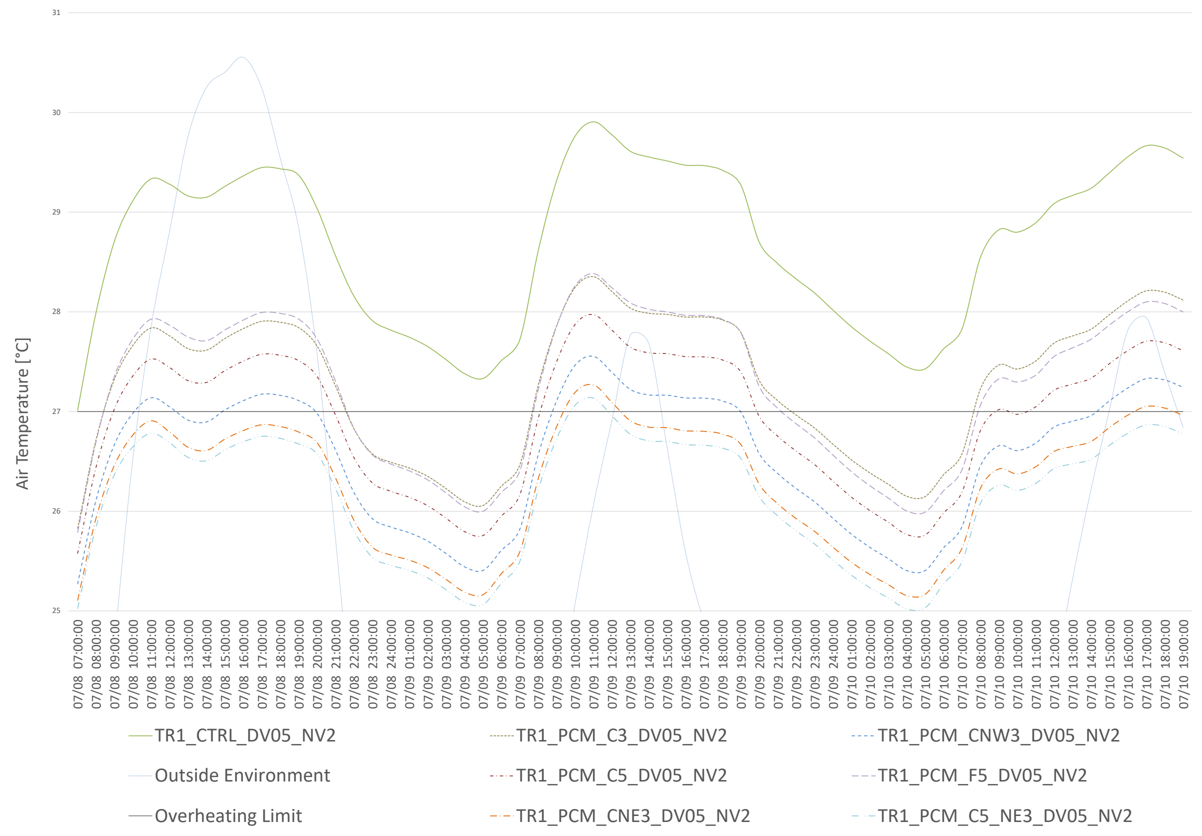

Figure 19: TR1 ventilation strategies & position and quantity simulation cases with the same ventilation pattern on a peak day

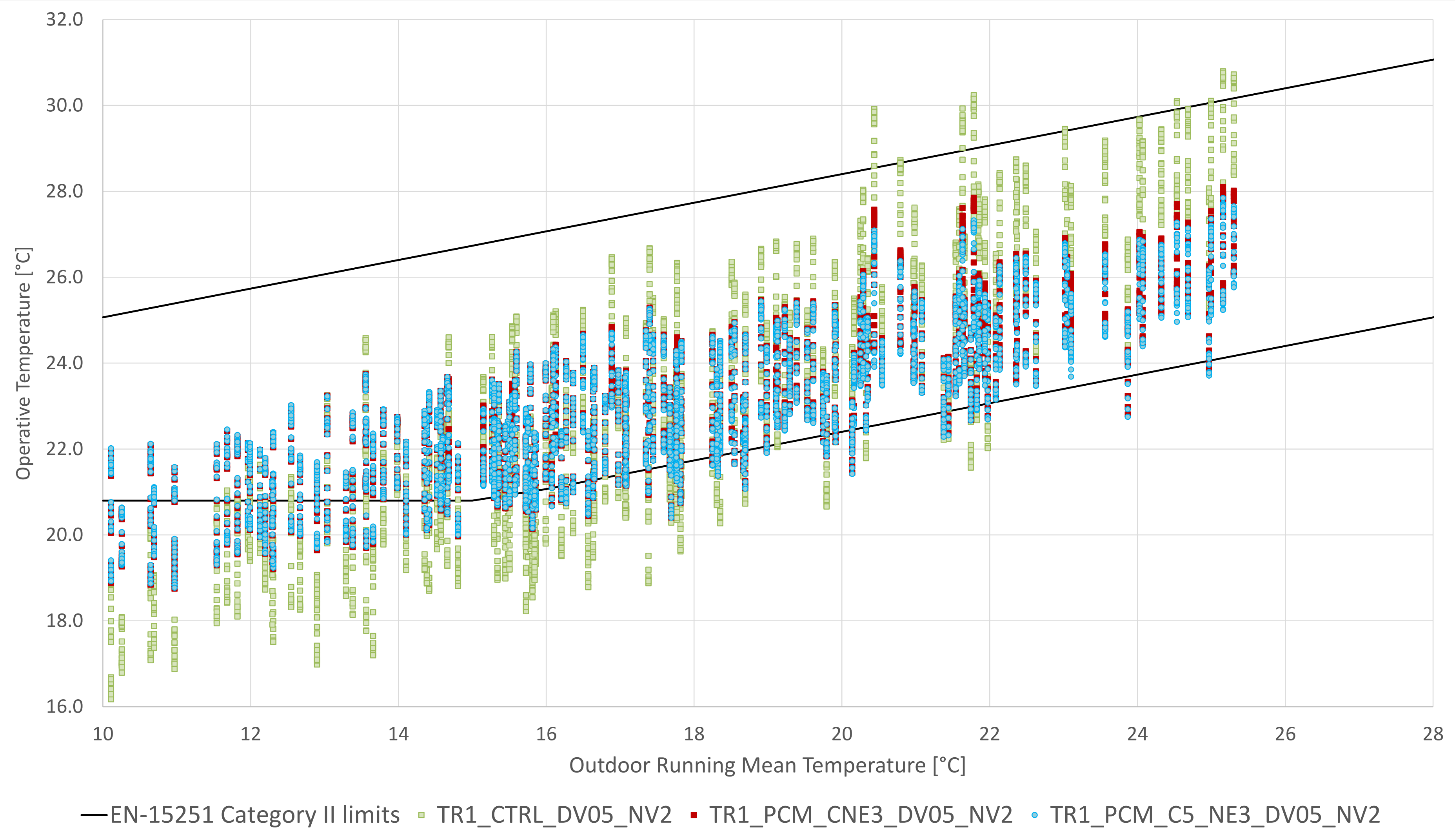

Figure 20: EN-15251 Adaptive comfort category II acceptability limits for best performing TR1 position and quantity scenarios

3.3.2 TR2 results

Implications of position and quantity for TR2 simulations were done over two different ventilation scenarios. Due to the higher solar gains, TR2 needs a more serious air change rate in order to make use of the installed PCMs. *Table 13* shows how different positioning and layer thickness behaved under two ventilation scenarios with the highest air change rates.

Table 13: TR2 position and quantity scenarios simulation results compared to ventilation strategies scenarios with same patterns

Simulation scenario	TR2_CTRL_DV1_NV4	TR2_PCM_RRT7_DV1_NV4	TR2_PCM_RRT7_DVNV4	TR2_PCM_RRTNE5_DV1_NV4	TR2_PCM_RRTNE5_DVNV4	TR2_PCM_RRTNE7_DV1_NV4	TR2_PCM_RRTNE7_DVNV4
PCM quantity [m^3]	0	1.54	1.54	1.80	1.80	2.52	2.52
Temperature above 27°C [Hours]	1222	816	558	573	355	379	277
Temperature above 27°C [%]	33.28%	22.22%	15.20%	15.60%	9.67%	10.32%	7.54%
Mean temperature [°C]	24.98	24.48	23.51	24.01	23.21	23.69	23.06
Maximum temperature [°C]	36.93	35.06	32.32	34.13	31.31	30.48	30.22
Minimum temperature [°C]	13.37	16.58	16.07	17.38	17.03	17.43	17.09
EN15251 Category II Acceptability Limits [Hours]	1180.67	1020.3	1154.57	904.9	1082.43	751.53	1067.83
EN15251 Category II Acceptability Limits [%]	31.38%	27.12%	30.69%	24.05%	28.77%	19.98%	28.38%

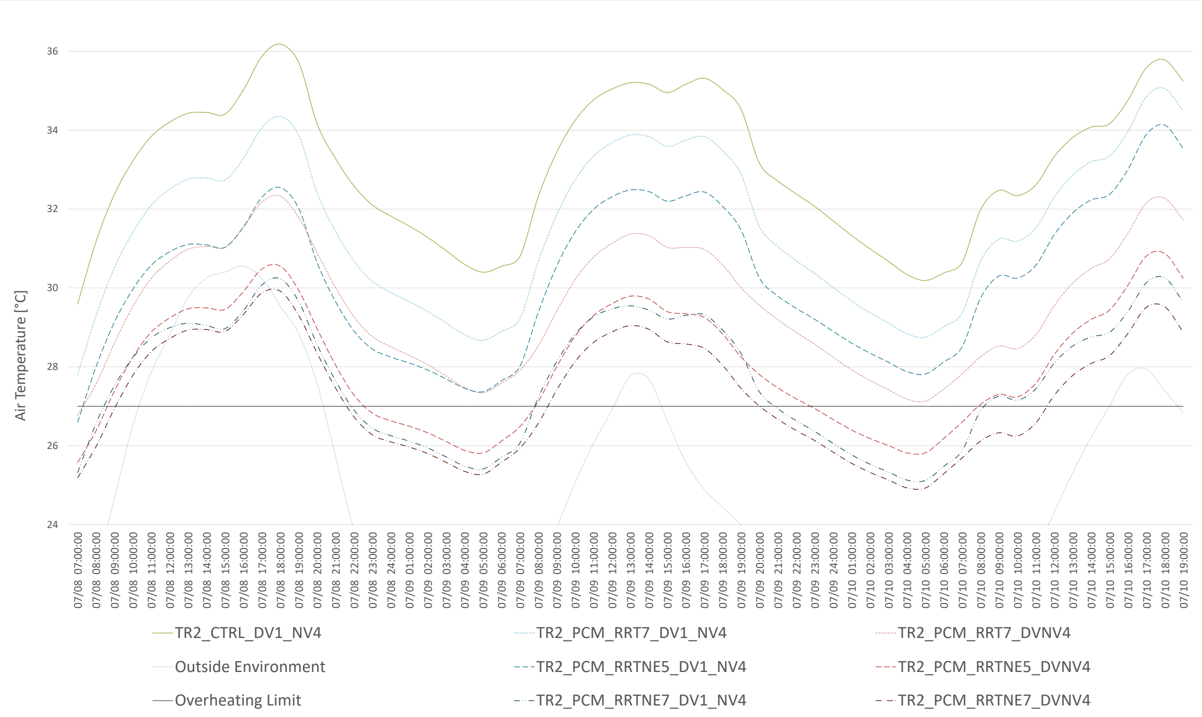

Figure 21: TR2 ventilation strategies & position and quantity simulation cases with same ventilation patterns on a peak day

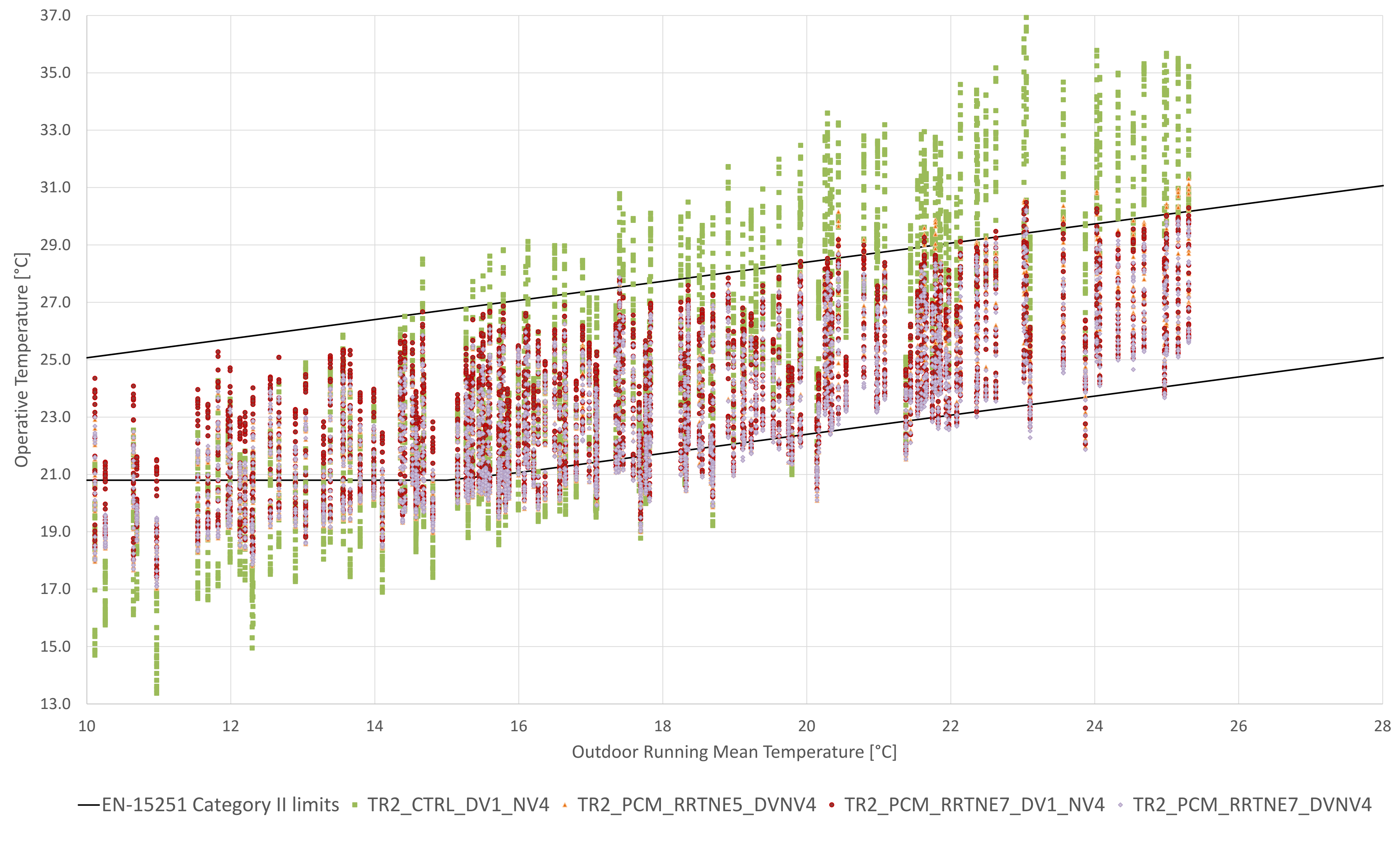

Figure 22: EN-15251 Adaptive comfort category II acceptability limits for best performing TR2 position and quantity scenarios

3.4 Implications of weather assumptions

To understand how a room equipped with PCMs would behave under more severe weather assumptions, a single PCM design alternative and corresponding control case (thought to be the best performing) for each test room was simulated with the real-year weather file, derived based on the data from TU Vienna weather station in 2012.

3.4.1 TR1 TU Vienna weather scenario

Because of the increased temperatures in the weather file, the chosen ventilation pattern to simulate it is the one with open windows throughout the day and night. As for PCM layer thickness and positioning, a 3cm layer on the ceiling and northeast partition wall was chosen. Furtherly analysed in the discussion why, the chosen positioning and thickness seemed to be most efficient in respect to the total amount of PCM.

Table 14: TR1 TU Vienna weather scenario simulation results compared to its respective control simulation

Special simulation scenario	TR1_CTRL_DVNV2_TU*	TR1_PCM_CNE3_DVNV2_TU
Temperature above 27°C [Hours]	1305	861
Temperature above 27°C [%]	35.54%	23.45%
Mean temperature [°C]	25.69	25.01
Maximum temperature [°C]	33.35	32.64
Minimum temperature [°C]	16.53	18.41
EN15251 Category II Acceptability Limits [Hours]	707.47	361.4
EN15251 Category II Acceptability Limits [%]	18.81%	9.61%

** TU abbreviation denotes the TU Vienna weather file*

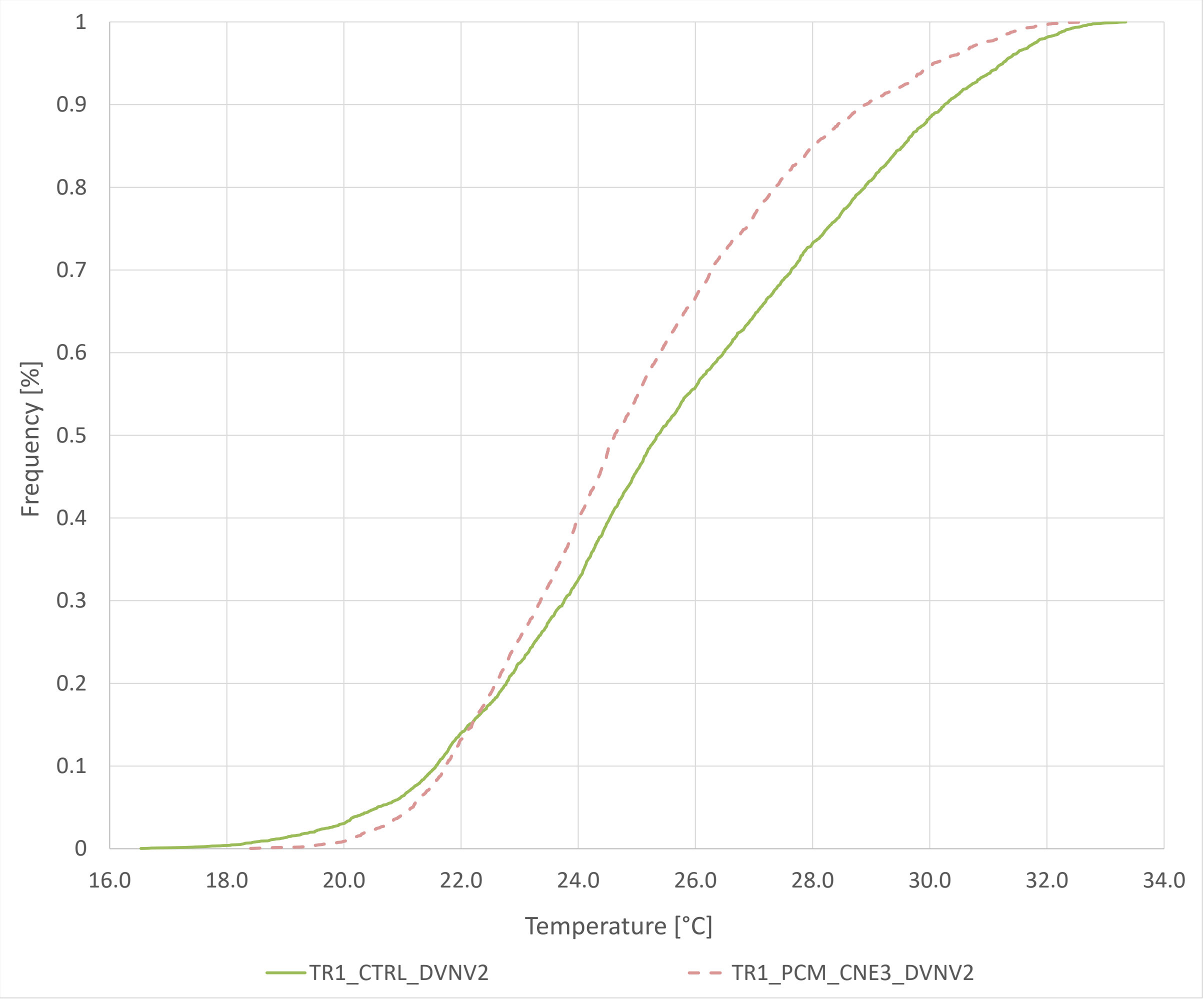

Figure 23: CDF graph for TR1 TU Vienna weather scenario

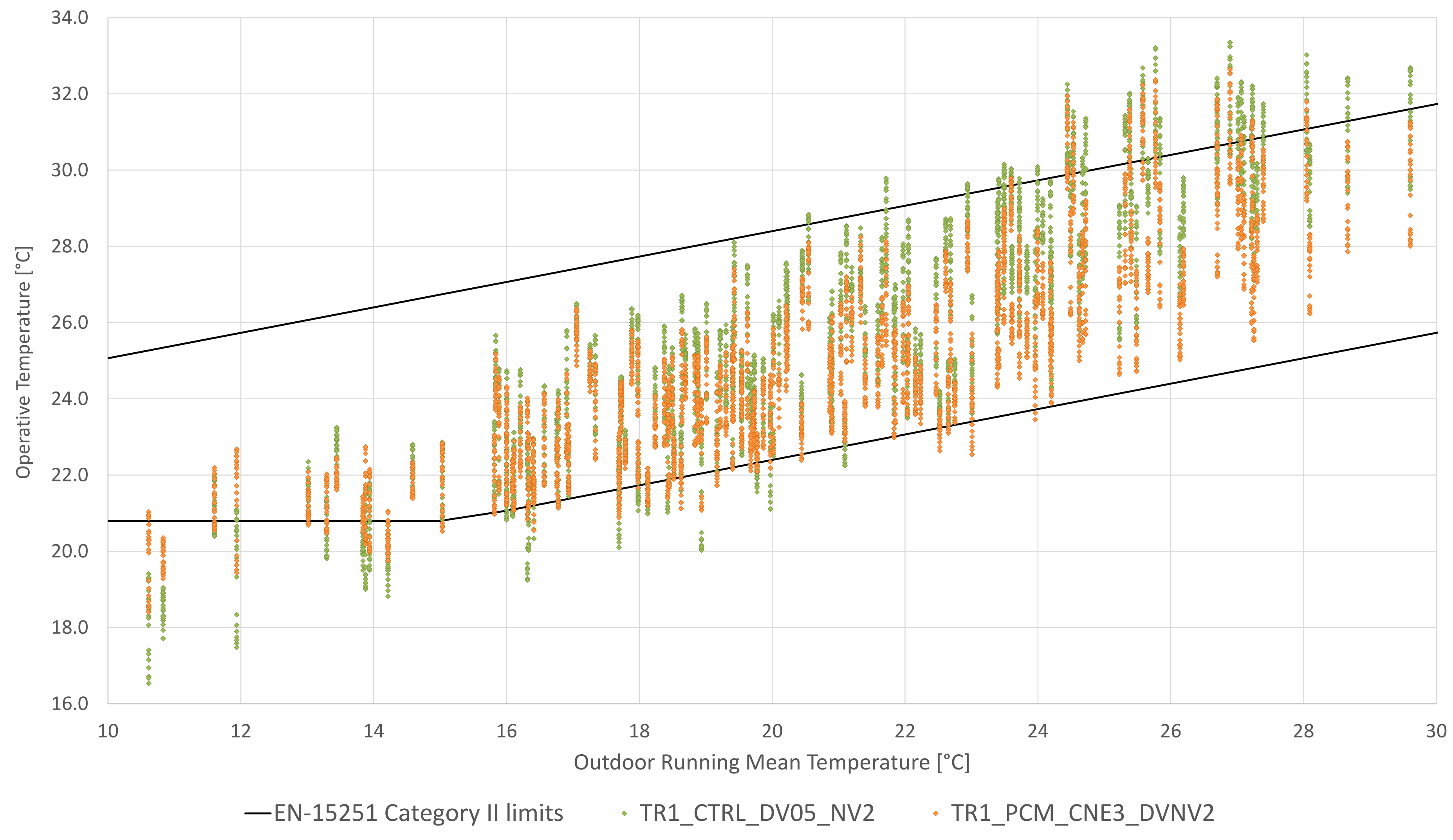

Figure 24: EN-15251 Adaptive comfort category II acceptability limits for TR1 TU Vienna weather scenario

3.4.2 TR2 TU Vienna weather scenario

Having previous simulations (and TR2s' performance) in mind, the increase in heat gains from this weather file will bring severe impacts on the performance of TR2. In order to test the possibility (or the extend of it) to cool TR2 passively, TU Weather file was simulated on the scenario with open windows throughout day and night and the largest simulated PCM quantity (a 7cm layer placed on the roof, tilted roof and northeast partition wall).

Table 15: TR2 TU Vienna weather scenario simulation results compared to its respective control simulation

Special simulation scenario	TR2_CTRL_DVNV4_TU	TR2_PCM_RRTNE7_DVNV4_TU
Temperature above 27°C [Hours]	1961	1250
Temperature above 27°C [%]	53.40%	34.04%
Mean temperature [°C]	27.52	25.97
Maximum temperature [°C]	40.42	39.92
Minimum temperature [°C]	14.71	17.49
EN15251 Category II Acceptability Limits [Hours]	1815.1	1070.6
EN15251 Category II Acceptability Limits [%]	48.25%	28.46%

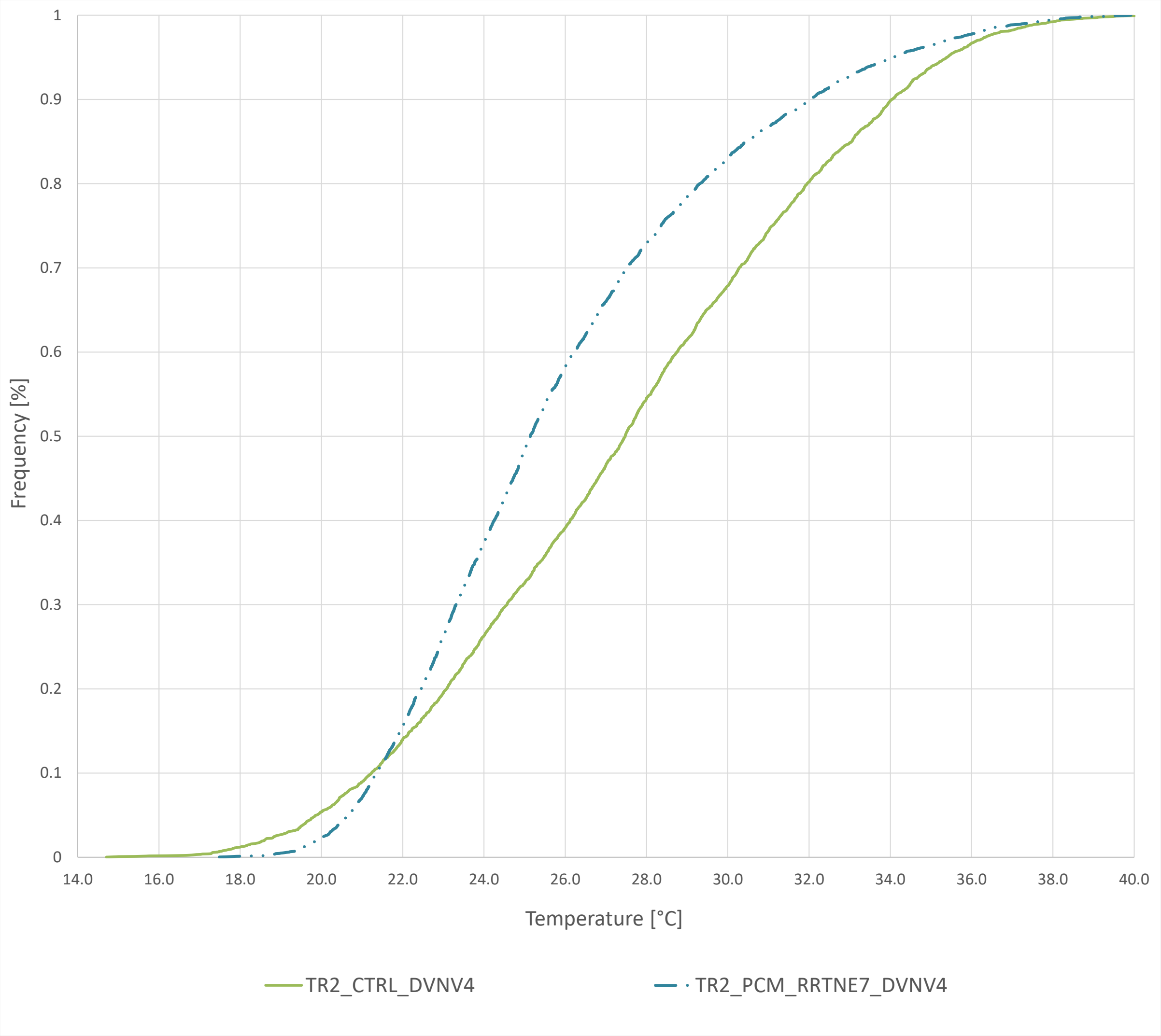

Figure 25: CDF graph for TR2 TU Vienna weather scenario

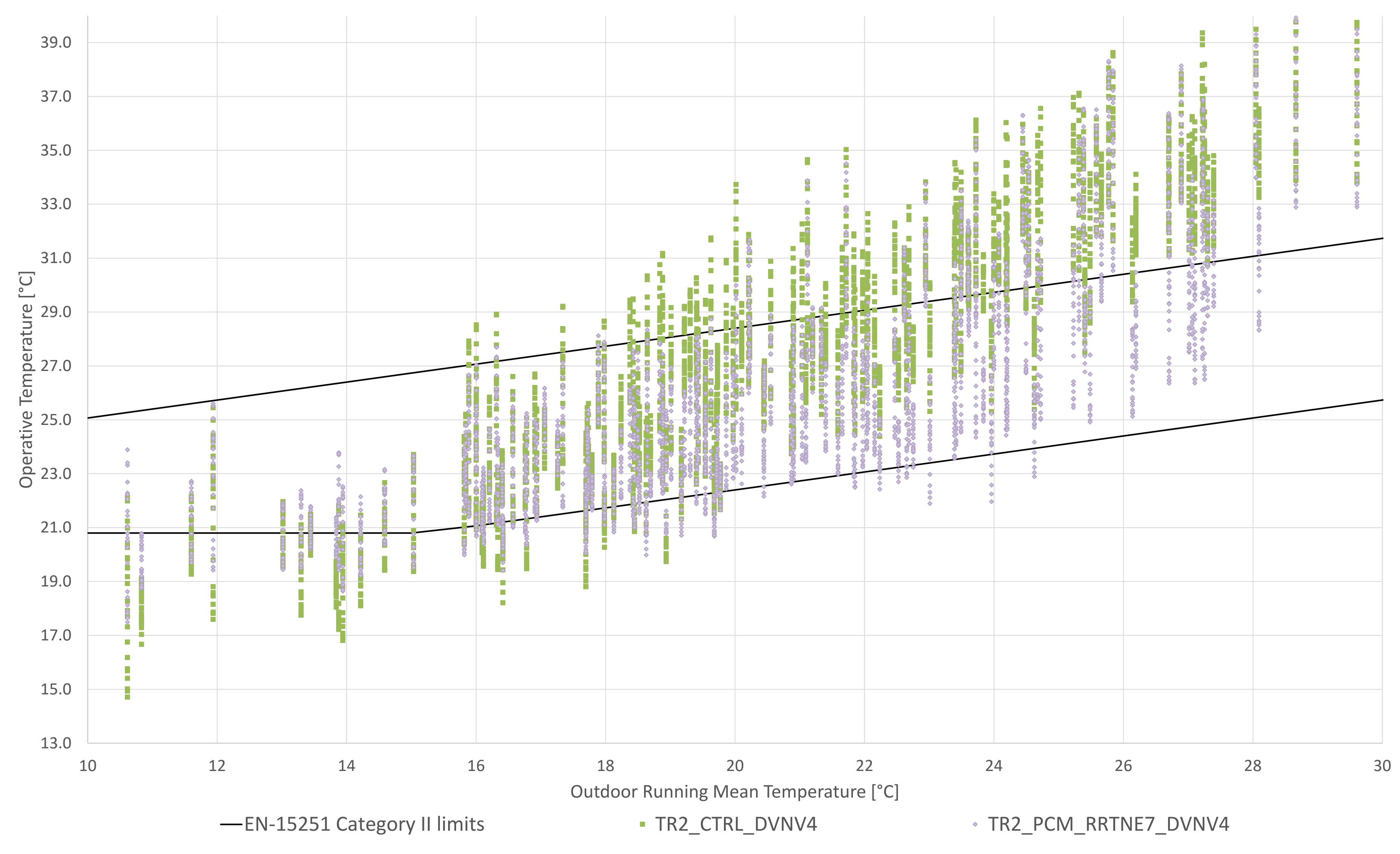

Figure 26: EN-15251 Adaptive comfort category II acceptability limits for TR2 TU Vienna weather scenario

4 DISCUSSION

Test rooms were selected to represent two different overheating scenarios. *Table 7* gives a good starting point for the discussion. TR1 represents a normal, typical, Viennese room that could have overheating issues. It is oriented southeast with two windows and not much shading, being on the 3rd floor of the building. However, TR1 has only one outside-facing wall (16.35 m^2), unlike TR2 that is located in the attic, therefore being much more exposed to outside conditions (33.15 m^2 of outside-facing surfaces). Looking at the total transmitted solar radiation through windows, TR1 and TR2 are proportionally similar, nonetheless TR2 has 2.6 times the fenestration surface of TR1, therefore adequately higher transmitted solar radiation. The control simulations show that both TR1 and TR2 are not extremely pleasant rooms during the summer.

4.1 TR1 scenarios

Table 8 and *Figure 9* immediately uncover some crucial aspects of PCMs incorporation, along with their benefits and drawbacks without even getting into a more detailed analysis. No matter the ventilation scenario, introducing a 5cm PCM layer on the ceiling managed to narrow the temperature amplitude and increase minimum temperature while maintaining a fairly similar mean temperature during the study data. Analysing data from *Table 8* as well as *Figures 9, 10 and 11*, three distinctive groups (by ventilation scenario) can be differentiated. One group consists of ventilation scenarios with open windows during the evening (*TR1_PCM_C5_DV05_NV2*, *TR1_PCM_C5_DVNV2*, *TR1_PCM_C5_NV2*), the other of scenarios with tilted windows during the evening (*TR1_PCM_C5_DVNV05*, *TR1_PCM_C5_NV05*) and the third of the case without ventilation (*TR1_PCM_C5_DVNV0*).

The spontaneous formation of these groups just goes to show how important ventilation is, when implementing PCMs. Improperly ventilated cases, even though they narrowed the amplitude of temperature change, were not successful in decreasing peak temperature and hours above the overheating limit and, ultimately, were performing at the level or worse than a properly ventilated control room. However, that was not the case with scenarios that were adequately ventilated. Table below shows three best performing ventilation scenarios and the improvements in relation to the control (baseline) simulation.

Table 16: TR1 ventilation strategies & position and quantity best performing scenarios and respective differences to the baseline case

	TR1_PCM_C5_DV05_NV2	TR1_PCM_C5_DVNV2	TR1_PCM_C5_DVNV2_VC	TR1_PCM_C5_NV2	TR1_PCM_CNE3_DV05_NV2	TR1_PCM_C5_NE3_DV05_NV2
	Difference to TR1_CTRL_DV05_NV2					
Temperature above 27°C [Hours]	-328	-377	-398	-290	-398	-434
Mean temperature [°C]	-0.1	-0.7	-0.67	+0.21	-0.09	-0.14
Maximum temperature [°C]	-2.25	-2.33	-2.57	-2.08	-2.7	-2.95
Minimum temperature [°C]	+1.94	+1.23	+2.5	+2.19	+2.57	+2.59
EN15251 Category II Acceptability Limits [Hours]	-457.04	+116.63	+100.5	-633.57	-615.27	-613.6

An interesting value that needs to be commented is number of hours adaptive comfort EN15251 Category II limits were not met. One of the best performing cases, in terms of lowering peak temperature and number of hours over 27°C has worse thermal comfort than the control simulation, according to the standard. Taking a closer look on the adaptive thermal comfort graph (*Figure 12*), it is clear that for cases with higher ventilation air change rates, overcooling in the evening hours occurs rather often, while breaches on the upper temperature limit are extremely rare. That is, in general, not a problem for this specific study because there is no occupancy assumed during the evening (as the test room is supposed to be a living room), nonetheless if overcooled, morning hours could be unpleasant. Poorly ventilated cases tend to fall out of the range only on the upper side of the limit. However, it is important to mention once again that the weather file used in this set of simulations is underestimating Viennese summer temperatures. In the latter part of the text, the special case simulated with a weather file from TU Vienna will be discussed.

PCM layer thickness variations presented in the results give the impression that the difference between those cases is not extremely obvious. That is, in part, because TR1 does not have enough internal solar gains to make proper use of the additional PCM latent heat storage capacity. *Figure 13* shows that the only significant separation between cases occurs at peak values. Even then, the difference in peak temperature reduction is rather small. *Table 9* indicates that, for cases with open windows during the evening, a higher PCM quantity managed to reduce the number of hours over 27°C, however reduction in peak high temperatures was low, 0.59°C for *DV05_NV2*, 0.50°C for *DVNV2* and 0.72°C for *NV2* scenarios. Differences in minimum temperatures were even lower, so that for the three discussed ventilation scenarios the amplitude of temperature change was narrowed by a maximum of 0.85°C by using a 7cm instead of a 3cm PCM layer on the ceiling. Shortly, inducing more than double the quantity of PCM did not seem to provide enough benefits to be justified. That is, of course, due to the internal gains of TR1, which is incapable of completely melting such thick layers of PCMs. In position and quantity scenarios, more simulations with 3cm layers are explored. An interesting comparison can be observed from cases *TR1_PCM_C5_NV2*, *TR1_PCM_C5_DV05_NV2* and *TR1_PCM_C3_DVNV2*. As seen in *Table 9*, these three simulation scenarios have similar values, despite a different ventilation pattern and PCM layer thickness. First impression could be that a thinner PCM layer can outperform or match a thicker one, if properly ventilated. Taking a deeper look reveals that the room's behaviour is not that similar in those cases. As PCM layer thickness increases, so does thermal comfort and minimum temperature, despite having less ventilation (however it is important to note that what is considered as less ventilation in this phase is still enough to cool PCMs well enough – otherwise with improper ventilation performance will drop no matter the quantity). Strictly from a thermal comfort perspective, it is better to have more latent heat storage possibility and not overcool the space, because it provides a more constant feel of the indoor temperature. Another thing to point out is that well ventilated scenarios did not show any signs of PCM saturation. That implies TR1 could function better with a thinner layer which covers more surface area, as it could completely melt. Higher PCM quantity is not necessary.

When testing positioning possibilities, as expected, ceiling proved to be the best option. Not only for practical reasons, explained previously, but also performance wise. A 5cm layer placed on test room's floor (which has the same surface area as the ceiling) performed almost identical to a 3cm layer on the ceiling, ultimately meaning that misplacing a PCM layer can reduce performance as if the quantity was reduced by approximately 40%. Additionally, a 3cm layer over more surface is performing better than a 5cm layer over less surface, even if the total PCM quantity is similar. *Table 12* shows position and quantity simulation scenarios compared to the control simulation and to the 5 and 3cm layer on the ceiling simulated in ventilation strategies scenarios. It can be observed that a 3cm layer with total PCM quantity in the range of 1.2 to 1.5 m^3 has by far the best quantity to performance ratio. For instance, case *TR1_PCM_C5_NE3_DV05_NV2* does not improve performance drastically in comparison to case *TR1_PCM_CNE3_DV05_NV2*, even though it features 25% more PCM volumetric quantity. In fact, the performance improvement is minimal even for peak days, pictured in *Figure 19*. That is because in such a room as TR1, which has overheating issues, but does not suffer from extreme solar gains, a 3cm layer can melt congruently and completely as opposed to a 5 or 7cm layer.

Figure 20 pictures the adaptive comfort limits for the best performing cases, and it shows the potential TR1 has, when equipped with PCMs. Operative temperatures were firmly below the comfort limit, indicating that TR1, in such a setting and surrounding, could operate under thermal comfort limits with more extreme weather conditions. That is the theme of the special case, which simulated the case thought to be best performing with the increased heat gains (*TR1_PCM_CNE3_DVNV2*) with the weather file provided from the TU Vienna weather station. Although special case outside temperatures reached as high as 36°C, TR1 did not come close too often. Maximum temperature of the PCM scenario was 32.64°C, which was 0.71°C lower than the peak high temperature of the control simulation with the TU Vienna weather file. This rather small improvement indicates on PCM saturation during heatwave periods. However looking at the CDF graph of the TU Vienna weather scenario (*Figure 23*), it is visible that those peak temperatures occur unfrequently. To go along, from hours over 27°C and the adaptive thermal comfort, it can be seen that a 3cm PCM layer, placed over the ceiling and a partition wall, can bring significant benefits – according to EN15251 adaptive comfort criteria, special case PCM simulation was the most comfortable of all aforementioned ones (*Figure 24*). Of course, with the increased solar gains, in order to achieve improvements like in previous simulations, PCM quantity would have to be increased. Since the goal of this special case is to show the relationship between the weather file and test room performance, as well as exploring if the test room, designed for a mild weather file, can cope with significantly increased outside temperatures, larger quantity will not be tested further.

4.2 TR2 scenarios

From the very first comparison of both test rooms (given in *Table 7*), it becomes obvious that TR2 is different and that approaches used in TR1 will not be enough. Out of six ventilation patterns, only two clearly improved test room's performance. Dealing with so much solar gains, any reduction to the ventilation air change rate resulted into worsened performance (*Table 10*). Simulations of ventilation strategies, therefore, gave a good clue on which patterns should be used to explore different PCM layer thickness and quantity.

Figures 15 & 16 demonstrate temperature change over 10-day spans A & B. It can be observed that, at the beginning of both 10-day spans, all but one ventilation scenario (*DVNV0* stands out) are under the *TR2_CTRL_DV1_NV4* (baseline case) line. At the end of those 10-day spans, only case *TR2_PCM_RRT5_DVNV4* was still under the baseline case, by a significantly smaller margin than at the beginning of the 10-day spans. This clearly indicates to PCM saturation and it is best visible when comparing *TR2_CTRL_DV1_NV4* and *TR2_PCM_RRT5_DV1_NV4*. The only difference between these two simulations is the presence of a 5cm PCM layer placed on the roof and tilted roof of TR2. By the end of 10-day spans A & B, *TR2_PCM_RRT5_DV1_NV4* temperature line matched almost perfectly with its control simulation. Simulations of position and quantity scenarios tackled with this issue and will be discussed in the latter part of the text.

Due to the high solar gains, higher air change rates and relatively low internal mass of TR2, the amplitude of temperature change for the control simulation was extremely wide, resulting in a 23.56°C difference between the minimum and maximum indoor temperature. To put it into perspective, that difference was 14.62°C for TR1. In order for TR2 to fit the EN15251 adaptive comfort category II limits, the amplitude of temperature change must be significantly reduced. As visible in *Table 11*, some scenarios succeeded in narrowing the difference between maximum and minimum temperature quite significantly. *Figure 18* shows CDF lines graph of different PCM layer thicknesses. The first separation of curves for 3, 5 and 7cm layer thickness starts at closely 25°C. This shows how the additional PCM quantity becomes useful only during peak temperature periods.

Table 17: TR2 ventilation strategies & position and quantity best performing scenarios and respective differences to the baseline case

	TR2_PCM_RRT7_DV1_NV4	TR2_PCM_RRT7_DVNV4	TR2_PCM_RRTNE7_DV1_NV4	TR2_PCM_RRTNE5_DVNV4	TR2_PCM_RRTNE7_DVNV4
	Difference to TR2_CTRL_DV1_NV4				
Temperature above 27°C [Hours]	-406	-664	-843	-867	-945
Mean temperature [°C]	-0.5	-1.47	-1.29	-1.77	-1.92
Maximum temperature [°C]	-1.87	-4.61	-6.45	-5.62	-6.71
Minimum temperature [°C]	+3.21	+2.70	+4.06	+3.65	+3.71
EN15251 Category II Acceptability Limits [Hours]	-662.59	-528.26	-429.14	-98.24	-112.84

The best performing scenario of TR2 ventilation strategies simulations would have to be *TR2_PCM_RRT7_DVNV4*. Still underperforming accordingly to EN15251 adaptive comfort category II standard, but significantly improved in comparison to *TR2_CTRL_DV1_NV4*. Maximum temperature lowered by more than 4°C, minimum increased by almost 3°C, therefore narrowing the amplitude of temperature change by 7°C. Number of hours over 27°C was cut in half and hours EN15251 category II criteria was not met was reduced by 30% (*Table 15*).

On another note, it is important to point out that case TR2_PC*M_RRT7_DVNV4* has a higher ventilation rate during daytime than the control simulation. When comparing *TR2_PCM_RRT7_DV1_NV4* to the control simulation (same ventilation pattern, only difference in the presence of a PCM layer), improvements are more modest. Nonetheless, number of hours over 27°C were reduced by 33% and hours EN15251 category II criteria was not met was reduced by almost 40%. Maximum temperature decreased by almost 2°C, minimum increased by more than 3°C and the amplitude of temperature change narrowed by 5°C.

Results of ventilation strategies scenarios are not final and as such are used for better setting up position and quantity and special case simulations. That being said, these results, although still relatively uncomfortable, are promising that a critically overheating space can be turned into a thermally comfortable only by using PCMs and ventilating it properly.

Position and quantity set of simulations finally provided significant improvements to the baseline case, as well to other PCM scenarios from ventilation strategies simulation sets. Three scenarios are performing significantly better than the rest (scenarios *TR2_PCM_RRTNE5_DVNV4*, *TR2_PCM_RRTNE7_DVNV4* and *TR2_PCM_RRTNE7_DV1_NV4*, as seen in T*able 13*), being able to lower maximum temperature to below 32°C with a 5cm and below 31°C with a 7cm PCM layer, increase minimum temperature, while significantly reducing hours over the Austrian overheating limit and improving thermal comfort. *Figure 21* shows one of the peak days, where most TR2 PCM scenarios had significant saturation issues, almost completely merging with the baseline case curve. Increased PCM quantity in position and quantity simulation scenarios succeeded in diminishing, or completely eliminating the PCM saturation issue, hence overheating hours and peak temperatures dropped significantly. In the case of a room which is critically prone to overheating, such as TR2, adding serious amounts of PCM produces noteworthy results. The amplitude of temperature change was narrowed to approximately 13°C for scenarios *TR2_PCM_RRTNE7_DVNV4* and *TR2_PCM_RRTNE7_DV1_NV4*, which is more than 10°C of difference from the control simulation. Number of hours EN15251 adaptive comfort category II criteria was not met was reduced by a considerable margin in comparison to the baseline scenario. Nonetheless, numbers are still quite high. *Table 13* shows that even the scenario with the least amount of hours of not meeting category II criteria was outside of the range almost 20% of the time (in the study period). However, comparing *Figures 17 & 22* displays another view angle. While ventilation strategies simulation scenarios fall out of the range from both sides of the limit, ultimately meaning that both overcooling and overheating are present, position and quantity scenarios (pictured three best-performing ones) are almost completely within comfort limits on the overheating side. It becomes clear that most of the uncomfortable hours are due to low temperatures. The significance of these results will be discussed further in the conclusion.

Best performing case of TR2 scenarios (*TR2_PCM_RRTNE7_DVNV4*) simulated with the TU Vienna weather file showed similarities with TR1s' special case. While performance (compared to the control case with the same weather file) improved from a thermal comfort standpoint (*Figure 26*), peak high temperature could not be significantly lowered (*Table 15*). However, the CDF graph of the special case (*Figure 25*) shows that the occurrence of such high temperatures is considerably lower when PCMs are introduced into a room. Further discussion on this topic will follow in the conclusion.

5 CONCLUSION

5.1 Overview

This work is simulation based. Although it ties its assumptions of simulation conditions to standards and tries to be as accurate as possible, certain circumstances cannot be accounted for, or have to be simplified. Used weather file is possibly underestimating Viennese summer temperatures. Test rooms are isolated from adjacent rooms' conditions. Schedules (from occupancy to ventilation) are defined in a fixed way. In a realistic scenario it would be extremely difficult to obtain such clear and constant ventilation patterns and air change rate throughout the study period. In real conditions air change rates would oscillate from one hour to the other, ultimately influencing outputs. However, this study aims to understand and explain PCM behaviour under given conditions, not to accurately predict test rooms' operative temperatures or energy savings. As already explained in the introduction, EnergyPlus was validated by several studies as a simulation tool that accurately predicts PCM behaviour. That being said, these results are more general and standardised, and while empirical testing might probably produce more colourful results, the general picture should be very similar.

This study examines 38 different simulation cases for two test rooms. Discussion of results already showed some qualities, benefits and limitations of PCM incorporation. Most conclusions were formed by comparing simulation scenarios to identify which change brought the most performance improvement. Best performing cases, which are being previously mentioned, were not selected purely based on best output parameters, but also on the relation between performance and simulation conditions (such as PCM quantity, ventilation pattern, etc.).

TR1 is a reference to a normal room/space that could be subjected to such a renovation. Hence all conclusions for TR1 simulations that follow are considering scenarios that are easily applicable and not excessive. TR2 represents a more extreme case, which was tested also to see PCMs' limitations. Rooms such as TR2 can be brought within thermal comfort by using only PCMs, but with quantities that are possibly unnecessary. Such rooms could have hybrid systems, not completely passive, where mechanical ventilation could be used to increase air change rates and therefore PCM discharge, rendering the room more efficient. In addition, lack of thermal storage could be improved by adding actual mass into the room, which should as well be a cheaper solution. Adding shading devices to help minimise heat gains from the outside could also bring TR2 closer to a performance range that can be significantly improved by using similar PCM quantities as in TR1.

After several iterations, significant improvements were brought upon both TR1 and TR2. That helped to identify crucial aspects of PCM incorporation.

5.2 Answers to research questions

Consideration of specific characteristics of each space is the first step towards a successful PCM integration. As seen from the results of this work, TR1 and TR2 had very different operative conditions, despite being in the same building and having same climatic conditions. Those conditions require different PCM setting, therefore the second step is relating ways of PCM integration to the respective space.

PCM quantity and layer thickness are intertwined with defining parameters of the room, solar gains, ventilation possibilities and thermal mass. All of those room conditions define what a good PCM setting is. Ventilation and solar gains help determine the quantity and layer thickness. Since a PCM layer can be seen as a thermal mass layer, quantity can be increased in order to compensate for lack of thermal mass in the room.

This work was done with two rooms that had different natural ventilation air change rates. As previously explained, TR1 was assumed to have one sided ventilation and TR2 two sided. If solar gains of the room are moderate, such as TR1, ventilation can be somewhat limited (one sided natural ventilation does not have a great cooling potential) and still bring significant benefits, like case *TR1_PCM_CNE3_DV05_NV2* did. Analogically, for a room such as TR2, where solar gains are significantly higher and thermal mass within the room lower, PCM quantity must be increased, therefore ventilation needs to be fully exploited in order to compensate for the increased PCM quantity. A good example would be to look at the comparison between cases *TR2_PCM_RRT5_DV1_NV4* and *TR2_PCM_RRT5_DVNV1* (*Table 10*). The case with moderate ventilation during the evening performed even worse than the control case, due to PCM saturation. In real conditions, higher air change rates for TR1 could have been achieved by creating 2 sided ventilation through the whole apartment, by opening windows on the opposite side of TR1. But for simplification and clear presentation of results, test rooms were observed as isolated entities. This, however, goes as an advantage for rooms with moderate solar gains, showing that performance can be significantly improved also with limited ventilation. Ventilation is one of, if not the, most important aspects of a given space. Improper ventilation was, no matter the quantity, always leading to saturated PCM layers, resulting in worsened performance. On the other hand, bigger the achievable air change rates, better the performance of test rooms. The only drawback of high air change rates was that rooms had a tendency to overcool which affects thermal comfort in early morning hours. To solve the issue, an indoor temperature limit can be set, after which ventilation will be shut off, as in TR2 special case. As long as this limit temperature is below the melting temperature of the PCM, solidifying will not be slowed down notably. Nights in Vienna proved to be cool enough for a PCM with a solidifying temperature of 22°C to completely solidify during most of the study period, if ventilated properly.

Positioning of the PCM layer within the room has big influence on the performance. Foremost, from a physics perspective, placing the PCM layer on the ceiling is the most efficient positioning. That has been tested and proven for TR1 (*Table 12*), and the same analogy can be accepted for TR2. Secondly, if the layer on the ceiling is not sufficient, it makes most sense placing another layer on the wall with the least amount of thermal mass (tested by placing the second layer on the northwest or northeast partition wall – although PCM quantity slightly differs, performance decrease is not proportional to it – *Table 12*).

When increasing PCM quantity, results showed that better results were produced when the surface area of the PCM increased, rather than layer thickness. In other words, between two simulation cases with almost the same volumetric quantity of PCM, the case with a thinner layer spread across a larger surface behaved significantly better. That can be explained by the ability of thinner layers to melt and solidify entirely.

5.3 Summary

- The performance of two rooms with high overheating risk was significantly improved just by adding a PCM layer. Hours outside of comfort range according to standard EN15251 decreased by 615 hours for TR1 and by 429 hours for TR2 compared to the control simulation with the same ventilation pattern (*Tables 16 & 17*).
- A room with moderate heat gains (such as TR1) can be passively cooled only with adequate ventilation and PCM integration.
- Rooms with extremely high overheating tendency (such as TR2) can be significantly improved, however immense quantities of PCM are needed to do so. Having such amounts would not be convenient. Alternatively, PCMs can be used in combination with active systems during peak diurnal temperatures, therefore bringing such rooms within thermal comfort limits at all times.
- According to the both the standard and TU Vienna weather file, evenings are cool enough to solidify the PCM (even to overcool the rooms).
- Thinner layers work better than thicker ones in moderate conditions – it is important to have the right quantity. PCM quantity does not correlate linearly to performance improvement, at a certain point the higher quantity helps only during peak days.

- Best positioning within a room from a performance perspective is the ceiling – same quantity and layer thickness placed on the ceiling and floor proved that ceiling performs significantly better.
- Ventilation is one of the most important aspects of PCM incorporation. This work focused on natural ventilation (simplified – air change rates will vary in reality). If improperly ventilated, PCM can increase the overheating effect (no time to discharge, keeping the thermal energy within the room). Rooms that have very high internal solar gains, such as TR2 can be dealt with by adding more PCM or, if that does not work, by increasing ventilation air change rates by means of mechanical ventilation. That was not tested with this work, but the pattern is clear: The higher the ventilation, the better the room's performance (with the additional challenge of room overcooling prevention).

5.4 Future possibilities

This work showed that the majority of Viennese rooms placed in historical buildings could significantly benefit from applying PCMs. Special case simulation for TR1 covered a case where a weather file with higher temperatures was used, which could give a good representation of future years as, according to many, summer temperatures are not going to decrease in the upcoming years. Even with increased solar gains, TR1 was mostly within thermal comfort when PCMs were introduced. Such rooms could benefit from PCM implementation for the years to come. For rooms like TR2, hybrid systems will need to be made in order to use the potential of PCM integration. Those systems could range from automatically regulated mechanical and/or natural ventilation, to shading devices, etc.

Having in mind that PCMs are still a niche material, these results look very promising. Once the industry embraces PCM integration, research will follow and, very likely, massive improvements in quality and performance.

6 INDEX

6.1 List of Figures

6.2 List of Tables

6.3 List of abbreviations

(1) UHI – Urban Heat Island
(2) TES – Thermal Energy Storage
(3) PCM – Phase Change Material
(4) CTRL - Control
(5) TR1 – Test room 1
(6) TR2 – Test room 2
(7) NE – Northeast
(8) SE – Southeast
(9) NW – Northwest
(10) SW – Southwest
(11) IWEC – International Weather for Energy Calculation
(12) TU – Technical University
(13) CDF – Cumulative Distribution Function

7 LITERATURE

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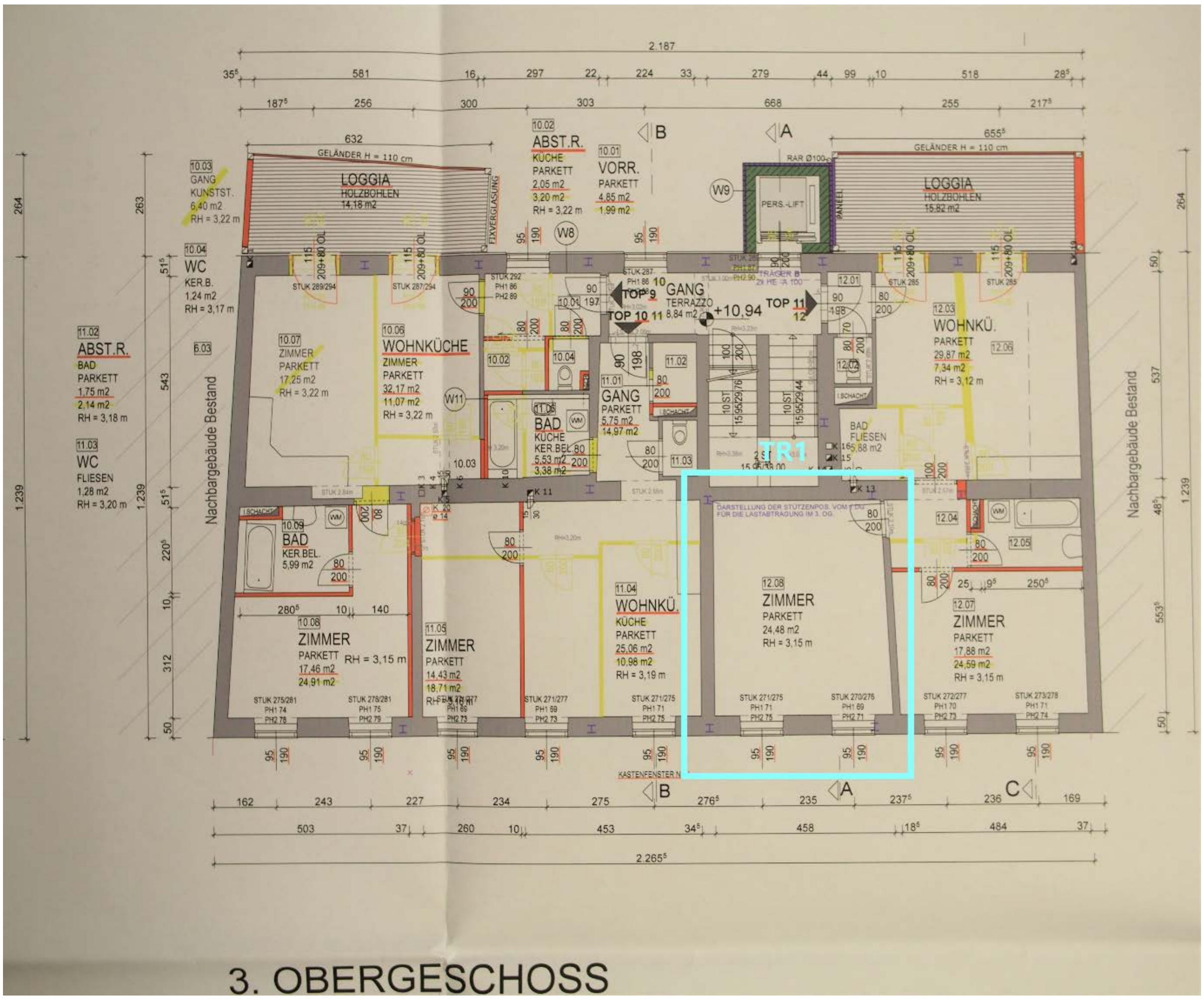
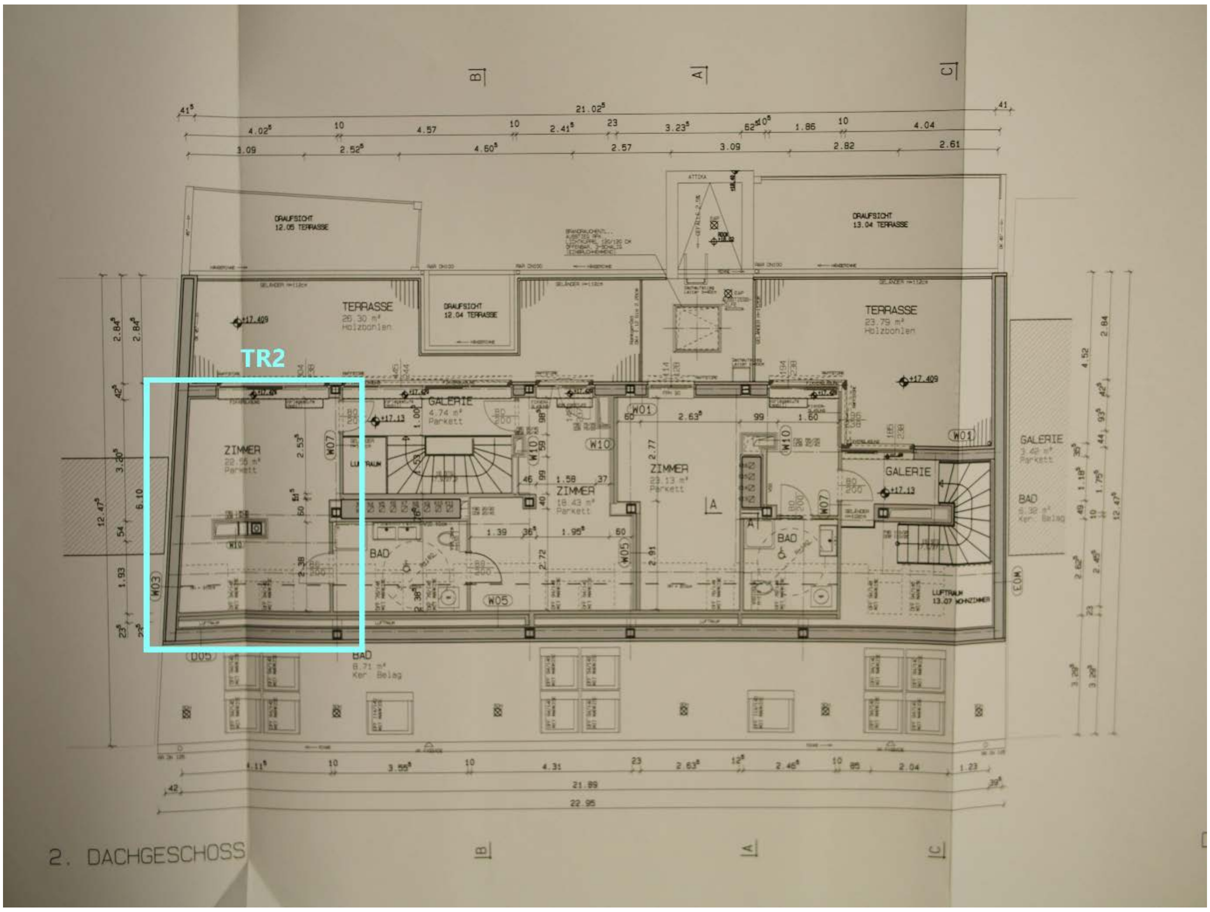
8 APPENDIX

8.1 Appendix A: Floor plans for both test rooms




TR2
TERRASSE
ZIMMER
GALERIE
BAD
2. DACHGESCHOSS