Overheating Evaluation via Normative Calculation and Dynamic Simulation

A Comparison of Methods

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KURZFASSUNG

Die Vermeidung von sommerlicher Überwärmung gilt als einer der wichtigsten Aspekte für die zukünftige Gebäudeplanung. Moderne Konstruktionsmethoden, wie Leichtbauweisen oder ein hoher Anteil von transparenten Elementen, erhöhen das Risiko von Überwärmung in heißen Perioden. Die globale Erwärmung verursacht eine höhere Häufigkeit und Intensität dieser Hitzeperioden, und insbesondere städtische Gebiete sind durch verstärkende mikroklimatische Auswirkungen, die als *Urban Heat Island*-Effekt bekannt sind, betroffen. Die Planung von Neubauten, Gebäudeerweiterungen sowie Gebäudesanierungen erfordert daher verlässliche Methoden, mit denen festgestellt werden kann, ob die Gefahr von sommerlicher Überwärmung besteht. Die vorliegende Arbeit vergleicht die österreichischen normativen Methoden mit einer gängigen dynamischen thermischen Simulationsmethode. Dabei bestehen wesentliche Unterschiede hinsichtlich der Auflösung der Eingabe- und Ausgabedaten, Komplexität und Anwendbarkeit der Methoden. Der vereinfachte normative Nachweis basiert auf elementaren Berechnungen mit nur wenigen Eingabeparametern und wird hauptsächlich im Rahmen der Energieausweis Erstellung für Wohngebäude eingesetzt. Der detaillierte normative Nachweis erfordert bereits komplexere Eingabedaten in etwas komplexeren Berechnungen. Dieser ist nach derzeit gültiger Rechtlage jedoch nicht verpflichtend und wird daher nur selten verwendet, soll aber zukünftig auch in die offiziellen Baurichtlinien einbezogen werden. Die dynamische Simulation erfordert aufgrund der Vielzahl erforderlicher Eingabedaten und möglicher Berechnungssettings sowie der Bedienung der für die komplexen Berechnungsalgorithmen erforderlichen Spezialsoftware, spezielles Know-how. Dies führt auch zu großen Unterschieden hinsichtlich der Anzahl und Auflösung der Ausgabedaten. Um auch einen praktischen Vergleich der Methoden durchführen zu können, sowie eine Analyse der Ergebnisse vornehmen zu können wurden eine *Fallstudie* und eine darauf aufbauende *parametrische Studie* durchgeführt. In der Fallstudie wurden vier spezifische Entwürfe eines Dachgeschoßausbaus mit Wohnnutzung in Wien bewertet. Kritische Voraussetzungen wie geringe thermische Masse und hoher Verglasungsgrad zeigten insbesondere die Grenzen der normativen Methoden auf. Dabei stellte sich unter anderem heraus, dass Räumlichkeiten, die nach der vereinfachten Methode als überwärmungssicher eingestuft werden, bei detaillierten Berechnungen und Simulationen dennoch Raumtemperaturen jenseits des Komfortbereichs aufweisen. In der parametrischen Studie wurden 48 verschiedene Designvarianten mit der detaillierten Methode und der dynamischen Simulation bewertet. Zum einen wurde gezeigt, dass die Ergebnisse der beiden Methoden, trotz unterschiedlicher Auflösung größtenteils korrelieren. Zum anderen kam es zu Abweichungen aufgrund spezieller Designelemente oder der Verwendung zukünftiger Wetterdaten, was beides nur mittels Simulation berücksichtigt werden kann. Generell zeigen die Ergebnisse, dass die Vermeidung von sommerlicher Überwärmung schon in naher Zukunft sehr viel schwieriger werden könnte und dass die derzeitigen normativen Methoden und Kriterien dafür wohl stringent weiterzuentwickeln sind.

Schlagwörter

Sommerliche Überwärmung, Normative Methoden, Parametrische thermische Gebäudesimulation

ABSTRACT

Summer overheating avoidance is considered to become one of the most critical building performance aspects in upcoming years. Design specifications, such as contemporary construction methods, the usage of materials with low thermal mass or a high ratio of transparent elements, increase the tendency of overheating during hot periods. Global warming triggers higher frequency and intensity of those hot periods. In particular, urban areas are affected through microclimatic implications known as *Urban Heat Island* effect. The planning of new buildings, building extensions, such as rooftop extensions, and building retrofit thus require robust methods that are capable to determine if a building design is in risk of summer overheating. This contribution compares the Austrian normative methods with a common dynamic thermal simulation method. There are major differences regarding complexity and usability of the methods. The simple normative method is based on elementary calculations with only a limited set of input parameters. It is mainly used in the course of the mandatory energy certification for residential buildings, based on the Austrian building guidelines. The detailed normative method processes more input data and features more advanced calculations. It is not stipulated by building regulations and therefore it is rarely used. However, future changes in the regulations intend to incorporate this method into the official building guidelines. Dynamic simulation requires special know-how due to the variety of possible input data and the operation of the specialized software tools to be able to utilize these powerful but complex calculation algorithms. This also leads to major differences regarding the resolution and appearance of the output data. As such, a direct comparison of results from the different methods is not possible. For the practical comparison of the methods and the analysis of their outputs a case study and a parametric study have been conducted. The case study evaluated four specific designs of a roof top extension for residential use in Vienna. Critical preconditions such as low thermal mass and high glazing ratio particularly illustrated the limitations of the normative methods. Some results even suggest that simple normative calculations would specify specific rooms as safe against overheating, while the more advanced normative procedures and the thermal simulation point towards overheating tendencies. The parametric study evaluated a set of 48 design variants with the detailed method and the dynamic simulation. Despite their different resolution, the results of the two methods showed mainly correlation regarding overheating evaluation. Moreover, occurring divergences due to special design elements or the use of future weather data for the simulation were analyzed. Generally, the results show that the avoidance of overheating will become more challenging in close future. As such an update of the normative methods and the used key performance indicators is highly recommended.

Keywords

Summer overheating, normative procedures, thermal building performance simulation, parametric study, key performance indicators

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1 INTRODUCTION

The avoidance of summer overheating in worldwide building planning gains importance in recent years. This is due to a set of reasons: *(i)* Contemporary construction methods, that rely on light-weight materials and a high ratio of transparent elements increase the tendency of overheating during hot periods. *(ii)* Moreover, the global warming causes higher frequencies and intensities of such hot periods- In particular, urban areas are affected by microclimatic implications known as *Urban Heat Island* (UHI) effect. This already leads to higher indoor temperatures in buildings, causing discomfort and affecting health, wellbeing and productivity of the occupants (Mylona et al. 2015). *(iii)* Overheating in buildings is often compensated with energy intensive active cooling systems. As a result, these systems additionally contribute to a positive feedback loop by affecting the microclimatic conditions in urban areas by warm exhaust air. Especially in regions with a moderate climate such as central Europe, summer overheating could be avoided without active cooling, but with sophisticated and careful planning.

While in past times, building planners had to rely on experiences described by their predecessors and literature to plan and predict the overheating tendencies, today different assessment methods are available, which offer a pre-building summer overheating assessment of buildings. These methods range from simple calculations to sophisticated simulation and differ in complexity and resolution of their results. In Austria, there is a normative approach based on the national standards that is used for building energy certification. Building designs and retrofit projects can be assessed with this simple normative method. As such, the method allows to ensure a certain safety against severe summer overheating. Such certifications can be required for getting a subsidy grant or receiving a building permit. However, the normative methods are based on rather simplified calculations to avoid a high degree of complexity for the building planners. This results in limitations regarding input data and boundary conditions, such as climate data. As a result, the results of these methods are limited in their meaningfulness. Compared to that, dynamic simulation is occasionally used for a more detailed analysis of the thermal behavior of future buildings. The complexity of this method demands more effort and expertise but can provide highly detailed results based on flexible input data and boundary conditions. Within this contribution, the different methods are compared regarding their results for summer overheating assessments and analyzed concerning their potentials and limitations. A set of designs for a roof top extension of an existing *Gründerzeit* building (erected around 1900) in Vienna is used for special case studies and a general parametric study.

1.1 Motivation and Background

The regulation and directives for building planning in countries that are heating dominated are mainly based on the term *thermal protection* in the sense of reducing heat losses to the cold environment. Thermal protection in the sense of avoiding also summer overheating is often underrated but gains importance due to climate change and contemporarily used construction methods based on materials of low thermal mass. Even if the energy demand for cooling remains small in comparison to the heating demand in the cold season, the peak loads and mainly the risk of discomfort and health issues in overheated buildings will further increase as the heat waves of the last years have already shown. In the Austrian directive for energy saving and thermal protection, the *OIB Guideline 6* of the institute of building technology (OIB 2015), a single sentence regarding thermal protection in summer for residential buildings can be found. It refers to the simple normative method of the only Austrian standard for the topic of summer overheating, *ÖNORM B 8110-3* (ASI 2012). This simple calculation method is mainly based on thermal mass calculation but does not consider ambient temperatures or internal gains. Calculations and comparison to thermal simulation in the course of a dissertation about thermal protection in summer showed that the simple normative method strongly tends to underestimate the risk of overheating (Nackler 2017). The second Austrian normative method based on *ÖNORM B 8110-3*, is the so-called detailed method. This method represents a more detailed calculation considering more detailed input data and the ambient temperature of one typical summer day as boundary condition. Different tools have been developed to examine summer overheating assessments based on this detailed normative method. Most of them e.g. *ArchiPHYSIK (A-NULL 2019)* are based on a prototype tool that uses a combination of a time-step and a steady-state calculation. All these tools have in common that they only can be applied to single rooms and that they are based on a steady-state boundary condition, a virtual summer day (15^{th} of July), which is assumed to be part of a moderate heat period. The resulting operative room temperatures occurring on that day is the only standard output of the detailed normative method. Dynamic simulation tools, e.g. *EnergyPlus (DOE 2018)*, which are not implemented into Austrian standards use the time-step calculation method over a certain time period and can be applied to a set of rooms or zones. These methods can be considered to be closer to the physical reality. Therefore, they demand detailed input data such as hourly climate data, information about the physical properties of the building envelope and detailed occupancy data. The setup of the required input data will be part of parametric variations and sensitivity analyses based on previous studies and works (Lomas and Porritt 2017; Nackler 2017). Once all the input data is set, the thermal behavior of the investigated building can be analyzed in a very detailed fashion. Internationally, there are very different approaches used to evaluate overheating risk via thermal simulation. Therefore, the analysis and comparison of overheating definitions and evaluation criteria will be a constituent part of this work. The case study building is an existing Viennese *Gründerzeit* building with a set of different designs for a rooftop extension. This building can be considered to be a typical representative of the European building stock with summer overheating risk due to the large envelope area in comparison to occupied volume, direct exposure to sunlight for remarkable timesteps and limited possibility to integrate thermal mass compartments into the design.

1.2 Objectives and Outline

There is **first part** of the work that deals with theoretical research about the definition, the criteria, the influencing parameters and the assessment methods of summer overheating. The main focus lies on the comparison of the normative calculation methods and dynamic simulation, mainly regarding the differences of the input and output parameters.

The **second part** is dedicated to the practical application of the methods and the comparison of the required inputs and the resulting outputs. The case study, a roof top extension is a representative example for a central European building with potential overheating risk. The building type and the available design variants feature the following basic specifications:

- Rather low thermal mass
- Highly exposed critical rooms
- Large exterior glazing / high glazing ratio
- Dominantly residential use
- Naturally ventilated via windows

The case study variants differentiate in special design elements such as overhang façades or fixed shading. However, a common aspect is that they can be considered critically regarding overheating tendencies. Given the main objective of this contribution, the overheating evaluation method comparison, the case study provides also a chance for evaluation of the limitations of the different applied methods. In addition to the case study that deals with critical design variants, a parametric study has been conducted. This study provides a large set of design variants and offers more generally valid, thus generic, results.

For the comparison and analysis of the results, appropriate evaluation criteria had to be developed. This was done based on the background research about the existing methods.

2 THEORETICAL FRAMEWORK

2.1 Summer Overheating Definition and Criteria

A variety of definitions, evaluation criteria and evaluation methods for summer overheating assessment of buildings exist. For instance, overheating can be defined as *"[…] that state of mind that expresses dissatisfaction with the environment caused by prolonged high temperatures"* (Mylona 2015: 1). This general definition stated by the Chartered Institution of Building Services Engineers (CIBSE) shows the subjective element in the topic of building overheating assessment. Dissatisfaction with the indoor environment, respectively comfort or well-being, depends not only on thermal comfort but also on other factors such as visual comfort, acoustical comfort and air quality. Furthermore, thermal comfort is not only represented by indoor air temperature but also radiant temperature, air speed and humidity as well as subjective personal factors like age, state of health, clothing and activity levels (Fanger 1970). Additionally, the adaptive thermal comfort approach was developed within many international works (CIBSE 2006) and also introduced in different standards, for example *EN 15251* (CEN 2007) or *ASHRAE 55* (ANSI 2010). This adaptive approach takes also the dynamic change of comfort criteria dependent on outside temperatures into account. Altogether, the mentioned references illustrate the complexity in definition of overheating criteria and developing proper evaluation approaches. Internationally, very different methods have been established that also utilize very different criteria, resulting in very diverse national standards and easy-or-not-easy to apply methods for overheating assessment. Whereas these normative methods often are stipulated by building regulations, they have in common that they use simplified calculations and criteria. This ensures feasibility for planners and stakeholders on one hand but also leads to a very limited meaningfulness of the results on the other hand. More advanced calculation and simulation methods with sophisticated criteria are only in part integrated into standards and national regulations, and thus rarely used in practice. Rather, they are deployed in scientific research and development. The evaluation and validation of proper overheating criteria is a complex task, that has been approached in many recent works, but "[…] *there are still many issues to confront*" (Lomas and Porritt 2017: 1). Within this cntribution only the Austrian normative methods with their standard criteria will be analyzed in detail and compared to the dynamic thermal simulation method. A convenient overview about different European and International assessment methods and criteria is provided below.

Austria

In Austria, mandatory criteria for thermal performance of buildings are defined within the *OIB-Guideline 6* (OIB 2015). This directive of the Austrian *Institute of Construction Engineering* (OIB) is also implemented into the official legal regulations for construction in Austria. It regulates the general criteria for official energy certification. Regarding summer overheating evaluation the guideline refers to *ÖNORM B 8110-3* (ASI 2012) a standard of the *Austrian Standard Institute* (ASI). Within this standard the simple normative method and the detailed normative method, which are part of this works analyses, are defined. Both methods should evaluate the overheating risk of single critical rooms.

The simple method requires calculations of the effective thermal mass involving solar gain approximations. The result is compared to a threshold value which leads to a *yes* or *no* decision. Other parameters such as outside conditions or internal gains are widely neglected for the calculations. However, according to the standard there are two restrictions for the use of the simple method. Firstly, the standard outside temperature of the location must not exceed a certain maximum value. Secondly, all windows of the critical room have to be openable during the night. Surprisingly these restrictions are widely disregarded in the official *OIB-Guideline 6* (OIB 2015). The first restriction about the outside temperature is definitely overruled and the second one is not mentioned. Apart from its feasibility this might be another reason why the simple method is primarily used in Austria.

The detailed normative method is not explicitly stipulated by the official *OIB-Guideline 6* (OIB 2015) but according to *ÖNORM B 8110-3* (ASI 2012) it should be used if the simple method is not applicable. In the standard this method is described as calculation of hourly operative temperatures for one day under certain predefined input parameters with the help of a calculation tool that meets the requirements of the standard *ÖNORM EN ISO 13791* (ASI 2010b). In fact, this standard is outdated since the year 2012 and replaced by the standard *ÖNORM EN ISO 52016-1* (ASI 2017) and there is no further information what requirements have to be met exactly. Nevertheless, some tools that are primarily used for energy certification have also implemented the detailed method. Precisely, this method could also be declared as simplified periodic simulation. But opposed to typical thermal simulation methods with longer calculation periods such as a whole year, the detailed normative method calculates only one day, nominally the 15th of July. Contrary to the simple method, input parameters about outside conditions, internal gains and detailed ventilation are also considered. The inputs for internal gains and ventilation are defined with minimum default values that are normally used, independent of actual circumstances.

As overheating criteria, a maximum operative temperature of 27°C during daytime and 25°C for bedrooms during nighttime are allowed.

For dynamic simulations with a yearly period no Austrian normative regulations exist. The *klimaaktiv* initiative (ÖGUT 2017) of the *Austrian Federal Ministry for Sustainability* and the *Austrian Society for Environment and Technology* (ÖGUT) provides criteria for energy efficient and sustainable buildings. A certification can be obtained by evaluation of different categories with a point-based system. There are also criteria regarding summer overheating and dynamic thermal building simulation. The minimum requirement states a maximum of 10% of hours exceeding the reference temperature of 26°C. For the maximum of points only 3% of the hours may exceed 26°C.

Germany

In Germany, the standard *DIN 4108-2* (DIN 2013), specified by the *German Standard Institute* (DIN), represents requirements for thermal protection. Regarding summer overheating evaluation there is also a simple calculation method defined that is used primarily in practice. Optionally, dynamic thermal building simulation with certain evaluation requirements is suggested especially when the simple method is not applicable. The restrictions for the use of the simple method are the appearance of double skin façades or transparent insulation systems. Additionally, calculation or simulation methods can become unnecessarily if certain requirements regarding the window area ratio of the critical room are met.

The German simple normative method uses a different approach compared to the Austrian method. It primarily considers *solar immission* but thermal masses of the construction components are not directly integrated. The general thermal mass, the ability of night-ventilation and the outside conditions are all considered, by selecting one out of three categories (e.g. light, medium or heavy construction). Internal gains are not considered. An actual and maximum *solar immission coefficient* are calculated and compared for a *yes/no* decision regarding summer overheating risk.

For the dynamic simulation approach, opposed to the Austrian detailed method, a typical simulation tool for dynamic thermal simulations has to be used, because a whole year simulation is required. Again, diverse parameters such as default inputs for ventilation and internal gains are defined but regarding outside conditions, a whole standard test reference year (TRY) of a certain climatic region has to be used. The crucial criterion for residential buildings is the maximum value of 1200 degree hours per year over a certain reference temperature. With an operative temperature of either 25°C, 26°C or 27°C as reference depending on the climate region.

Switzerland

The *Suisse institute for standards* (SIA) regulates thermal protection in summer within chapter 5 of the SIA 180 standard (SIA 2014). For summer overheating evaluation three methods are available. There is the first method without calculation but with certain simple criteria. If one criterion is not met the second method, a simple calculation of certain requirements has to be used. If one requirement is not fulfilled then the third method, a dynamic thermal simulation has to be conducted.

The criteria of the first method imply certain requirements for shading, glazing properties, glazing ratio, construction components and efficient night-ventilation. For the second method more detailed requirements have to be proven with simple calculations. Maximum values for solar transmission values and interior surface temperatures of the glazing are defined. Minimum values for heat capacity and night-ventilation have to be achieved. Both simple normative methods again neglect outside conditions and internal gains.

For the third method, dynamic simulation with a period of six month from the mid of April until the mid of October is required. Default inputs such as internal gains and project specific inputs such as climate data are used to calculate the operative temperatures for every hour. In contrary to other standards the overheating criterion is not a fixed maximum temperature or maximum number of degree hours. The maximum operative temperature dynamically depends on the mean outside temperature over 48 hours and must not be exceeded at all. This approach corresponds to the adaptive comfort theory.

United Kingdom

Due to the moderate climatic conditions in the United Kingdom summer overheating evaluations are not mandatory for building planning. Within the government's *Standard Assessment Procedure* (SAP) for energy rating of dwellings there is just an optional simple calculation method for summer overheating assessment integrated (SAP 2012). Nevertheless, recent years show great effort to establish profound overheating methods and criteria (Jenkins et al. 2011). Due to climate change, existing constructions and present renovation methods, the risk of summer overheating will critically increase even in the United Kingdom (Gupta and Gregg 2013).

Most recent publications related to summer overheating assessment consent that dynamic thermal building simulation is the most promising method to use. As already mentioned, the major challenge in this field of research is the definition of proper overheating criteria. This is also shown by two publications of the *Chartered Institution of Building Services Engineers* (CIBSE).

The 2006 edition of the *CIBSE Guide A* (CIBSE 2006) recommended 25°C as an acceptable indoor design operative temperature in summer and suggested limiting the expected occurrence of operative temperatures above 28°C to 1% of the annual occupied period. In 2013 a new approach was published (CIBSE 2013). A room or building that fails two of the three new criteria is classed as overheating. Criterion 1: The number of hours during which the operative temperature exceeds the threshold temperature during the period May to September inclusive shall not be more than 3 percent of occupied hours. The threshold temperature can be calculated from the running mean of the outdoor temperature according to the adaptive comfort theory. Criterion 2: To allow for the severity of overheating the weighted exceedance based on *EN 15251* (CEN 2007) shall be less than or equal to 6 degree hours in any one day. Criterion 3: To set an absolute maximum value for the indoor operative temperature the difference to the threshold temperature shall not exceed 4 K at all.

Estonia and Finland

Surprisingly, it was found that these northern countries are two of few countries that defined dynamic simulations as mandatory methods for summer overheating evaluations into their national regulations. In Finland even *“multi-zone dynamic simulations are required by the Building Code”* (Simson et al. 2017a: 192).

The Estonian regulations require dynamic simulations for critical rooms using test reference year climate data and standard inputs for internal gains and ventilation. The crucial criterion is the maximum value of 150 degree hours over the base temperature of 27°C during the summer period (Simson et al. 2017b).

Comparison

All investigated standards contain simplified parameter calculations, but they use very different procedures and criteria. Only in the German and Suisse standards, there are criteria for dynamic simulation defined. The Austrian detailed normative method is somewhere in between the simple calculation methods and dynamic simulation and cannot directly be compared to the other methods. *Table 1* shows that the criteria for the simulation methods can differ greatly. In Austria and Germany there are fixed threshold temperatures (T_o = operative room temperature). The Suisse and the newer English criteria use adaptive threshold temperatures. ($T_{adapt.comf.}$ = threshold according to adaptive comfort theory).

Table 1: Comparison of common European evaluation methods and criteria

Country	Method	Type	Criteria
Austria	ÖNORM B 8110-3 Simple calculation method	Parameter calculations	yes/no
	ÖNORM B 8110-3 Detailed method	Periodic single day calculation	$T_{o,max}$ = 27°C
	klimaaktiv Dynamic simulation	Whole year simulation	T_o > 26°C max.10% / 3% recom.
Germany	DIN 4108-2 Simple calculation method	Parameter calculations	yes/no
	DIN 4108-2 Dynamic simulation	Whole year simulation	T_o > 25/26/27°C max. 1200 Kh
Switzerland	SIA 180 Simple criteria method	Parameter criteria	yes/no
	SIA 180 Simple calculation method	Parameter calculations	yes/no
	SIA 180 Dynamic simulation	Summer period simulation	$T_o > T_{adapt.comf.}$ 0%
UK	SAP 2012 Simple calculation method	Parameter calculations	yes/no
	CIBSE Guide A 2006 Dynamic simulation	Whole year simulation	T_o > 28°C max. 1%
	CIBSE TM52 2013 Dynamic simulation	Summer period simulaton	$T_o > T_{adapt.comf.}$ max. 3% $\Delta T_{o,daily}$ < 6 Kh

2.2 Summer Overheating Parameters

The most important parameters that influence buildings overheating risk are defined and ranked similarly by a variety of studies. Mainly there are the outside conditions, the solar radiation transmission, shading, the ventilation mode, internal gains and the thermal mass of the construction components. Usually this ranking represents also the priority of the parameters regarding their influence on room temperatures in contemporary buildings. (Nackler 2017)

The Austrian standard *ÖNORM B 8110-3* (ASI 2012) describes the control of the following parameters as effective to avoid overheating:

- Orientation, measures and quality of transparent components
- Effective thermal masses of construction components and furniture
- Ventilation, especially night-time ventilation
- Shading

Additionally, to all above mentioned parameters there are also *thermal transmission* through the envelope and *thermal absorption* of the exterior surfaces, which must also be considered for detailed calculations. However, effects caused by these two parameters are much lower compared to the other main parameters. *Figure 1* provides an overview over the main parameters regarding summer overheating evaluation.

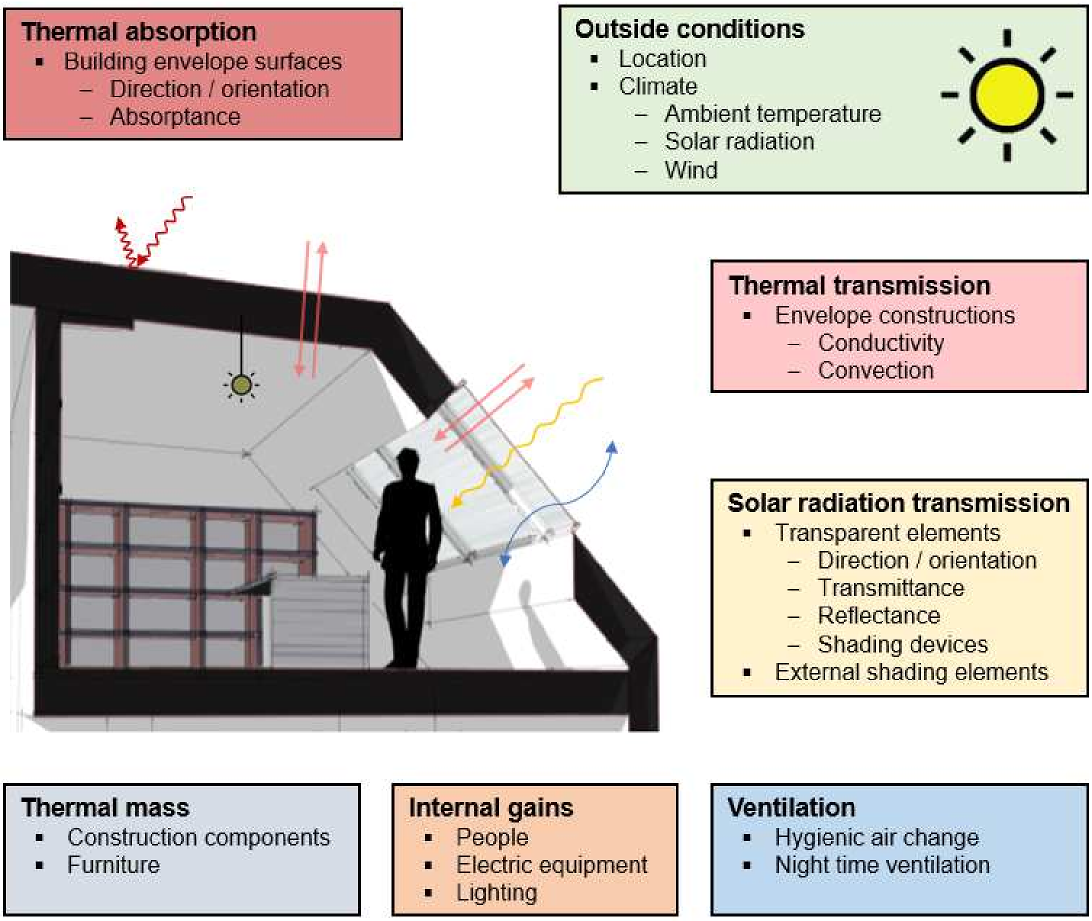


Figure 1: Summer overheating parameters (own figure)

Depending on the evaluation method, a specific set of parameters is used as input data for the calculations. The method specific details are described in the upcoming sections of this thesis. Important aspects and background information concerning the mentioned main parameters are presented below.

Outside Boundary Conditions (Environmental Conditions)

Naturally, the exterior boundary conditions have a major impact on the indoor conditions. Nevertheless, they are often not directly integrated, in particular in simplified overheating evaluation methods. Despite that, these methods are valid for whole countries or specific climatic regions. Although also for small countries like Austria there can be remarkable climatic differences between two locations. More detailed calculation and simulation methods implement location dependent input parameters that consider varying outside conditions. There are very different approaches how this is done, depending on the method. Simple periodic simulations for example use repeating fictive daily temperature profiles. Dynamic simulations require at least hourly weather data of temperatures, solar radiation and wind.

Solar Radiation Transmission

For residential buildings in a moderate climate, incident solar radiation through transparent building elements is the number one reason for high indoor temperatures. Therefore, the blocking of the sun rays is the most efficient measure to avoid overheating. Naturally, parts of the radiation spectrum are already reflected or absorbed by the glazing, depending on its material properties. Low transmission glasses, represented with low g-values, can also have disadvantages regarding limited transmission of visible radiation and reduced solar gains in winter. Additional shading devices for glazed elements such as blinds or screens can be very flexible and effective, in particular if they are mounted externally. Due to their flexibility, their actual efficiency is very much dependent on their actual utilization. This also can conflict with daylight issues and is difficult to predict, which is challenging for assessments of future overheating risk. The efficiency of fixed shading elements such as overhangs mainly depends on their position and measures as well as on the orientation of the windows.

Thermal Mass

The influence of thermal mass on the overheating risk is subject of many studies with partly controversial conclusions, often depending on the sponsor. Generally, it is known that mainly the effective heat capacity of the interior layers of construction components effects the thermal behavior of rooms. Crucial for lower indoor temperatures is also the efficiency of unloading this thermal mass, in particular through night-time ventilation. Studies also show that other parameters such as behavior of occupants concerning shading and ventilation have much more influence on overheating risk than thermal mass (Wurm 2016; Frank 2009). This is particularly relevant for critical buildings such as roof top extensions where the implementation of thermal mass is very limited. For overheating evaluation, the thermal masses of the construction components are assessed through the thermal properties of their layers. The consideration of furniture is also relevant and depends on the evaluation method.

Thermal Transmission and Thermal Absorption

In heating dominated countries like Austria the buildings are usually very well insulated. This leads in summer to very low influence of the ambient temperature or the surface temperature on the indoor temperature. Only in regions with high solar radiation and low building standards, high absorption and low insulation lead directly to overheating. The disadvantage of high insulation is the reduction of desired heat losses. Therefore, other measures such as increased night-time ventilation have even more priority. Simple overheating evaluation methods often neglect thermal absorption and transmission. Detailed methods and simulation consider all thermal properties of the building construction components.

Ventilation

In naturally ventilated buildings there are two types of ventilation during summer. During occupancy there is the hygienic air change, normally a minimal airflow controlled through window openings by the occupants. It can contribute to overheating if high outdoor temperatures are present. The control depends on the occupants and is very difficult to predict. The same applies to night-time ventilation which should decrease the temperature level of the room and its thermal masses to avoid overheating on the next day. The actual efficiency additionally depends on the ventilation opening area, the temperature difference between outside and inside and the wind driven forces. Depending on the method, there are different approaches to define input parameters accordingly. Normative methods normally use estimated air change rates or simple air flow calculations to avoid unnecessarily high complexity. Dynamic simulation tools would be able to consider more complex input data and their correlations but still are sensitive to uncertain inputs such as window opening schedules.

Internal Gains

Residential buildings are passively heated by people and electric equipment such as computers, fridges, TVs, lighting and so on. This can hardly be avoided but partly reduced by using energy efficient equipment and controls. The occupants, respectively their behavior regarding shading and ventilation control are very critical regarding overheating assessment. They control the crucial parameters and it is again not quite possible to predict those actions exactly. Normative methods partly ignore internal gains and partly provide standard default values for heat gains and ventilation rates. Detailed simulation methods require detailed specifications regarding internal gains, ventilation control and their schedules. Due to the uncertainty of this data studies try to develop more reliable occupancy-related models (Tahmasebi 2016). Nevertheless, simulations still cannot really predict the exact future building performance, but they can simulate the performance based on the certain input data.

2.3 Climate Change and Urban Heat Island Effect

Many studies, nationally and internationally, show that the Earth’s climate is changing rapidly. With the main effects of rising temperatures and increased frequency of extreme weather conditions. The *Fifth Assessment Report* (AR5) of the *Intergovernmental Panel on Climate Change* (IPPC) states that: *"Each of the last three decades has been successively warmer at the Earth’s surface than any preceding decade since 1850"* (IPCC 2014: 2). Anthropogenic greenhouse gas emissions are the main drivers of the recent climate change. The future emissions and resulting concentration of greenhouse gases in the atmosphere will therefore mainly influence the occurring temperatures. There are four different main scenarios called *Representative Concentration Pathways* (RCPs). They are named regarding the increase in radiation energy compared to pre-industrial times: *RCP2.6* (2.6 W/m²), *RCP4.5* (4.5 W/m²), *RCP6.0* (6.0 W/m²), *RCP8.5* (8.5 W/m²). *RCP2.6* represents a stringent mitigation scenario, *RCP4.5* and *RCP6.0* underlie moderate climate protection measures and *RCP8.5* indicates business-as-usual with very high greenhouse gas emissions. (Chimani et al. 2016a)

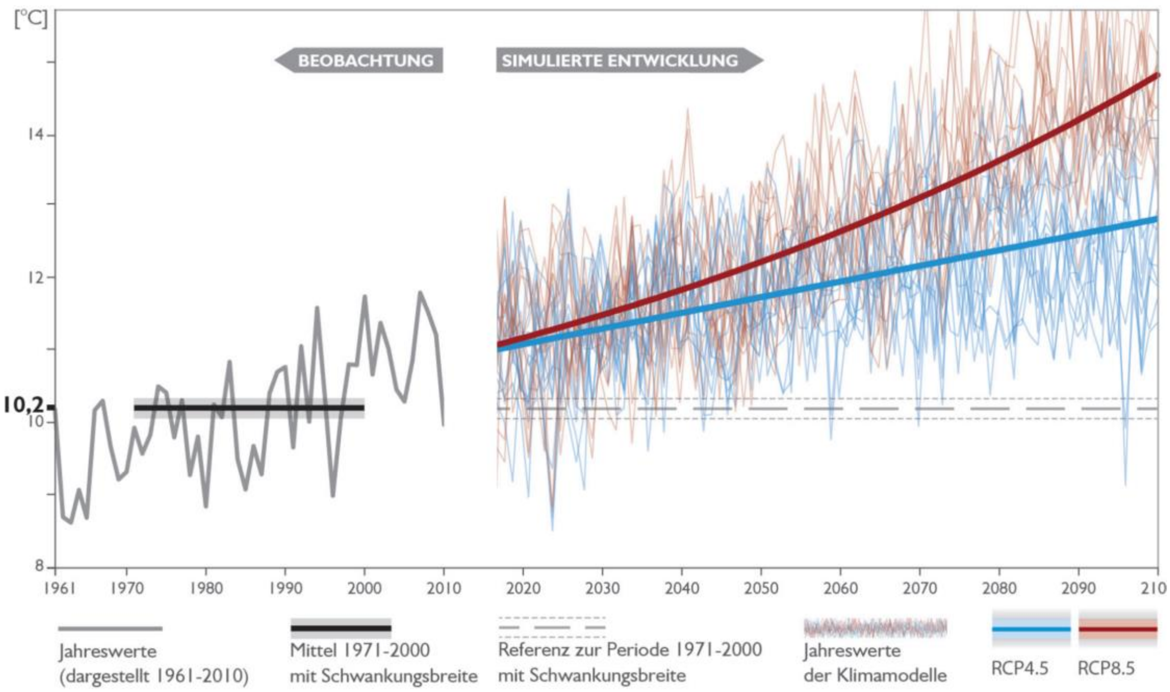


Figure 2: Measured and simulated mean temperature changes for Vienna - License: CC BY-NC-SA 4.0 (Chimani et al. 2016b)

Future climate projections become increasingly important for building planning and overheating assessment. *Figure 2* shows simulated mean temperatures based on *RCP4.5* and *RCP8.5* compared to historical data of Vienna. The thin colored lines represent yearly simulations of 13 single models for the two scenarios. The thick colored lines represent the average trend of all simulations. This shows on the one hand that the different models have a big fluctuation range because there are many uncertain influencing parameters and a long time period. Nevertheless, the trends indicate significant temperature rise, clearly above the present fluctuation range (black thick line with grey background).

Besides general global warming there are also microclimatic effects that particularly affect urban areas. The so-called *Urban Heat Island* effect causes significantly warmer temperatures in city centers compared to surrounding areas. *Figure 3* shows a satellite image of the city of Louisville, Kentucky. The *at-satellite brightness temperature* of the land is measured by NASA's Earth-facing Landsat satellite, in degrees Kelvin. Here the temperature range from 294 K (blue) over 300 K (yellow) to 306 K (dark red) is illustrated. Generally this report found that in 57 of 60 of the largest U.S. cities measurable *Urban Heat Island* effects occurred in the period of the past ten years. (Kenward et al. 2014)

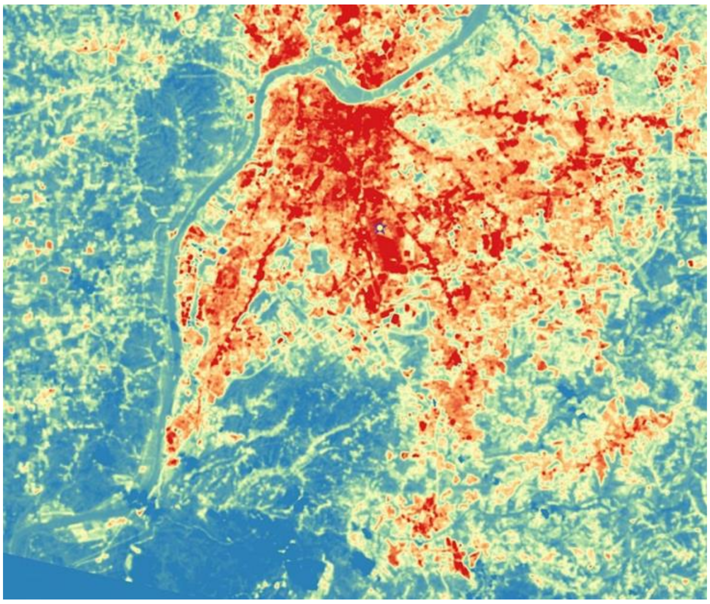


Figure 3: Urban heat measured by satellite in Louisville, Kentucky - License: free to use (Climate Central 2014)

Also, European studies show similar results for cities like Vienna, Rome, Prague, Barcelona and so on. The *climate-fit.city* project combines the *RCP* scenarios and the *Urban Heat Island* effects and creates future weather data that can be used with dynamic simulation tools. (Lauwaet et al. 2017)

2.4 Summer Overheating Evaluation Methods

The basic theoretical background information about the two Austrian standard overheating evaluation methods, the simple normative method and the detailed normative method are presented in the following. Subsequently, a typical dynamic thermal building simulation method is described.

2.4.1 Simple Normative Method

For the simple method according to *ÖNORM B 8110-3* (ASI 2012) two main parameters of a critical room have to be calculated. The effective thermal mass and the ventilation rate, both in relation to the so called *immission area* A_I. This notional area takes also parameters regarding solar radiation transmission into account. The two main parameters are then used for the decision whether or not the room has overheating potential.

Table 2: Minimum thermal mass due to hourly airflow

Hourly airflow $V_{L,s}$ $[m^3 \cdot h^{-1} \cdot m^{-2}]$ based on immission area	**Thermal mass** $m_{w,I,min}$ $[kg \cdot m^{-2}]$ based on immission area
≥ 100	≥ 2000
75	≥ 4000
50	≥ 8000

The calculated *total effective thermal mass based on the immission area* $m_{w,I}$ has to be higher than the minimum value $m_{w,I,min}$ at a certain *airflow based on immission area* $V_{L,s}$ (*Table 2*). In the following the main parameters of the simple method, thermal mass, immission area and ventilation rate are described.

Other parameters such as internal gains or outside conditions are not required for this method.

Immission Area

To consider solar radiation transmission into the room in a simplified way the *immission area* A_I (*1*) was introduced in the standard. It represents the actual window area A_{AL} $[m^2]$ reduced by the glazing ratio f_G, the g-value, the F_c-value, the shading factor for obstructions F_{Sc} and the orientation factor Z_{ON}.

$$A_I = A_{AL} \cdot f_G \cdot g \cdot F_c \cdot F_{Sc} \cdot Z_{ON} \qquad (1)$$

Thermal Mass

The prescribed calculation method of the effective thermal mass of construction components such as walls, roofs and ceilings is stated in *ÖNORM B 8110-3*, but specified in the Austrian standard *ÖNORM EN ISO 13786*. This method is based on the layers of each construction component and their dimension and thermal properties.

$$X = \frac{T}{2\pi} \cdot \left(\left| \frac{Z_{11} - 1}{Z_{12}} \right| \right) \quad (2)$$

$$m_{w,B,A} = \frac{X}{c_0} \quad (3)$$

$$m_{w,B} = m_{w,B,A} \cdot A \quad (4)$$

The layer matrix elements Z_{11} and Z_{12}, of the so-called thermal matrix of one construction component, derive from the *periodic penetration depths* ξ. ξ depends on the layer thickness, the *periodic time T* and the following thermal properties of the layer: conductivity, density and specific heat capacity. With a *periodic time* of one day (86400 seconds) the *effective heat storage capacity* X $[J \cdot K^{-1} \cdot m^{-2}]$ of the component is calculated *(2)*.

By division with a *reference heat capacity* $c_0 = 1046{,}7\, J \cdot kg^{-1} \cdot K^{-1}$ *(3)* and multiplication with the component area *A (4)* the *effective thermal mass* $m_{w,B}$ $[kg]$ of the component is derived.

The thermal mass of the furniture and textiles $m_{w,E}$ $[kg]$ is calculated with the following equation, which is based on the floor area of the examined critical room *(5)*.

$$m_{w,E} = 38\, kg \cdot m^{-2} \quad (5)$$

To derive the total *effective thermal mass* m_w in kg of the room, the thermal mass of all construction components and the furniture are summed up *(6)*.

$$m_w = \sum m_{w,B} + m_{w,E} \quad (6)$$

This value has to be based on the *immission area* A_I to use it for the final decision process about summer overheating according to *Table 2*.

Ventilation Rate

The *airflow based on immission area* $V_{L,s}$ $[m^3 \cdot h^{-1} \cdot m^{-2}]$ *(7)* is calculated with the volume V $[m^3]$ of the room and the air-change rate n_L $[h^{-1}]$ according to *Table 3*.

$$V_{L,s} = n_L \cdot \frac{V}{A_I} \tag{7}$$

Table 3: Theoretical air-change rate for simple normative method

Number of façade or roof areas with openings	n_L $[h^{-1}]$
One façade or roof area	1.50
Two façade or roof areas	2.50
Three or more façade or roof areas	3.00

In the standard it is stated that these numbers for the air-change rate have no realistic physical background and are only useful for the simple normative method.

2.4.2 Detailed Normative Method

The detailed normative method is the second Austrian standard method for summer overheating assessment. It describes the calculation of the hourly profile of the operative temperature for one critical room at one summer day. The main boundary conditions and the normative input parameters are defined within the standard *ÖNORM B 8110-3* (ASI 2012) and will be presented in the following. The exact calculation procedure is not defined. It is only stated that the used calculation tool has to fulfill the requirements of the standard *ÖNORM EN ISO 13791* (ASI 2010b), which also allows different interpretations. There are different tools available and many of them are based on a prototype spreadsheet tool, which was developed together with the standard. An overview of the calculation procedure of this tool is presented in *Appendix B: Pseudocode Detailed Method*.

Outside Boundary Conditions

In contrast to the simple normative method, ambient temperature and solar radiation are considered as input parameters for the calculation of the operative room temperatures. The standard mean ambient temperature $T_{NAT\text{-}13}$ is designated for the detailed method and defined within *ÖNORM B 8110-5* (ASI 2010a). This is the temperature that is exceeded only 13 times per year statistically.

With the help of a spreadsheet tool *NAT-T13.xls* (Pöhn 2009), it can be calculated for a specific Austrian location with a certain elevation. With this single mean temperature an hourly temperature profile for one summer day, nominally the 15th of July, has to be created. This happens with standard deviation values which are defined in *Appendix A* of *ÖNORM B 8110-3* (ASI 2012). That leads to an hourly sine-shaped profile which can be used as input for the calculations.

The standard solar radiation determination for the 15th of July based on a default Austrian location is also defined in *Appendix A* of *ÖNORM B 8110-3* (ASI 2012). Global and diffuse solar radiation intensity for a certain elevation can be calculated. The radiation on certain building elements like windows can be calculated based on their orientation and tilt angle.

Solar Radiation Transmission

The calculation of the solar radiation transmission through transparent building elements depends on the following properties:

- actual measures, orientation and direction of all transparent elements for standard radiation calculation
- g-value and ε-value of the glazing
- transmittance, reflectance and position (exterior, integrated, interior) of the shading device
- effective angles of external shading elements such as buildings, or overhang and wingwall constructions

Thermal Mass

The thermal mass calculation of the construction components corresponds to the procedure of the simple normative method (see previous chapter). Generally, the measures and thermal properties of all components are considered.

For the thermal mass of the furniture, its total mass must be considered which is then multiplied by a default specific heat capacity.

Thermal Transmission and Thermal Absorption

The heat flow calculation between outside and inside is based on standard static *U-value* calculations. The measures of all exterior construction components and the conductivity of their layers are the main input parameters.

Thermal absorption is considered by the actual direction and orientation of all exterior surfaces together with default absorptance values.

Internal Gains and Ventilation

The consideration of internal gains from people and electric equipment is also a major difference compared to the simple normative method. Also, the ventilation in terms of hygienic air flow as well as night-time ventilation are part of the heat balance calculations for this method. Due to standardization, the internal gains and the hygienic air flow are determined as fixed input parameters. *Table 4* shows the standard values for residential use as they are defined within *ÖNORM B 8110-3* (ASI 2012).

Table 4: Standard values for internal gains and ventilation - detailed normative method

Daytime	**Equipment**	**People**	
	specific heat	specific heat	specific hygienic air flow
h	$W \cdot m^{-2}$	$W \cdot m^{-2}$	$m^3 \cdot m^{-2} \cdot h^{-1}$
00:00 - 01:00	1.76	3.76	1.411
01:00 - 02:00	1.67	3.76	1.411
02:00 - 03:00	1.80	3.76	1.411
03:00 - 04:00	1.80	3.76	1.411
04:00 - 05:00	2.61	3.76	1.411
05:00 - 06:00	5.76	3.76	1.411
06:00 - 07:00	5.09	3.76	1.411
07:00 - 08:00	8.06	0.94	1.411
08:00 - 09:00	6.84	0.94	0.353
09:00 - 10:00	6.30	0.94	0.353
10:00 - 11:00	5.67	0.94	0.353
11:00 - 12:00	4.10	0.94	0.353
12:00 - 13:00	3.47	0.94	0.353
13:00 - 14:00	3.33	2.82	0.353
14:00 - 15:00	5.36	2.82	1.058
15:00 - 16:00	6.00	2.82	1.058
16:00 - 17:00	7.70	2.82	1.058
17:00 - 18:00	6.71	3.76	1.058
18:00 - 19:00	6.26	3.76	1.411
19:00 - 20:00	5.36	3.76	1.411
20:00 - 21:00	4.32	3.76	1.411
21:00 - 22:00	3.11	3.76	1.411
22:00 - 23:00	2.70	3.76	1.411
23:00 - 24:00	1.98	3.76	1.411

For night-ventilation (22:00-08:00) through windows, the standard specifies the following air flow calculation *(8)*.

$$\dot{V} = 0.7 \cdot C_{ref} \cdot A \cdot \sqrt{H} \cdot \sqrt{\Delta T} \qquad (8)$$

$\dot{V}$ Air flow through the opening $[m^3 \cdot h^{-1}]$

C_{ref} Exchange coefficient; $C_{ref} = 100 \ m^{0.5} \cdot h^{-1} \cdot K^{-0.5}$

A Area of ventilation opening according to *Figure 4* $[m^2]$

H Height of ventilation opening according to *Figure 4* $[m^2]$

ΔT Temperature difference between outdoor and indoor air $[K]$

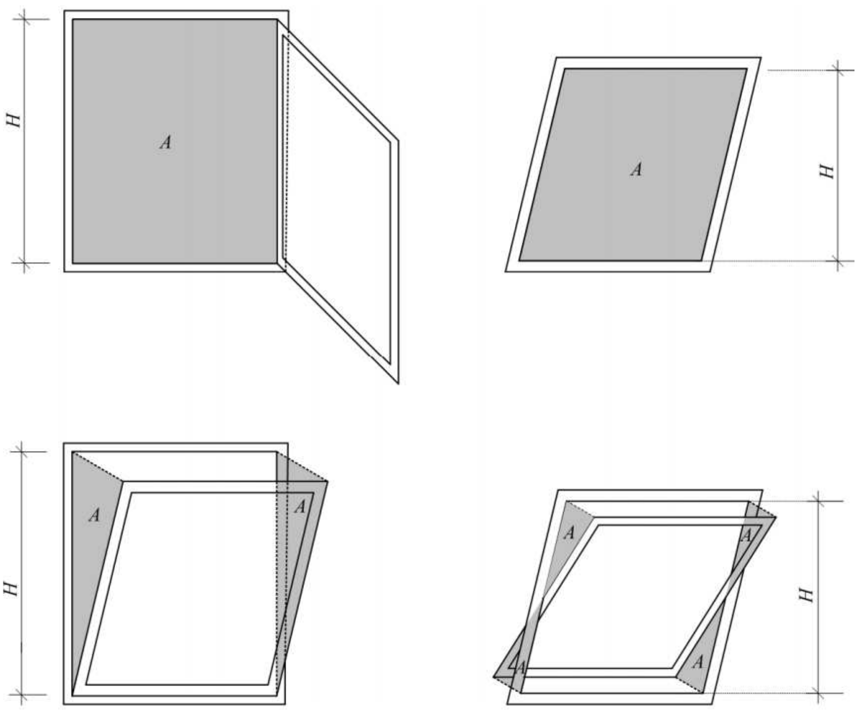


Figure 4: Definition ventilation opening - detailed method (ASI 2012)

2.4.3 Dynamic Simulation

Dynamic or transient simulations are time-dependent calculations of physical processes. For detailed determination about the dynamic thermal behavior of rooms, transient thermal building simulation tools are needed. One advantage is the possibility to model and simulate not only one room but also a set of rooms or even whole buildings. Another main difference compared to static calculations is that all boundary conditions and all influencing parameters are considered dynamically over a certain time period. This is the basis for realistic evaluations and effective optimization of planned buildings. There are various software tools available and they differentiate regarding structure, calculation algorithms and user interface, but the basic principles are similar. In the following, basic information of the tool *EnergyPlus* (DOE 2018) will be presented as an example.

EnergyPlus is an internationally used simulation program, developed for design engineers or architects that wish to size appropriate HVAC equipment, develop retrofit studies for life cycle cost analyses or optimize energy performance. The following list of some of the program's main characteristics gives a good overview of general specifications of dynamic simulation tools (DOE 2016b):

- **Integrated, simultaneous solution** where the building response and the primary and secondary systems are tightly coupled (iteration performed when necessary)
- **Sub-hourly, user-definable time steps** for the interaction between the thermal zones and the environment; variable time steps for interactions between the thermal zones and the HVAC systems (automatically varied to ensure solution stability)
- **ASCII text based weather, input, and output files** that include hourly or sub-hourly environmental conditions, and standard and user definable reports, respectively
- **Heat balance based solution** technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at both in the interior and exterior surfaceduring each time step
- **Transient heat conduction** through building elements such as walls, roofs, floors, etc. using conduction transfer functions
- **Thermal comfort models** based on activity, indoor dry bulb temperature, humidity, etc.
- **Anisotropic sky model** for improved calculation of diffuse solar radiation on tilted surfaces
- **Advanced fenestration calculations** including controllable window blinds, electrochromic glazings, layer-by-layer heat balances that allow proper assignment of solar energy absorbed by theb window panes, and a performance library for numerous commercially available windows

The general program structure of *EnergyPlus* contains two central parts, the *Heat and Mass Balance Simulation* and the *Building Systems Simulation*. They are linked to each other as well as to different separated calculation modules and they process all inputs to produce the resulting outputs. The inputs for the building description and the outputs can additionally be processed by external programs and interfaces.

Detailed information about internal processes, calculation algorithms, input parameters and output variables can be found in the *Engineering Reference* (DOE 2016a) and the *Input Output Reference* (DOE 2016c) documentations. In the following, information about calculation details and input parameters that are relevant for this work is presented.

Outside Boundary Conditions - Weather Data

Proper information about the environmental conditions is crucial. Not only because they are a main influencing parameter, but because without hourly or sub hourly weather data in the right format, dynamic simulations cannot be started. Different tools normally require differently formatted data. *EnergyPlus* mainly uses the **.epw* format, which contains hourly data for the following meteorological parameters:

- Dry bulb air temperature
- Dew point temperature
- Relative humidity
- Direct and diffuse solar radiation, horizontal infrared radiation
- Atmospheric pressure, wind speed and direction
- Presence of rain and snow

Generally, there are various sources for weather data. For *EnergyPlus* there exists an open source database that contains free data for 227 international locations. This data set was the result of a research project. The files are derived from up to 18 years (1982 - 1999 for most stations) of hourly weather data archived at the *U.S. National Climatic Data Center*. The weather data are supplemented by solar radiation, estimated on an hourly basis from earth-sun geometry and hourly weather elements, particularly cloud amount information. (ASHRAE 2001)

Though these free weather data sets are easy to obtain and perfectly validated they are in fact outdated. Other reliable sources often have restricted access. *Meteonorm* (Meteotest 2019) is one of Europe's common sources which provides up-to-date weather data for many international locations and for the different common simulation tools.

Solar Radiation Transmission

There are two different possibilities for modeling windows in *EnergyPlus.* Firstly, by defining layer by layer. For that, the thickness and all thermal and spectral properties of the glass layers are needed. Additionally, the thickness and type of the gas layers have to be defined. Generally, data sets with material and construction libraries are provided. Alternatively, there is a simplified glazing system module that only needs the *U-value* and the *g-value* (*solar heat gain coefficient*) as input. This simplifies the data input but can lead to uncertainties in the calculations, in particular for detailed window variant evaluations.

For shading devices, a shading material type has to be defined. It contains measures, conductivity, solar transmittance/reflectance and visible transmittance/reflectance. This material type can be integrated in the window construction or just defined by position (interior, exterior or between glass). Additionally, a shading control type is required. This parameter defines when the shading device is active. It can be scheduled individually or pre-defined with one of the following default settings (selection):

- *OnIfHighSolarOnWindow*: Shading is on if beam plus diffuse solar radiation incident on the window exceeds the set point (W/m^2) and a schedule, if specified, allows shading.
- *OnIfHighHorizontalSolar*: Shading is on if total (beam plus diffuse) horizontal solar irradiance exceeds the set point (W/m^2) and a schedule, if specified, allows shading.
- *OnIfHighZoneAirTemperature*: Shading is on if zone air temperature in the previous time step exceeds the set point (°C) and a schedule, if specified, allows shading.

Heat and Mass Balance Simulation

For most dynamic simulation programs, the parameters *thermal mass*, *thermal transmission* and *thermal absorption* are part of the central simulation engine. In *EnergyPlus* this system is called *heat and mass balance simulation* and it calculates the physical processes in and around the construction components of the building. Examples for the influencing processes and parameters are (from outside to inside):

- Short wave radiation including direct, reflected and diffuse sunlight
- Longwave radiation from the environment
- Convective exchange with outside air
- Conduction into wall
- Convective heat exchange with zone air
- Longwave radiation from internal sources
- Longwave radiation exchange with other surfaces in zone
- Shortwave radiation from solar and internal sources

The main difference to static or simplified calculation tools is that here the boundary conditions are not static but change dynamically with every time step. Thusly, the heat and mass balance have to be calculated for every time step of the whole simulation period. Different methods were developed for the different software applications. *EnergyPlus* uses now a combination of two common approaches, the *conduction transfer function* method and the *finite difference solution*. Additionally, there is a *heat and moisture transfer solution algorithm* based on a finite element model that simulates the movement and storage of heat and moisture in surfaces. Further details of all calculation models can be found in the *Engineering Reference* (DOE 2016a) of the *EnergyPlus* documentation.

For the user of *EnergyPlus* there is not much difference compared to other tools, because the input parameters regarding construction components are always similar. All construction elements such as walls, floors and ceilings have to be modeled by defining the material of every layer in the correct order. The material definition contains the following parameters:

- **Thickness**
- **Conductivity**
- **Density**
- **Specific heat**
- Roughness
- Thermal absorptance, solar absorptance, visible absorptance

The first four parameters are mandatory and can be specified freely. Generally, there are data sets with example materials and predefined properties available. The *roughness* can range from *very rough* to *very smooth*. For the absorptance parameters normally default values are used. For thermal absorptance the default value is 0.9, for solar absorptance 0.7 and for visible absorptance also 0.7.

Ventilation

Ventilation is the purposeful flow of air from the outdoor environment directly into a thermal zone in order to provide some amount of fresh air or non-mechanical cooling. *EnergyPlus* provides two standard models for ventilation. The *Ventilation Design Flow Rate* and the *Ventilation by Wind and Stack with Open Area*. The first model is normally used to specify a certain air flow coupled with a schedule to simulate a hygienic air change if people are present in a room. The second model can additionally be used to simulate night-ventilation through open windows based on temperature difference and wind. This total ventilation rate *(9)* calculated by this model is the quadrature sum of the wind *(10)* and stack *(11)* air flow components.

$$\dot{V}_{WindAndStack} = \sqrt{\dot{V}_W^2 + \dot{V}_S{}^2} \qquad (9)$$

$$\dot{V}_w = C_w \cdot A \cdot F_{schedule} \cdot v_w \qquad (10)$$

$$\dot{V}_s = C_D \cdot A \cdot F_{schedule} \cdot \sqrt{2 \cdot g \cdot \Delta H_{NPL} \cdot \frac{|T_{zone} - T_a|}{T_{zone}}} \qquad (11)$$

$\dot{V}_w$	Air flow driven by wind $[m^3 \cdot s^{-1}]$
C_w	Opening effectiveness [-]
A	Area of ventilation opening $[m^2]$
$F_{schedule}$	Open area fraction (user-defined schedule value) [-]
v_w	Local wind speed $[m \cdot s^{-1}]$
$\dot{V}_s$	Air flow due to stack effect $[m^3 \cdot s^{-1}]$
C_D	Discharge coefficient for opening [-]
ΔH_{NPL}	Height from midpoint of lower opening to the neutral pressure level [m]
T_{zone}	Zone air dry-bulb temperature [K]
T_a	Local outdoor air dry-bulb temperature [K]

Some of the parameters in the equations *(10)* and *(11)* are variable inputs and others are automatically calculated by *EnergyPlus*. The wind speed (v_w) and the temperatures (T_{zone}, T_a) come from the weather data and internal calculations. The area of the opening (A), the schedule for its opening fraction ($F_{schedule}$) and the effective height difference (ΔH_{NPL}) have to be defined by the user. The opening effectiveness (C_w) and the discharge coefficient (C_D) can be user defined or automatically calculated based on wind direction respectively temperature difference. Further details can be found in the *Engineering Reference* (DOE 2016a) of the *EnergyPlus* documentation.

Internal Gains

The heat generated by people, lights and other internal zone equipment can affect the thermal room conditions considerably. Hence, they are normally part of the direct user defined inputs for dynamic simulations. In *EnergyPlus* the gains of occupants can be defined in different ways. Either by the absolute number of *people per thermal zone* or by *people per zone floor area* or by *zone floor area per person*. Together with a schedule for the fraction of occupancy the total number of people for different periods is defined. Also, an activity level schedule with the heat gain in Watts for the different time periods must be defined. The multiplication of the total occupant’s number and their activity results in the people’s heat gain for every time step. For lights and other equipment, a design level of

Watts or *Watts per floor area* or *Watts per person* together with a schedule are needed as input parameters.

2.4.4 Comparison

Table 5: Overview and comparison of input parameters

		Simple normative method	**Detailed norm. method**	**Dynamic simulation**
Outside conditions	Location		Location, elevation	Location, elevation
	Climate data			*.epw weather file
Thermal mass	Construction components	Layers: thickness, density, conductivity, specific heat	Layers: thickness, density, conductivity, specific heat	Layers (homogeneous): density, conductivity, specific heat
	Furniture	Default spec. mass (38 kg/m² floor area)	Mass (>0 kg/m² floor area)	Construction, surface area
Thermal trans-mission	Construction components		Convection coefficients Layers: thickness, conductivity	Layers (homogeneous): density, conductivity, specific heat, roughness
	Windows		U-value glazing U-value frame Conductance edge	Glass and gas material properties Frame material properties
Thermal absorption	Construction surfaces		Orientation and tilt angles	Geometry and orientation
				Absorptance
Solar radiation trans-mission	Glazing	Orientation and tilt factor Z_{ON}	Orientation and tilt angles	Geometry and orientation
	Glazing	g-value	g-value, U-value	Glass and gas material properties
	Shading device	F_c-value	Transmittance $\tau_{e,B}$, reflectance $\rho_{e,B}$	Material properties Shading schedule
	Shading elements	Shading factor for obstructions F_{Sc}	Shading factor for obstructions F_{Sc}	Geometry of obstructions
Ventilation	Hygienic air change rate		Standard hourly airflow	Design flow rate parameters
	Night-time ventilation	Fictive air change rate (facades with openings)	Measures and properties of openings	Measures, properties, schedule of openings
Internal gains	People		Standard utilization type	Occupancy and activity schedules
	Equipment, lighting		Standard utilization type	Thermal power and schedule

These listings compare the necessary inputs (*Table 5*) and the resulting outputs *(Table 6*) of the three examined overheating evaluation methods.

The input overview (*Table 5*) particularly shows the quantitative difference of the simple method compared to the others. Also, the complexity of the required data is very low and therefore no special expertise is needed to use the simple method. It can be performed by basic spreadsheet calculations. The detailed method indeed requires more detailed inputs, but it is also rather convenient to use. It is mostly implemented into programs for energy certificate calculation which are very similar because they are all based on the Austrian standard *ÖNORM B 8110-3* (ASI 2012) respectively on a prototype spreadsheet called "*Prototyp für Bauphysiksoftware Österreich*" (Riccabona and Bednar 2013). A closer look on the table reveals also differences between the detailed method and the simulation method. The simulation, for example requires detailed weather data, more detailed material properties and schedules instead of standard types. Generally, the high complexity of thermal building simulation software originates from its diverse applicability. Besides overheating evaluation and many other applications, it can be used for calculations of the buildings different energy demands or simulation and sizing of heating, cooling and ventilation systems. Therefore, there are a lot of other input possibilities and this also explains the huge spectrum of possible output parameters (see *Appendix C: Outputs EnergyPlus*, for further examples):

Table 6: Overview and comparison of output parameters and available software

Method	Output parameter	Software
Simple normative method	▪ Effective thermal mass based on immission area	▪ Simple spreadsheet ▪ ArchiPHYSIK ▪ GEQ ▪ ECOTECH ▪ …
Detailed normative method	▪ Operative temperature profile for one day (15th of July)	▪ Complex spreadsheet ▪ ArchiPHYSIK ▪ GEQ ▪ ECOTECH ▪ …
Dynamic simulation (selection)	▪ Operative temperatur ▪ Air temperature ▪ Surface temperatures ▪ Humidity ▪ Air flow ▪ Irradiation ▪ Shading factors ▪ Heating/cooling power/energy ▪ …	▪ EnergyPlus ▪ TRNSYS ▪ Tas ▪ Geba ▪ …

3 METHODOLOGY

The second main part of this work deals with the practical application of the three overheating evaluation methods. Therefore, firstly a case study with four specific design variants is performed to analyze and compare the results of the different evaluation methods. The designs represent critical rooms of roof top extension projects. Then a parametric study with a large set of parametric design variants is used to further analyze possible method outputs and the effect of different climate data inputs.

This chapter firstly describes the procedures of the mentioned studies. Subsequently, the details of the used tools, the required input data and the detailed specifications of the case study and the parametric study will be described.

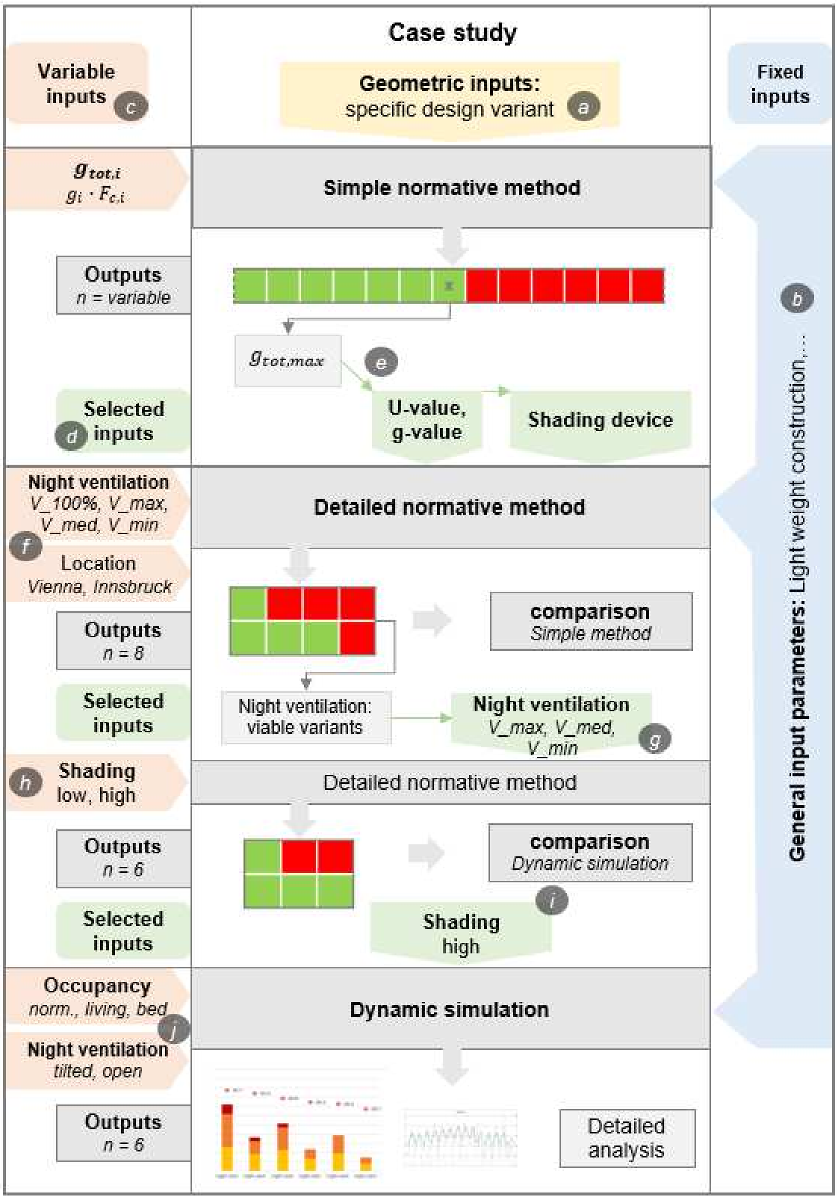


Figure 5: Methodology chart - case study (own figure)

Figure 5 shows the detailed procedure of the **case study**. All required inputs for the three evaluation methods as well as the calculated outputs are displayed. There are the *geometric inputs* (*a*) that represent specific data of each case study room. Mainly, these are the measures and the positions of the construction components and windows. The *fixed inputs* (b) are consistent for all case study rooms and for all three methods. Primarily these are the construction components and their material properties. The *variable inputs* (c) are used for sensitivity analyses for each method and the s*elected inputs* (d) are depending on their outputs and are then used for the following methods.

For the **simple normative method** only the *total g-Value* (g_{tot}) is variable. By variation of the *g-value* (glazing) and the F_c*-value* (shading), the maximum allowed value of this input is determined. Up to this maximum value the simple normative evaluation declares the room as save from overheating. For the comparison with the detailed normative method, this maximum total *g-Value* ($g_{tot,max}$) is the basis for the *selected input*s (*e*).

The **detailed normative method** requires also more detailed input data. For example the *U-value* and *g-value* of the glazing as well as the *transmittance* ($\tau_{e,B}$) and *reflectance* ($\rho_{e,B}$) of the shading device. These values are selected for each case study room based on the results of the simple method. Additionally, the inputs for night-time ventilation and location are needed (*f*). For a theoretical sensitivity analysis these inputs are varied, resulting in a set of eight outputs for each case study room. The variation of the night-ventilation includes the theoretical variant *V_100%,* which means all glazed areas are opened during night. If fixed glazing areas are present this variant would not be valid, but for the theoretical comparison with the simple method the *V_100%* variant is used anyways. For another sensitivity analysis firstly, shading properties are varied (*h*) and secondly only reasonable ventilation variants are selected (*g*). This means in case of fixed glazing elements, only the variants *V_max*, *V_med* and *V_min* are used. *V_max* means all openable windows are opened during the night and *V_min* includes only tilted windows. Further details about the input parameters follow in the next chapters. For the comparison with the simulation results only one shading type is selected (*i*).

For the sensitivity analysis of the **dynamic simulation**, the occupancy and the night-time ventilation variants are varied (*j*). Additional detailed analyses are carried out.

The procedure of the **parametric study** is shown in *Figure 6.* First, a set of 48 design variants is created by variation of: the number of windows, the main window orientation, the shading device properties and the *g-value* of the glazing. Then the detailed normative method is performed with normative occupancy and four nigh-ventilation variants, resulting in two sets of 92 outputs each. For the simulation method similar night-ventilation variants are used but in contrary to the detailed method also the occupancy is variated. Additionally, two different sets of climate data are applied to analyze the effect of climate warming. Altogether this leads to 384 simulation variants that can be compared.

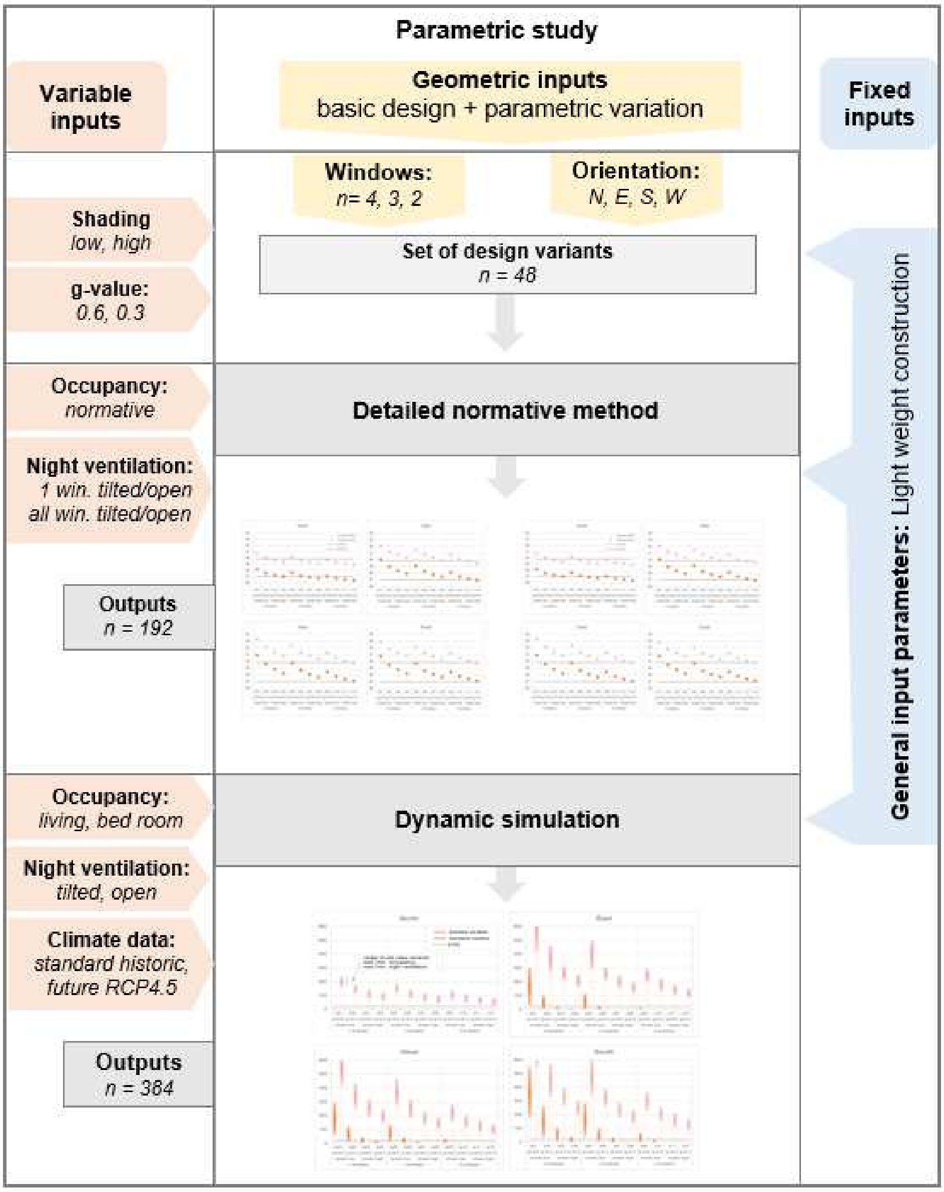


Figure 6: Methodology chart - parametric study (own figure)

3.1 Methods and Tools

This chapter describes the tools and procedures used within the three methods (simple normative, detailed normative and dynamic simulation) to create the desired outputs and results. The detailed theoretical background and the normative basic information of the methods are shown in chapter *2.4 Summer Overheating Evaluation Methods*. All required input parameters are specified and described in the next section *3.2 Input Parameters*.

3.1.1 Simple Normative Method

In principle both normative methods are implemented in several building physics tools that are mainly used for energy certification in Austria. Within this work the detailed method is mainly conducted with *ArchiPHYSIK (A-NULL 2019)*, which is one of the most common applications in this field. The calculations for the simple method are executed within *a* spreadsheet, because of the higher flexibility for variations. Only for the determination of the effective thermal masses of the construction components *ArchiPHYSIK* was used. This is done by building up each component layer by layer with the help of the integrated material libraries. The sum of all thermal masses, including the furniture, results into the desired *total effective thermal mass*. For the simple evaluation this value has to be based on the so called *immission area* and the resulting value ($m_{w,I}$) is compared to the minimal value ($m_{w,I,min}$).

The *immission area* depends on the following input parameters: glazed area, *orientation factor*, *shading factor of obstructions* and the *total g-value* (g_{tot}) of glazing and shading devices. The first three parameters mainly depend on the architectural geometry, so they are fixed as geometric inputs depending on the case study designs. According to real planning projects the *total g-value* (g_{tot}) is defined as questionable, hence variable input. *Table 7* shows typical values of g_{tot} which is depending on the *U-value* and *g-value* of the glazing and on the *transmittance* ($\tau_{e,B}$) and *reflectance* ($\rho_{e,B}$) of the shading device.

Table 7: Total g-values for simple normative method

U-value [W/(m²K)]		0.5	0.7	1	0.5	0.7	1	0.5	0.7	1
g-value [-]		0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5
$\tau_{e,B}$ [-]	$\rho_{e,B}$ [-]	g_{tot} [-]								
0.05	0.70	0.029	0.034	0.040	0.033	0.038	0.044	0.038	0.042	0.048
0.05	0.50	0.038	0.045	0.055	0.042	0.050	0.059	0.047	0.054	0.063
0.05	0.40	0.042	0.051	0.063	0.047	0.055	0.067	0.051	0.060	0.071
0.05	0.30	0.046	0.057	0.070	0.051	0.061	0.075	0.055	0.065	0.079
0.05	0.10	0.055	0.068	0.086	0.060	0.073	0.090	0.064	0.077	0.094
0.10	0.65	0.047	0.053	0.060	0.056	0.061	0.068	0.065	0.070	0.077
0.10	0.36	0.060	0.069	0.082	0.069	0.078	0.091	0.078	0.087	0.099
0.10	0.35	0.060	0.070	0.083	0.069	0.079	0.092	0.078	0.088	0.100
0.10	0.29	0.063	0.073	0.088	0.072	0.082	0.096	0.081	0.091	0.105
0.10	0.10	0.071	0.084	0.102	0.080	0.093	0.111	0.089	0.102	0.119
0.12	0.40	0.064	0.073	0.086	0.075	0.084	0.096	0.086	0.095	0.106
0.12	0.28	0.069	0.080	0.095	0.080	0.091	0.105	0.091	0.102	0.115
0.12	0.26	0.070	0.082	0.097	0.081	0.092	0.107	0.092	0.103	0.117
0.12	0.23	0.072	0.084	0.099	0.083	0.094	0.109	0.094	0.105	0.120
0.12	0.10	0.077	0.091	0.109	0.088	0.101	0.119	0.099	0.112	0.129
0.15	0.60	0.065	0.072	0.080	0.079	0.085	0.093	0.092	0.098	0.106
0.15	0.40	0.074	0.083	0.096	0.087	0.096	0.108	0.101	0.110	0.121
0.15	0.30	0.078	0.089	0.103	0.092	0.102	0.116	0.105	0.115	0.129
0.15	0.20	0.082	0.095	0.111	0.096	0.108	0.124	0.110	0.121	0.137
0.15	0.10	0.087	0.101	0.119	0.100	0.114	0.132	0.114	0.127	0.144

With a set of variations of g_{tot} (0.030 - 0.130) the overheating evaluation for every variation was executed. This leads to an inversely proportional relation between g_{tot} and the *total effective thermal mass based on immission area* ($m_{w,I}$). *Figure 7* also shows that the intersection with the minimum $m_{w,I}$*-value* according to the standard indicates the maximum *total g-value* for an acceptable overheating evaluation.

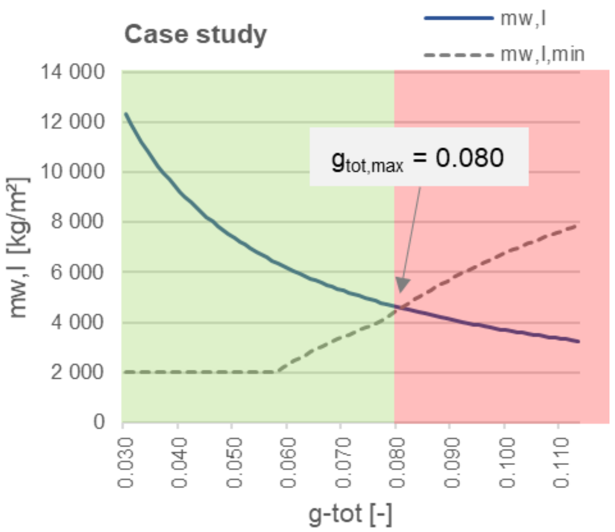


Figure 7: Methodology simple method (own figure)

For comparison with the detailed normative method, *Table 7* is used to select the required inputs based on $g_{tot,max}$.

3.1.2 Detailed Normative Method

After conducting the simple overheating evaluation with the thermal mass determination in *ArchiPHYSIK* and the calculations in *the* spreadsheet, the detailed normative method is performed within *ArchiPHYSIK*. Therefore, the already implemented construction components are used to build up the critical case study rooms according to their architectural design. For every component, the area, the orientation and the tilt angle have to be defined as geometric inputs. For windows also the *U-value* and the *g-value* of the glazing as well as the *transmittance* and *reflectance* have to be selected. This happens according to the outputs of the simple method.

Additionally, the measures of possible ventilation openings for night-time ventilation can be defined. As this is on the one hand a sensitive parameter regarding overheating evaluation and on the other hand difficult to define in most projects, it is set as variable input. For comparison with the simple normative method, one of the ventilation variants (*V_100%*) must define all glazed areas of the examined room as openable during the night. Another three opening variants that should address realistic night-ventilation modes are defined for a sensitivity analysis: The maximum variant *V_max* defines all openable windows as fully opened during night. The minimum variant *V_min* defines one or two windows as tilted and the medium variant *V_med* defines one or two windows as fully opened during the night, depending on the specific room design.

As opposed to the simple method also the specific location and utilization has to be defined. For the internal gains through occupancy and equipment the standard profiles are already implemented and can be used directly.

To show the impact of the location, two Austrian cities with different climate conditions are chosen. This leads to eight resulting outputs per case study room. They can be compared among each other and partly to the simple method.

Then the three viable ventilation variants and the more critical location are used for another evaluation with variation of the shading device properties. This results in another six outputs per room which will also be used for comparison with the dynamic simulation method. Generally, the main output parameter of the detailed normative method is the maximum operative temperature of each examined room. This parameter is also mainly used for the analyses and comparisons but also the daily profile of the operative temperature and the airflow will be used for further detailed analyses.

For the parametric study *ArchiPHYSIK* cannot be used because there is no possibility for automated parameter changes or output processing. Thus, the original prototype spreadsheet tool has to be used. It was provided as attachment of a textbook about building construction (Riccabona and Bednar 2013). The advantage of this spreadsheet tool is the possibility of creating different variants and linking specific inputs. Then, via *Visual Basic for Application* (VBA) within *Microsoft© Excel©* the calculation and the output consolidation can be automated.

Four night-time ventilation variants are used: *one window open*, *one window tilted, all windows open, all windows tilted.* Applied to the 48 parametric design variants, 192 output variants are derived and then compared to the simulation results.

The main output, the maximum operative temperature is the only evaluated parameter for comparison with the simulations.

3.1.3 Dynamic Simulation

The method of dynamic thermal building simulation requires a separate specialized tool. For this work *EnergyPlus* (DOE 2018) is used, which is a sophisticated and well-established application in the field of simulation-based building planning. The detailed required inputs and the desired outputs are generally defined using the text based specialized editor. The building geometry can also be defined graphically via *SketchUp*© plugin. Due to the comparison with the normative methods, also the simulation model will only contain one room. For the modeling of the construction components the different layers and their measures and properties have to be defined. Only homogeneous components can be built. For the detailed simulation of a whole year or a certain period also detailed information about climate, internal gains, ventilation and the schedules are required, which is the main difference compared to static or periodic calculations.

For the overheating assessment the simulation period is limited to the Austrian warmth period: 1st of May - 30th of September.

Because of the uncertainty of those detailed inputs they are not fixed for the evaluations within this work. They are defined as variable inputs, to examine sensitivity and detailed analyses. For the case study and the comparison to the detailed normative method, the occupancy (living room, bedroom) and the night-ventilation modes (low, high) are varied.

For the parametric study, additionally two different sets of weather data are used (standard historical and future RCP4.5). The parametric variation of all variable input parameters can be performed within *EnergyPlus*. With the integrated *parametric module,* up to 100 parametric runs can be defined. Then multiple parameters with variable values for every run can be set.

Totally there were 384 runs simulated. Every run created as output the operative room temperature for the whole summer period. The outputs were again automatically consolidated via *VBA* and then evaluated with diagrams.

The chosen evaluation method was based on the *adaptive comfort theory* (CEN 2007) and its interpretation of the *Chartered Institution of Building Services Engineers* (CIBSE 2013).

$$T_{max,adapt.comf} = 0.33 \cdot T_{rm} + 21.8 \qquad (12)$$

T_{rm} *Running (daily) mean of the outdoor temperature [°C]*

According to *(12)* (CIBSE 2013) $T_{max,adapt.comf}$ was set as adaptive threshold temperature. The evaluation criterion was based on the Suisse standards (SIA 2014), where overheating is present if any temperature value exceeds the threshold. This was extended based on CIBSE TM 52 (CIBSE 2013). Thus, up to a maximum of 0.5% of hours were the operative temperature exceeds the threshold the room is declared as low overheating risk. Above 0.5% and up to 3% the room shows high overheating risk and above 3% it is declared as severe overheating.

3.2 Input Parameters

Table 8: Input parameter definition

		Simple normative method	Detailed norm. method	Dynamic simulation
Outside conditions	**Location**		Location, elevation	Location, elevation
	Climate data			*.epw file
Thermal mass	**Construction components**	Layers: thickness, density, conductivity, specific heat	Layers: thickness, density, conductivity, specific heat	Layers (homogeneous): density, conductivity, specific heat
	Furniture	Default spec. mass (38 kg/m² floor area)	Mass (>0 kg/m² floor area)	Construction, surface area
Thermal trans-mission	**Construction components**		Convection coefficients Layers: thickness, conductivity	Layers (homogeneous): density, conductivity, specific heat, roughness
	Windows		U-value glazing U-value frame Conductance edge	Glass and gas material properties Frame material properties
Thermal absorption	**Construction surfaces**		Orientation and tilt angles	Geometry and orientation
				Absorptance
Solar radiation trans-mission	**Glazing**	Orientation and tilt factor Z_{ON}	Orientation and tilt angles	Geometry and orientation
	Glazing	g-value	g-value, U-value	Glass and gas material properties
	Shading device	F_c-value	Transmittance $\tau_{e,B}$, reflectance $\rho_{e,B}$	Material properties, Shading schedule
	Shading elements	Shading factor for obstructions F_{Sc}	Shading factor for obstructions F_{Sc}	Geometry of obstructions
Ventilation	**Hygienic air change rate**		Standard hourly airflow	Design flow rate parameters
	Night time ventilation	Fictive air change rate (facades with openings)	Measures and properties of openings	Measures, properties, schedule of openings
Internal gains	**People**		Standard utilization type	Occupancy and activity schedules
	Equipment, lighting		Standard utilization type	Thermal power and schedule

(yellow)	Geometric inputs - case study dependent
(blue)	Fixed inputs - for all case study rooms
(orange)	Variable inputs - parametric variations

The overview in *Table 8* shows the main input parameters of the three methods divided into categories according to the methodology. Below, the most important input parameters are described in detail.

3.2.1 Locations and Climate Data

Austria is the region of interest for this study, because mainly the Austrian standard overheating evaluation methods should be investigated. The city center of Vienna is also interesting because of the high number of realized and possible roof top extension projects as well as the high overheating potential through the *Urban Heat Island* effect. As an alternative location for analysis of the detailed normative method, the city of Innsbruck was chosen. *Table 9* shows the comparison of the main standard parameters of the two locations. The heating and cooling degree days are calculated from standard historical climate data sets that are freely available for *EnergyPlus* (ASHRAE 2001).

Table 9: Standard climate parameters of Vienna and Innsbruck

	Vienna	Innsbruck
Coordinates	N 48.21° E 16.34°	N 47.26° E 11.39°
Elevation	212 m	572 m
Standard temperature T_{NAT} (OIB 2015)	-11.2°C	-10.8°C
Standard temperature T_{NAT-13} (OIB 2015)	24.2°C	21.2°C
Heating degree days $HDD_{20/12}$	3343 Kd	3537 Kd
Cooling degree days $CDD_{18.3}$	203 Kd	99 Kd

Figure 8 presents the standard daily temperature profiles of the locations, based on the s*tandard temperature T_{NAT-13}* and the normative deviation (ASI 2012). These profiles and the elevation are the inputs for the detailed normative method.

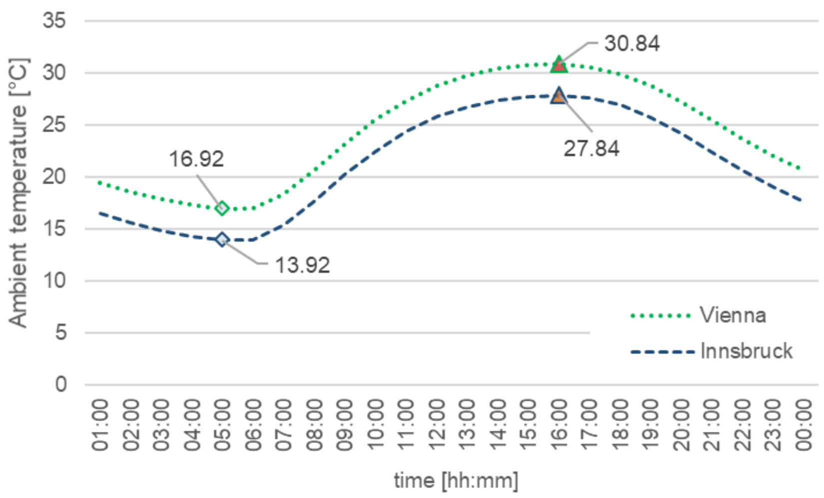


Figure 8: Standard temperature profile (NAT-13) - Vienna, Innsbruck (own figure)

For the dynamic simulation, two climate data sets for Vienna were used to compare their impact on the simulation results. Firstly, there is the standard *IWEC* data set (international weather data for energy calculations), which is freely available and contains aggregated data from the years 1982 - 1999 (ASHRAE 2001). The second set contains data according to future projections based on the *RCP4.5* scenario and was provided through *Meteonorm* (Meteotest 2019). Data are based on the project *climate-fit.city* (Lauwaet et al. 2017), which intends to combine the *RCP* scenarios with *Urban Heat Island* effects and implement it in climate data for building simulation tools.

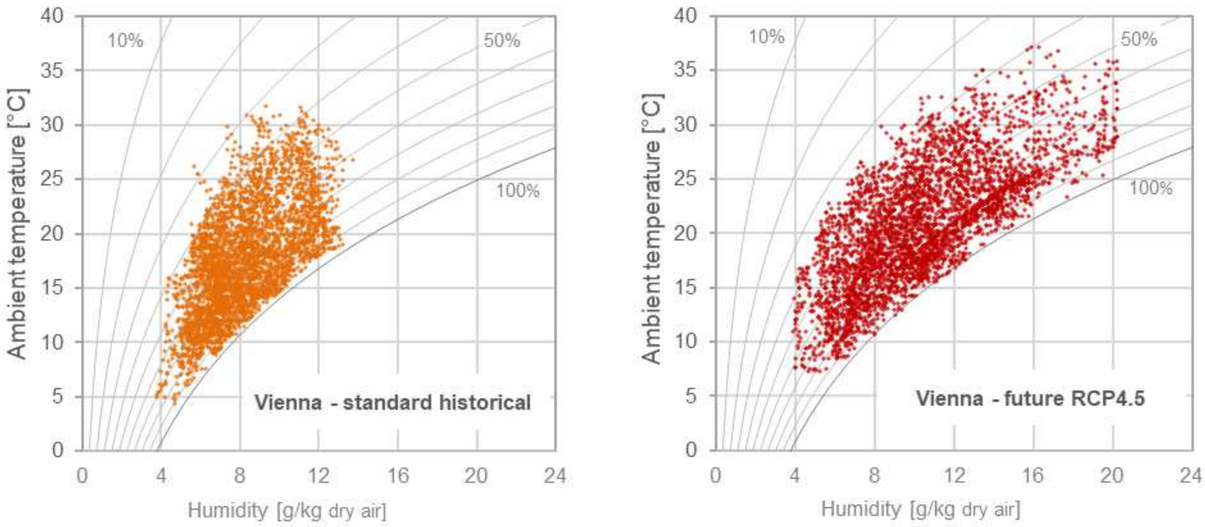


Figure 9: Mollier charts summer period - Vienna historical vs. Vienna future (own figure)

The comparison of the Mollier-charts within *Figure 9* shows the significant difference of the two data sets. All data pairs of ambient temperature and absolute humidity from the entire extended summer period (1st of May - 30th of September) are illustrated for both variants. The historic data show only a few values above 30°C or above 12 g/kg. For the future scenario, both a very hot and also a clearly more humid climate is projected. For the case study and the comparison with the detailed method the standard historic data are used. In the course of the parametric study the effects of both weather scenarios are analyzed.

3.2.2 Construction Components

In general, a light-weight construction method was assumed and fixed for all design variants of the studies. This is the most common construction type for roof top extension projects. *Table 10* presents the buildup of the major construction elements, with all layers as well as the detailed material properties.

Table 10: Construction elements

Exterior wall light			Thickness [m]	Density [kg/m³]	Heat capacity [J/(kg*K)]	Conductivity [W/(m*K)]
e	1	Wood	0.024	600	1610	0.15
	2	Mineral wool	0.050	33	1030	0.04
	3.0	Wood	0.200	700	1610	0.17
	3.1	Mineral wool	0.200	33	1030	0.04
	4	Vapor barrier	0.001	1100	1700	0.17
i	5	Gypsum plaster board	0.030	900	1050	0.21
		U-value [W/(m²*K)]	**0.176**			

Interior wall light			Thickness [m]	Density [kg/m³]	Heat capacity [J/(kg*K)]	Conductivity [W/(m*K)]
	1	Gypsum plaster board	0.125	900	1050	0.21
	2	Mineral wool	0.100	120	1030	0.04
	3	Gypsum plaster board	0.125	900	1050	0.21
		U-value [W/(m²*K)]	**0.317**			

Interior wall heavy			Thickness [m]	Density [kg/m³]	Heat capacity [J/(kg*K)]	Conductivity [W/(m*K)]
	1	Masonry	0.160	1700	900	0.70
	2	Air gap	0.200	1.2	1008	1.10
	3	Masonry	0.160	1700	900	0.70
		U-value [W/(m²*K)]	**1.114**			

Ceiling/Floor light			Thickness [m]	Density [kg/m³]	Heat apacity [J/(kg*K)]	Conductivity [W/(m*K)]
	1	Wood floor	0.015	700	1610	0.17
	2	Screed	0.060	2000	1080	1.40
	3	Step sound insulation	0.032	130	1030	0.04
	4	Filling	0.040	430	1000	0.12
	5	OSB	0.018	640	1700	0.13
	6.0	Steel/wood beam	0.200	40	1610	0.04
	6.1	Mineral wool	0.200	700	1030	0.17
	7	OSB	0.018	640	1700	0.13
	8	Air gap	0.030	1	1008	0.17
	9	Gypsum plaster board	0.030	900	1050	0.21
		U-value [W/(m²*K)]	**0.161**			

3.2.3 Windows and Shading

The case study room designs show different window types and sizes. For comparison, one general window specification is defined. According to the state of the art in building planning in Austria, a modern triple glazed window with external shading is used. For overheating evaluation, the crucial parameters are the *g-value* of the glazing and the *transmittance* $\tau_{e,B}$ and *reflectance* $\rho_{e,B}$ of the shading device. *Table 11* shows the values for the parametric variations.

According to the standards (ASI 2018a) this parameters can also be combined to the *total g-value* g_{tot} that is often used in literature and helpful for simple normative methods. Within the case study, the *critical* g_{tot}*-value* is calculated and used.

Table 11: Window and shading specifications

	variation	value	comment
U-value [W/(m²*K)]	-	0.7	modern triple glazing
g-value [-]	*V_g03*	0.3	typical *sun protection glazing*
	V_g06	0.6	typical *heat protection glazing*
transmittance [-], **reflectance** [-]	*low shading*	$\tau_{e,B}$ = 0.12 $\rho_{e,B}$ = 0.28	medium/low translucent, bright colored shading, e.g. screen
	high shading	$\tau_{e,B}$ = 0.05 $\rho_{e,B}$ = 0.40	very low translucent, medium colored shading, e.g. shutter

In reality, the control of the shading devices is crucial for their efficiency. Within the normative methods it is assumed that shading devices are used permanently. For simulations, it must be defined exactly when the shading is active and when not. The following control was set in *EnergyPlus*:

- Shading Control Type: *OnIfHighSolarOnWindow*
- Set point: 50 W/m²

This means, only if the sum of direct and diffuse solar radiation on the window exceeds 50 W/m², shading with the stated properties is active.

3.2.4 Ventilation

For the **simple normative method**, ventilation is not directly considered. A theoretical air change rate according to the number of façade openings has to be defined (*Table 3*). Furthermore, it is presumed that all glazed areas are openable and fully opened during the night. (ASI 2012)

The **detailed normative method** requires inputs about hygienic air change and additional night-ventilation through windows. *Table 4* defined the standard hourly values for hygienic airflow which are also mostly predefined within the software tools. Regarding night-ventilation, the effective opening area of windows that are opened or tilted during the night has to be declared. This can be done with the measures of the openable windows and the definition which windows are fully opened, tilted or closed. Due to the uncertainty of the window opening behavior, different variants are defined and analyzed. *Table 12* shows the overview and the explanations of all variants. For the case study there is one theoretical variant (*V_100%*) that is needed for comparison with the simple method. All other variants represent realistic scenarios for sensitivity analysis and comparison to the dynamic simulation. The effective air flow depends on the different window measures, the opening area and the temperature difference.

Table 12: Night-ventilation variants - detailed normative methods

case study	
V_100%	all glazed areas are fully opened during the night
V_max	all openable windows are fully opened during the night
V_med	one window is fully opened during the night
V_min	one window is tilted during the night
parametric study	
all windows opened	all openable windows are fully opened during the night
all windows tilted	all openable windows are tilted during the night
one window opened	one window is fully opened during the night
one window tilted	one window is tilted during the night

Within **dynamic simulation** methods, the ventilation specifications can be defined very flexible and in different ways. In *EnergyPlus,* the hygienic airflow is defined according to the detailed method with the same fixed hourly values. Regarding night-ventilation it was tried to define realistic variants that are comparable to the variants of the detailed method. Due to the different input parameters and calculation algorithms a direct comparison is not valid. Therefore, the following two general night-ventilation variants were defined for the case study and the parametric study:

- *Night-ventilation low* - compareable with one tilted window
- *Night-ventilation high* - compareable with one opened window

Here, the air flow depends on the opening area, the definition of the effective height, the temperature difference and the wind properties. To achieve comparability, the definition of proper input parameters was based on empirical tries. The results are illustrated within the detailed analysis of the simulation outputs.

3.2.5 Internal Gains

Within the **simple normative method**, internal gains such as people, lighting or other electric equipment are not considered at all.

For the **detailed normative method** an exact definition of the hourly values of all internal gains is defined in the standard (ASI 2012). *Figure 10* illustrates the hourly normative profile for one day for residential use.

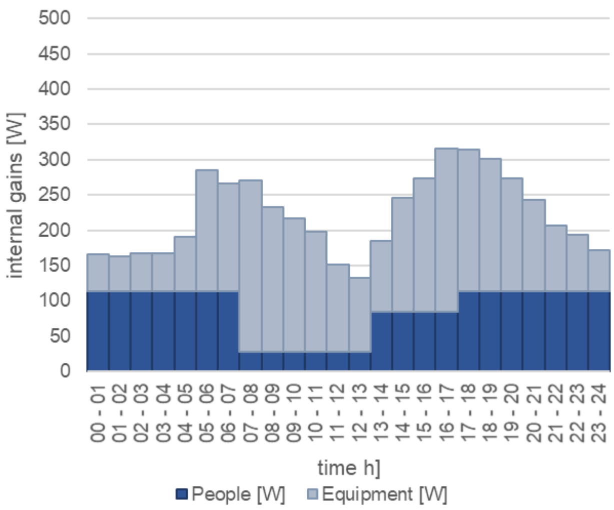


Figure 10: Internal gains - normative (own figure)

This normative profile implies standard worst-case values but cannot represent realistic occupancy.

For the **dynamic simulation** realistic repeating daily profiles have to be defined. Again, different variants are compared. For theoretical comparison with the detailed method, the normative occupancy was defined according to *Figure 10.* Additional, two realistic variants are integrated: *occupancy bed room* (*Figure 11*) and *occupancy living room* (*Figure 12*).

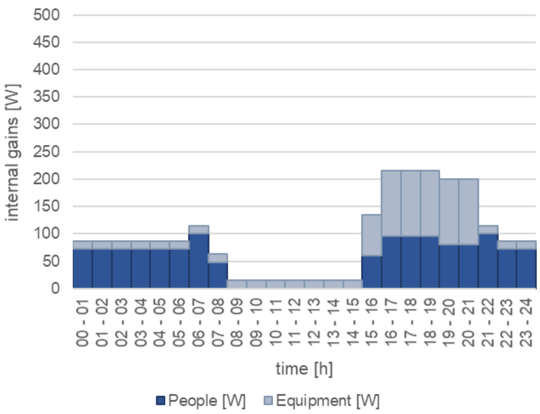


Figure 11: Internal gains - bed room (own figure)

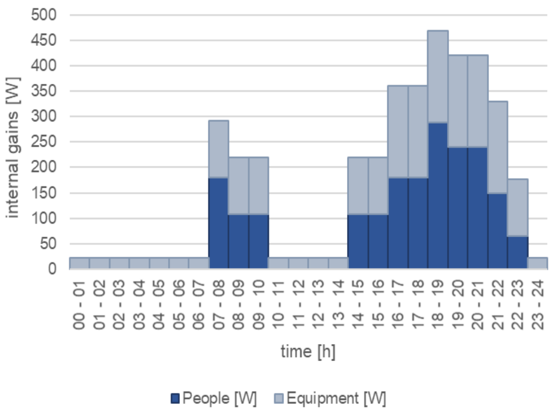


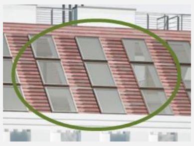
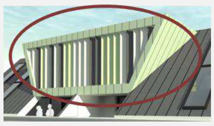
Figure 12: Internal gains - living room (own figure)

3.3 Case Study - Specifications

From a set of designs for a roof top extension of a Viennese *Gründerzeit* building, four critical rooms with similar measures are selected for the *case study* (CS). All four rooms are located at the top of the building and possess a south-oriented exterior façade with high glazing ratio. Every room shows a unique characteristic which makes the comparison interesting. For better recognition every room has got a *nickname* based on its special attribute. *CS Room1 - Glazed,* has got a fully glazed and slightly tilted south façade. *CS Room 2 - Skylights,* shows typical roof top windows with a 45 degrees pitch. The fully glazed south façade of *CS Room 3 - Overhang,* has an overhanging and fully glazed south façade and also a glazed west façade. *CS Room 4 - Shaded*, has fixed vertical shading elements in front of the vertical and glazed south façade.

Table 13 shows the comparison of the key parameters *floor area*, *volume* and *room height* of all case study rooms. Additionally, the *window to wall ratio* (WWR) and the pitch angle of the south façade are compared. The *window to wall ratio* represents the ratio of the total glazing area and the gross exterior wall area. The pitch angle of a vertical wall is equal to 90 degrees.

Table 13: Case study parameters - comparison

	CS 1 - Glazed 	**CS 2 - Skylights** 	**CS 3 - Overhang** 	**CS 4 - Shaded** 
Floor area	28.9 m²	35.9 m²	32.3 m²	26.8 m²
Volume	76.5 m³	133.6 m³	96.3 m³	67.0 m³
Room height	2.7 m	4.7 m	2.6 m	2.5 m
WWR	46%	44%	82%	57%
Pitch angle south	67.5°	45°	117°	90°

Regarding ventilation possibilities, a worst-case scenario is used for all rooms. There is only natural ventilation through windows without the possibility of cross ventilation or air exchange with other rooms.

Below, floor plans, sections and views of all case study rooms are presented.

Case Study Room 1 - Glazed

This room has a fully glazed south façade with a combination of mainly fixed glazing as well as three openable windows (*Figure 13*).

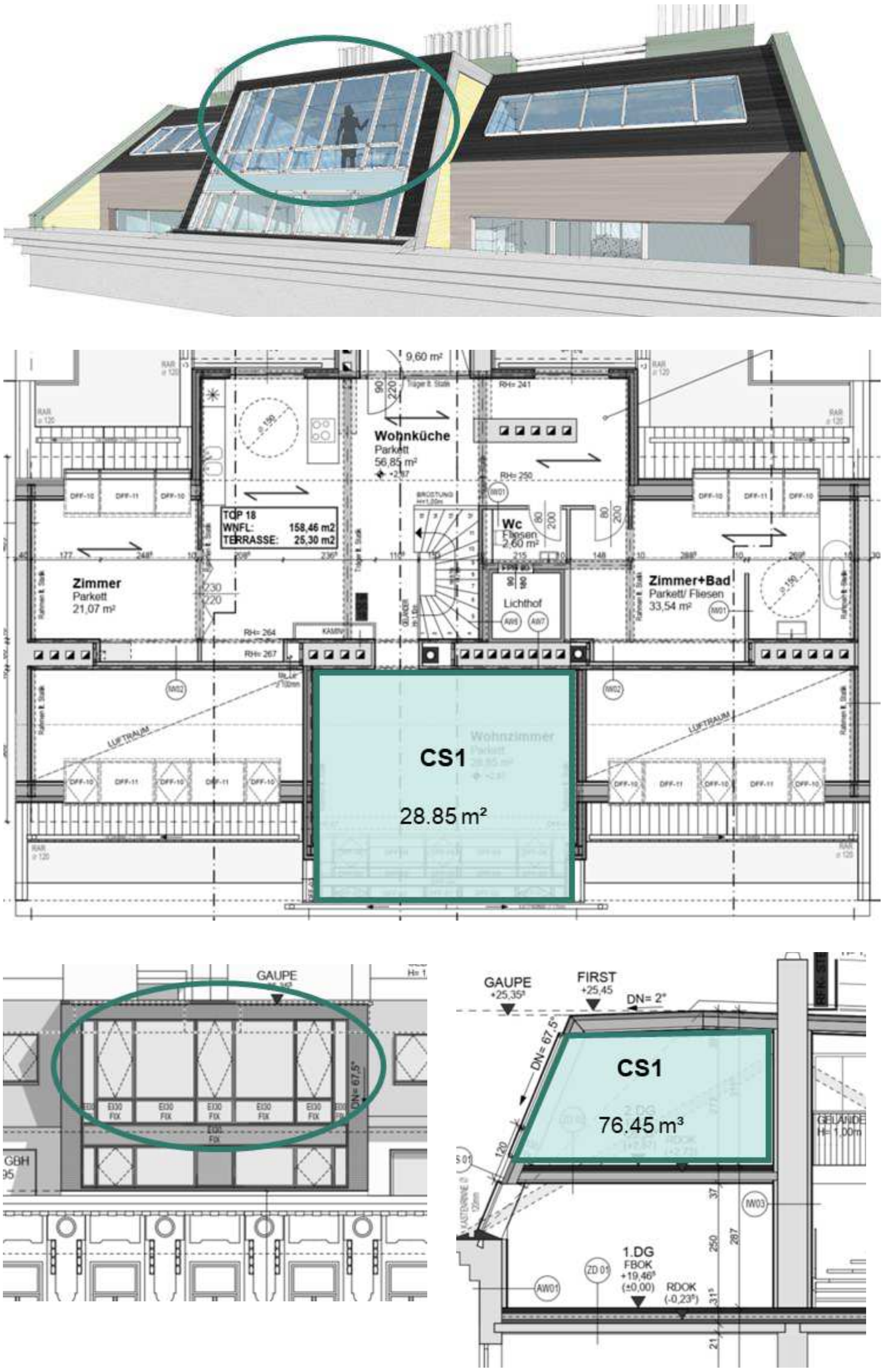


Figure 13: Case study room 1 - Glazed (Bauer et al. 2014)

Case Study Room 2 - Skylights

The second room shows typical skylight windows in the south orientated roof with a high glazing ratio. The room height extends over two floors (*Figure 14*).

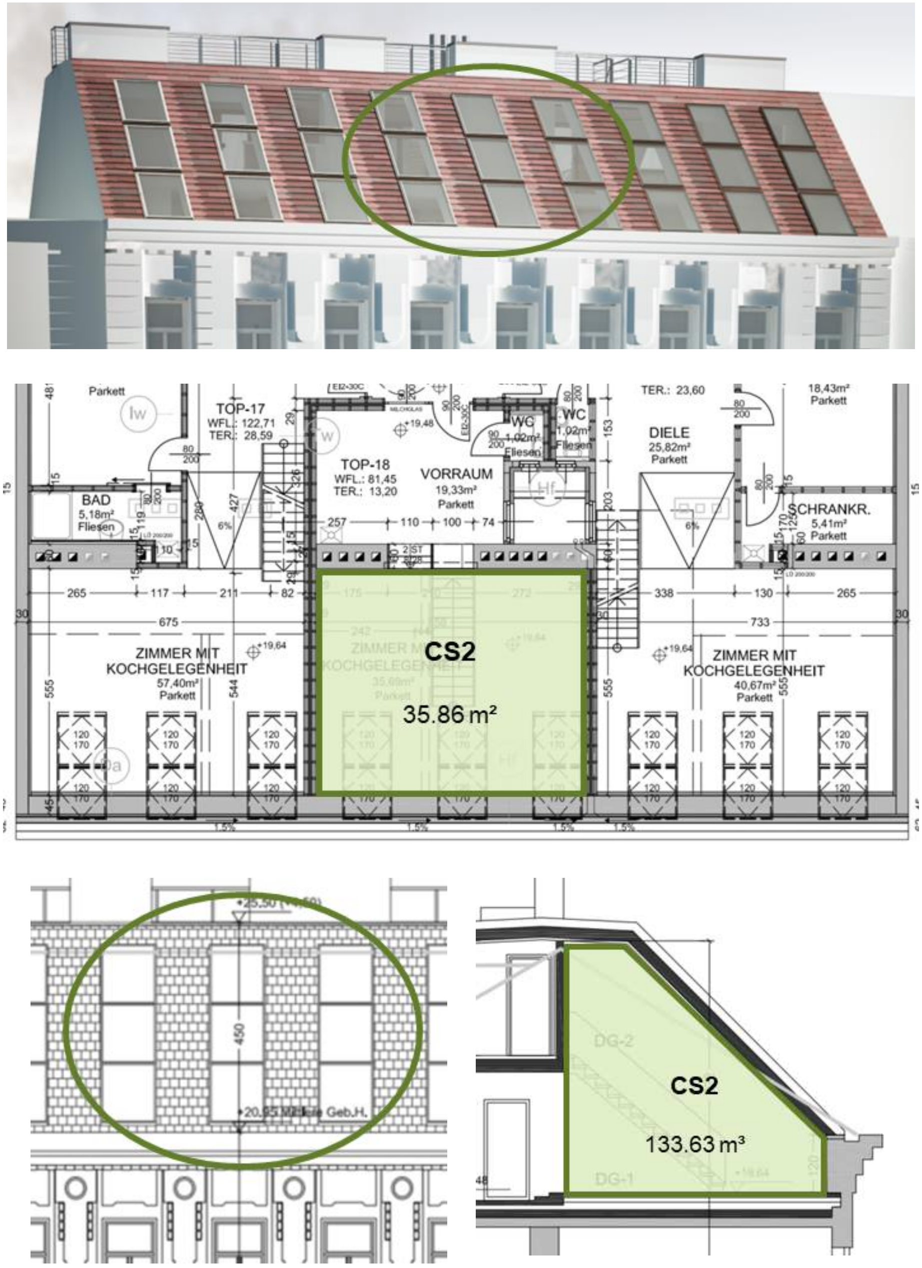


Figure 14: Case study room 2 - Skylights (Heid et al. 2014)

Case Study Room 3 - Overhang

Case study room 3 has got a south orientated overhang with fixed glazing and a glazed west orientated façade with an openable glass door (*Figure 15*).

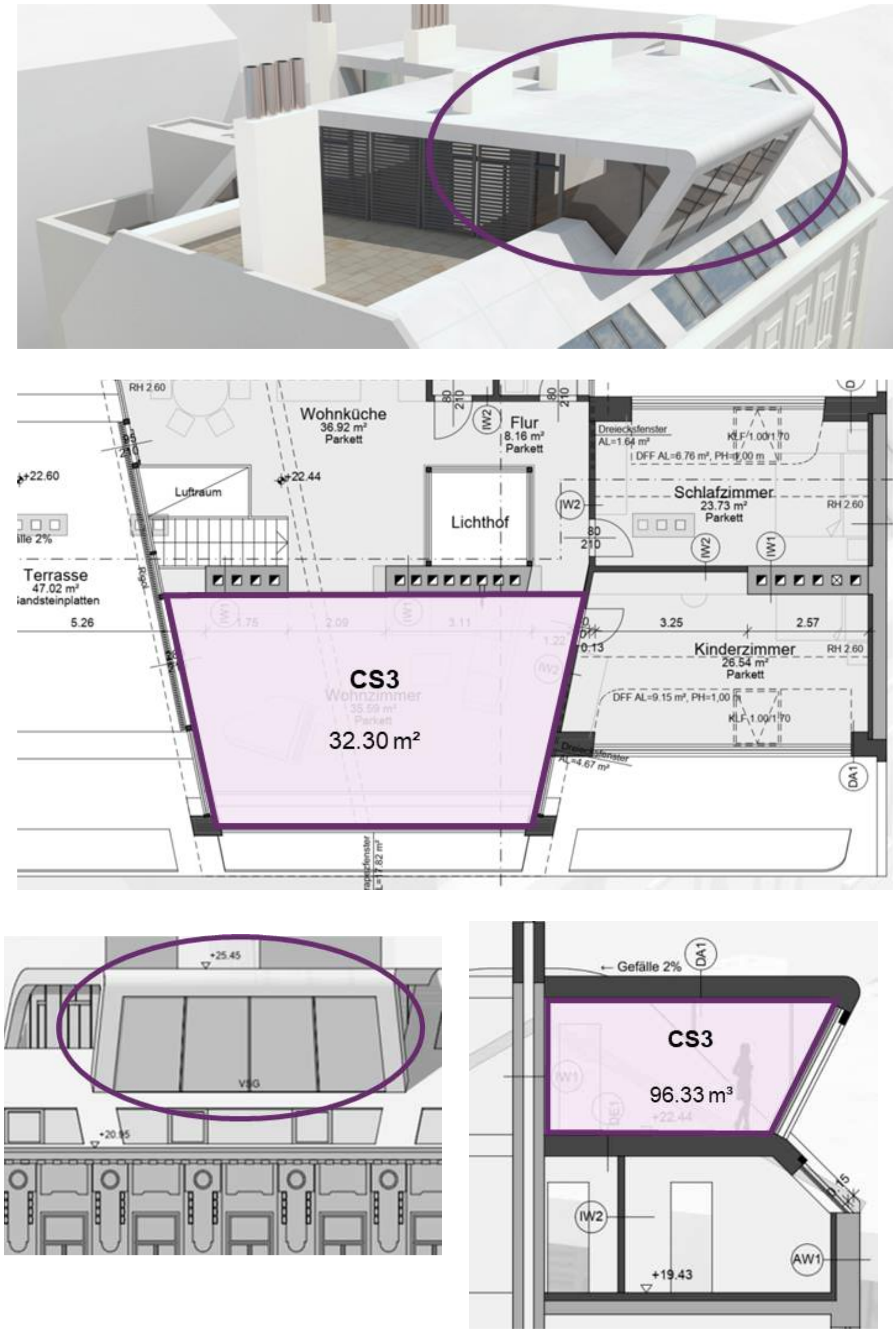


Figure 15: Case study room 3 - Overhang (Koliha and Pfister 2014)

Case Study Room 4 - Shaded

The design of the fourth case study room implemented fixed shading elements in front of the south façade with openable glass doors (*Figure 16*).

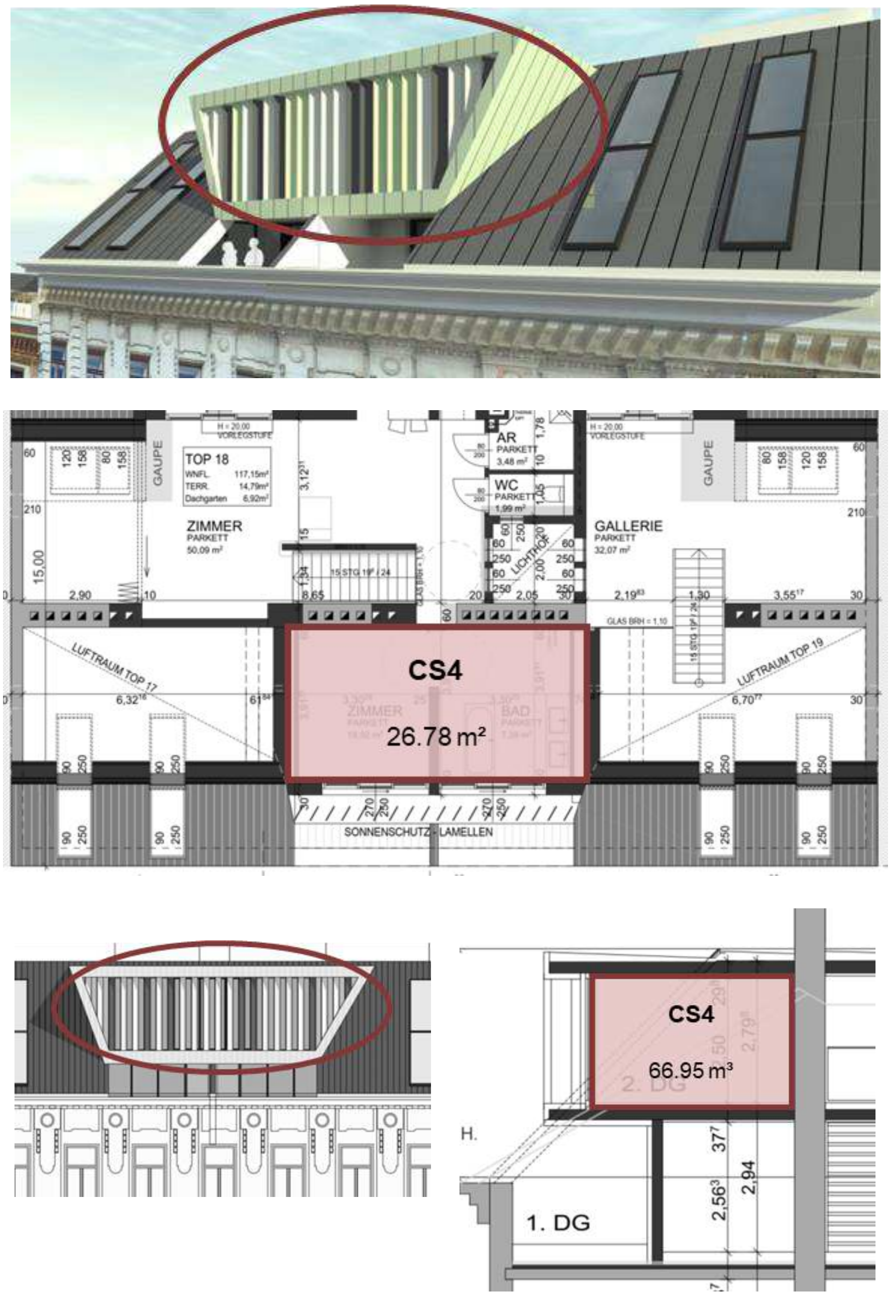
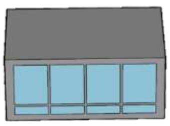
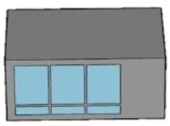
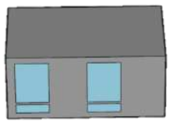


Figure 16: Case study room 4 - Shaded (Karhan and Malhotra 2014)

3.4 Parametric Study - Specifications

In contrary to the specific case study results, more generic outputs and conclusions are the purpose of the parametric study. The detailed normative method and the simulation method should be compared based on a large set of outputs. Therefore, the design in terms of glazed area, shading properties and window orientation is varied by parametric variation. The basis is the design of the first case study room *(CS1). Table 14* presents its general specifications as well as an overview over all design variations.

Table 14: Parametric study - 48 design variants

General specifications	**Location:** Vienna **Floor area:** 28.9 m² **Volume:** 76.5 m³ **Room height:** 2.7 m **Pitch angle:** 67.5°											
WWR	*46%*				*34%*				*23%*			
Number of Windows n = 3	 **4 windows**				 **3 windows**				 **2 windows**			
Shading n = 2	**low** $\tau_{e,B} = 0.12$ $\rho_{e,B} = 0.28$		**high** $\tau_{e,B} = 0.05$ $\rho_{e,B} = 0.4$		low $\tau_{e,B} = 0.12$ $\rho_{e,B} = 0.28$		high $\tau_{e,B} = 0.05$ $\rho_{e,B} = 0.4$		low $\tau_{e,B} = 0.12$ $\rho_{e,B} = 0.28$		high $\tau_{e,B} = 0.05$ $\rho_{e,B} = 0.4$	
g-value n = 2	**0.6**	**0.3**	0.6	0.3	0.6	0.3	0.6	0.3	0.6	0.3	0.6	0.3
g_{tot}-value	*0.11*	*0.08*	*0.06*	*0.05*	*0.11*	*0.08*	*0.06*	*0.05*	*0.11*	*0.08*	*0.06*	*0.05*
	→ window/shading variants general n = 3 * 2 * 2 = 12											
Orientation n = 4												
North	*n01*	*n02*	*n03*	*n04*	*n05*	*n06*	*n07*	*n08*	*n09*	*n10*	*n11*	*n12*
East	*e01*	*e02*	*e03*	*e04*	*e05*	*e06*	*e07*	*e08*	*e09*	*e10*	*e11*	*e12*
West	*w01*	*w02*	*w03*	*w04*	*w05*	*w06*	*w07*	*w08*	*w09*	*w10*	*w11*	*w12*
South	*s01*	*s02*	*s03*	*s04*	*s05*	*s06*	*s07*	*s08*	*s09*	*s10*	*s11*	*s12*
	→ total design variants general **n = 12 * 4 = 48**											

These variations lead to 48 different design variants. Moreover, different *use case* variants with varying occupancy and night-ventilation modes are defined and conducted. *Table 15* shows the definition of the standard occupancy and the variation of the night-ventilation for the **detailed normative method**, resulting in 192 output variants.

Table 15: Paramtetric output variants - detailed normative method

Occupancy n = 1	**normative occupancy**			
Night-ventilation n = 4	**all windows tilted**	**all windows open**	**one window tilted**	**one window open**
	→ use case variants *first diagram* n = 2		→ use case variants *second diagram* n = 2	
	→ use case variants detailed normative method n = 4			
	→ total output variants detailed method **n =** 48 * **4 = 192**			

The results of the detailed method will be presented with two diagrams according to *Table 15*: Firstly, with all windows opened or tilted, representing the default settings of most tools for this method. Secondly with just one window opened or tilted, representing more realistic variants.

For the **dynamic simulations**, not only occupancy and night-ventilation are varied but also different climate data are used. *Table 16* shows the variations that lead to a total number of 384 output variants for this method.

Table 16: Parametric output variants - dynamic simulation

Occupancy n = 2	**Living room**		**Bed room**	
Night-ventilation n = 2	**low (tilted)**	**high (opened)**	low (tilted)	high (opened)
	→ use case variants dynamic simulation n = 4			
Climate data n = 2				
Standard	*st_max*	*st_med1*	*st_med2*	*st_min*
Future RCP4.5	*fut_max*	*fut_med1*	*fut_med2*	*fut_min*
	→ total output variants dynamic simulation **n =** 48 * **4** * **2 = 384**			

The resulting outputs will be presented with a single diagram, separated into two climate data sets, each containing the results of the four *use case* variants from *min* to *max*.

4 RESULTS

4.1 Case Study

4.1.1 Simple Normative Method

The execution of the simple normative method results in a value of the actual *immission area* ($m_{w,l}$) which has to be compared to the minimal value ($m_{w,l,min}$). Parametric variation of the *total g-value* g_{tot} is used to determine the maximum value that results in an acceptable overheating risk evaluation ($m_{w,l} > m_{w,l,min}$) for every case study room (CS 1-4).

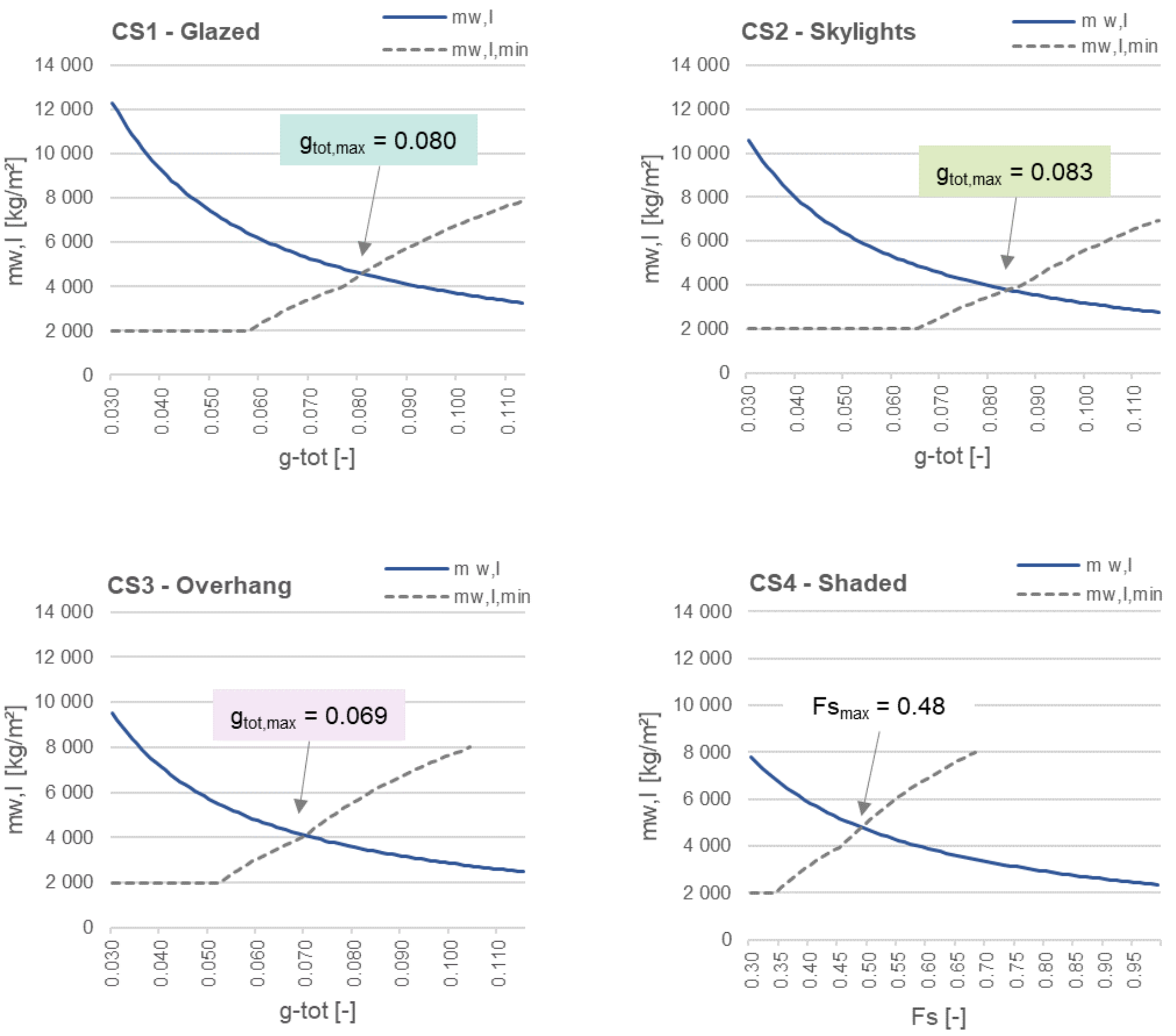


Diagram 1: Results - simple normative method

Diagram 1 shows the evaluation of the **maximum *g_{tot}-value*** for all case study rooms. For the first two case study rooms approximately 0.08 is the maximum value for g_{tot}. *CS 3* is a more critical room and therefore $g_{tot,max}$ is lower (0.069). The windows of *CS 4* have no shading device but there are fixed shading elements. Therefore, no *total g-value* can be calculated but a *shading factor Fs* that represents the solar- and light-transmittance of the shading elements.

Table 17 shows the selection of the shading device properties for the *case study rooms 1-3* based on the *U-value*, the *g-value* of the glazing and the maximum *g_{tot}-value*. These values for *transmittance* ($\tau_{e,B}$) and *reflectance* ($\rho_{e,B}$) are needed for the detailed normative method instead of the *g_{tot}-value*.

Table 17: Shading device properties

U-value [W/(m²K)]		0.5	0.7	1	0.5	0.7	1	0.5	0.7	1
g-value [-]		0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5
$\tau_{e,B}$ [-]	$\rho_{e,B}$ [-]	g_{tot} [-]								
0.05	0.70	0.029	0.034	0.040	0.033	0.038	0.044	0.038	0.042	0.048
0.05	0.50	0.038	0.045	0.055	0.042	0.050	0.059	0.047	0.054	0.063
0.05	0.40	0.042	0.051	0.063	0.047	0.055	0.067	0.051	0.060	0.071
0.05	0.30	0.046	0.057	0.070	0.051	0.061	0.075	0.055	0.065	0.079
0.05	0.10	0.055	0.068	0.086	0.060	0.073	0.090	0.064	0.077	0.094
0.10	0.65	0.047	0.053	0.060	0.056	0.061	0.068	0.065	0.070	0.077
0.10	0.36	0.060	0.069	0.082	0.069	0.078	0.091	0.078	0.087	0.099
0.10	0.35	0.060	0.070	0.083	0.069	0.079	0.092	0.078	0.088	0.100
0.10	0.29	0.063	0.073	0.088	0.072	0.082	0.096	0.081	0.091	0.105
0.10	0.10	0.071	0.084	0.102	0.080	0.093	0.111	0.089	0.102	0.119
0.12	0.40	0.064	0.073	0.086	0.075	0.084	0.096	0.086	0.095	0.106
0.12	0.28	0.069	0.080	0.095	0.080	0.091	0.105	0.091	0.102	0.115
0.12	0.26	0.070	0.082	0.097	0.081	0.092	0.107	0.092	0.103	0.117
0.12	0.23	0.072	0.084	0.099	0.083	0.094	0.109	0.094	0.105	0.120
0.12	0.10	0.077	0.091	0.109	0.088	0.101	0.119	0.099	0.112	0.129
0.15	0.60	0.065	0.072	0.080	0.079	0.085	0.093	0.092	0.098	0.106
0.15	0.40	0.074	0.083	0.096	0.087	0.096	0.108	0.101	0.110	0.121
0.15	0.30	0.078	0.089	0.103	0.092	0.102	0.116	0.105	0.115	0.129
0.15	0.20	0.082	0.095	0.111	0.096	0.108	0.124	0.110	0.121	0.137
0.15	0.10	0.087	0.101	0.119	0.100	0.114	0.132	0.114	0.127	0.144

	CS1: $g_{tot,max}$ = 0.080
	CS2: $g_{tot,max}$ = 0.083
	CS3: $g_{tot,max}$ = 0.069

For all case study variants, a ***U-value*** of **0.7 W/(m²·K)** and a ***g-value*** of **0.3** is selected. The selected shading device properties for CS1 and CS2 are: $\tau_{e,B}$ = 0.12, $\rho_{e,B}$ = 0.28. Case study room 3 needs different shading device properties: $\tau_{e,B}$ = 0.10, $\rho_{e,B}$ = 0.36.

4.1.2 Detailed Normative Method

The main output of the detailed method is the operative temperature profile of one periodic summer day. The **maximum operative temperature** is the essential parameter for this overheating evaluation method, and it should not exceed 27.0°C.

Diagram 2 illustrates the results of two variants from case study room 1 (CS1 – Glazed). Variant *V_100%* indicates the theoretical variant where all glazed areas are openable. Variant *V_min* represents a variant with one large window that is tilted overnight and opened only once in the morning and once in the evening. The temperature profiles are compared with the ambient temperature (*Ta*). Below the temperatures, also the airflow profiles of both variants are shown.

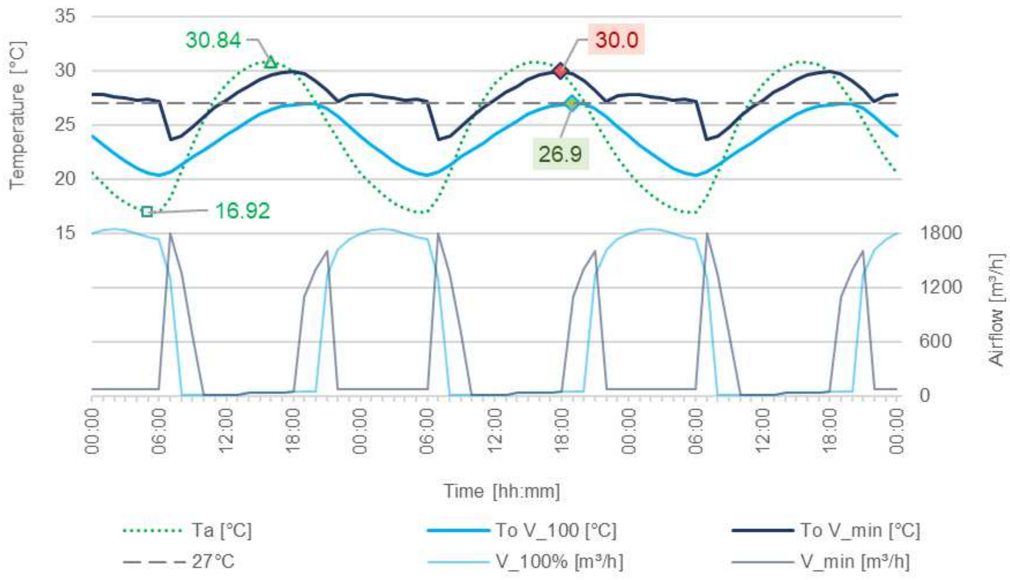


Diagram 2: Typical output – detailed normative method

Variant *V_100%* shows a maximum operative temperature (*To*) of 26.9°C and would therefore be declared as save from overheating. The lower night-ventilation airflow of variant *V_min* leads to 30°C room temperature which leads to severe overheating.

Comparison - Simple Normative Method

Diagram 3 shows the first set of results which are mainly based on the selected g_{tot}*-values* (see simple method results) and on the **variation of night-ventilation variants**. For the direct comparison to the simple normative method only the variant *V_100%* is valid. The other ventilation variants and the variation of the location are interesting for a sensitivity analysis of the detailed method. Additionally, the possibility and the impact of the **variation of the location** is shown.

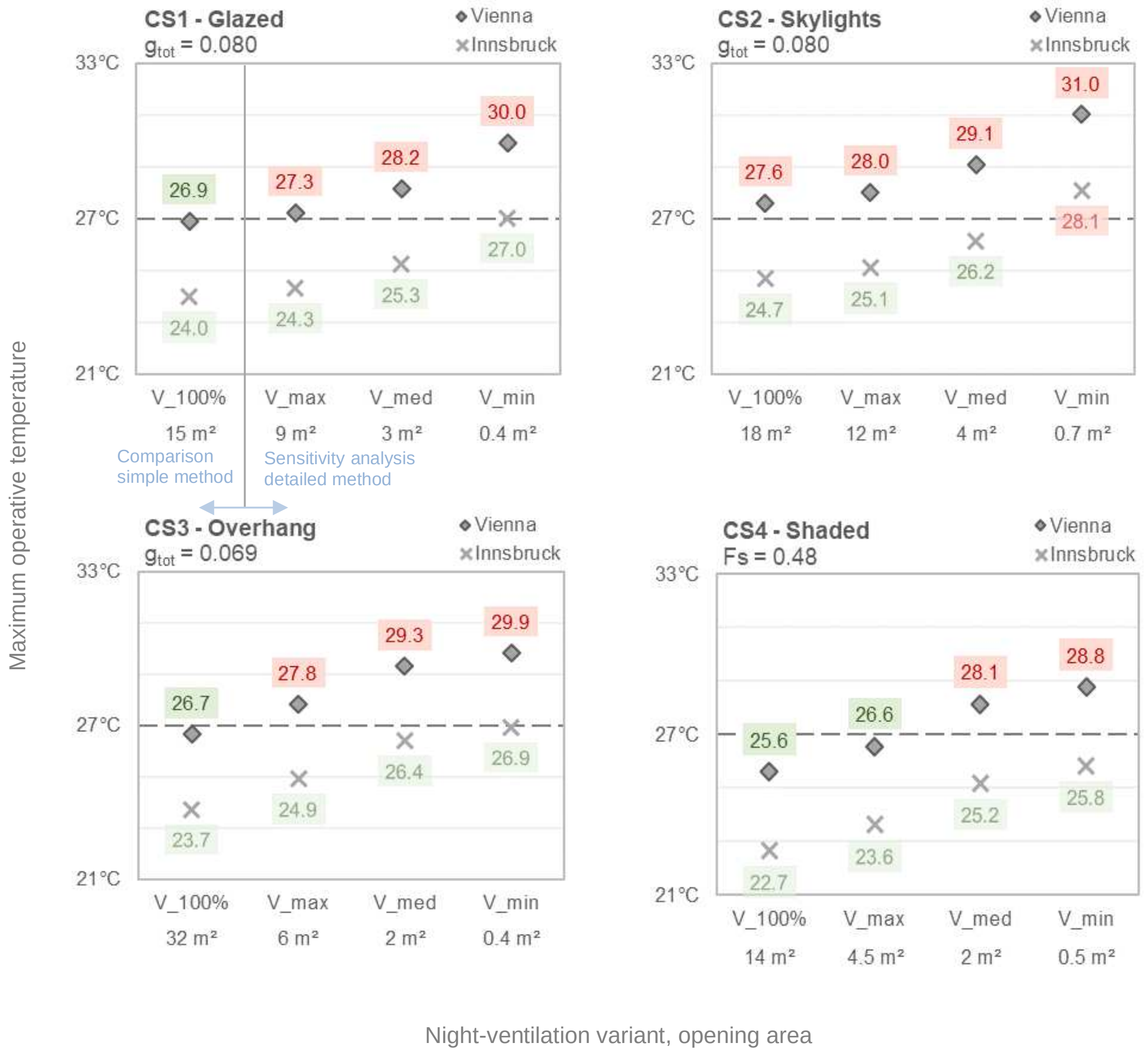


Diagram 3: Results detailed method – comparison with simple method

CS 1 and *CS 3* show the expected results for the *V_100%* variant, because they correlate with the simple method results. They are just at the edge between notionally overheating risk and notionally no overheating risk. *Case study room 2* gets warmer than expected from the simple method results. This is probably because of its critical south orientated roof with a pitch angle of 45°C that is considered differently by the two methods. In the case of *CS 4* lower temperatures occur. This can be explained by the fixed shading elements. Their shading effect is either underrated by the simple method or overrated by the detailed method.

Nearly all Viennese variants show that the realistic ventilation variants (*V_max, V_med, V_min*) can be problematic because the cooling effect through night-ventilation gets much lower compared to the *V_100%* variant with a bigger opening. Nearly all variants with location of Innsbruck show no overheating risk and indicate the strong impact of the location which is also totally ignored by the simple method.

Comparison - Dynamic Simulation

For the comparison with the simulation results, only the realistic ventilation variants with the location of Vienna are considered. The shading properties are changed to reduce the maximum temperatures for better comparability.

The increased shading quality leads to lower overheating risk for the realistic ventilation variants, but *Diagram 4* shows that even a very **low g_{tot}-*value* cannot prevent all variants from overheating** according to the results of the detailed normative method. In particular, the minimal night-ventilation variants and the *CS 3* variants with very high glazing area are critical.

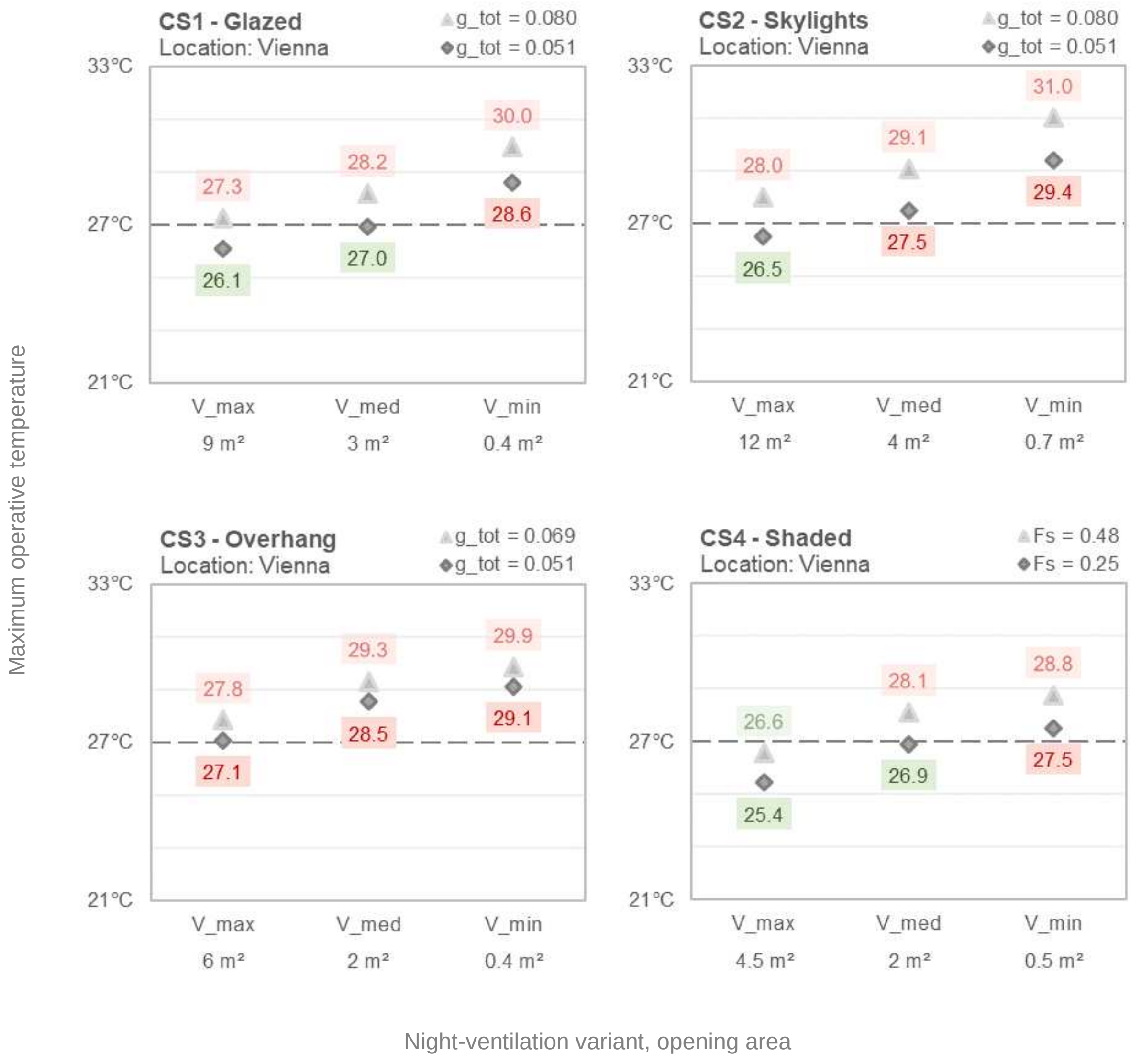


Diagram 4: Results detailed method – comparison dynamic simulation

4.1.3 Dynamic Simulation

The main difference compared to other methods is the calculation period of the dynamic simulation. For the present overheating evaluation simulations, the period is five months and the output time step equals to one hour. Therefore, for every single simulation variant and every output parameter (e.g. operative temperature) 3672 output values are calculated. *Diagram 5* shows the output of one of the simulation variants. There is the profile of the operative temperature (*To*) over the whole summer period together with the ambient temperature (*Ta*) and the maximum temperature according to the adaptive comfort theory (*Tmax*).

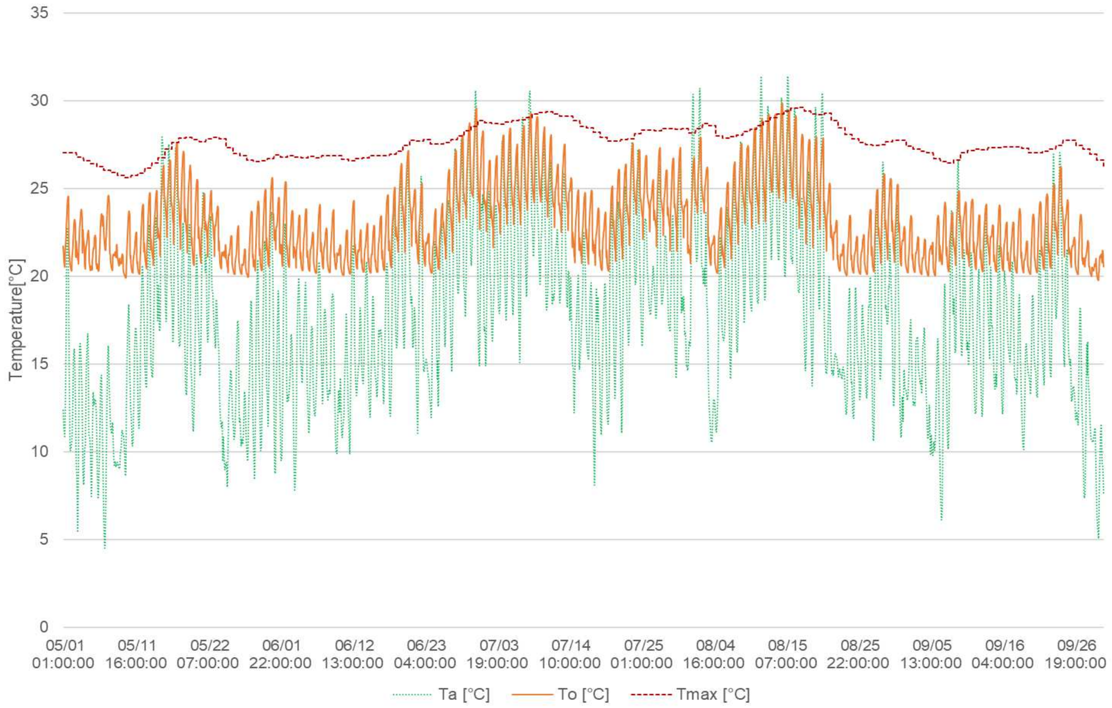


Diagram 5: Typical output - dynamic simulation

For the analysis of such outputs, particularly for many variants, only statistical evaluation methods make sense. For the following analysis of the simulated variants and outputs, different evaluation methods are used and discussed. For the details of the used input parameters see the *Methodology* chapter.

The statistical evaluation of all simulated variants is performed with two different methods. *Diagram 6* shows the **fixed threshold temperature evaluation** method for all variants of one case study room. Basically, the number of hours with temperatures over 26.0°C is compared for every variant. The amount is expressed in percentage based on the whole summer period, which is 3672 hours. Additionally, the percentage of hours with operative temperatures from 26°C to 27°C, from 27°C to 29°C and over 29°C is illustrated. The maximum operative temperatures of every variant are also indicated.

Diagram 7 shows the second approach for overheating evaluation of the same data. This diagram indicates the percentage of hours where the **maximum temperature, according to the adaptive comfort theory**, is exceeded. Additionally, the maximum daily exceedance in degree hours for every variant is displayed. An advantage of the first diagram is the more specific information, for example how often 29°C is exceeded. Generally the variable threshold according to the adaptive comfort theory became state of the art for overheating evaluation. On the other hand, for design decisions, the relative difference between variants is often more important than the absolute number.

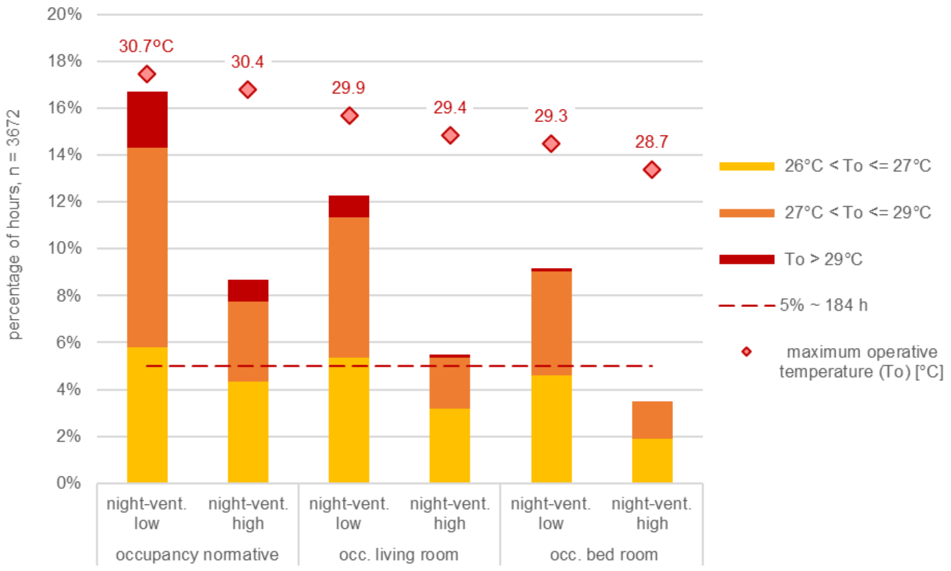


Diagram 6: CS1 - dynamic simulation – fixed threshold temperature statistics

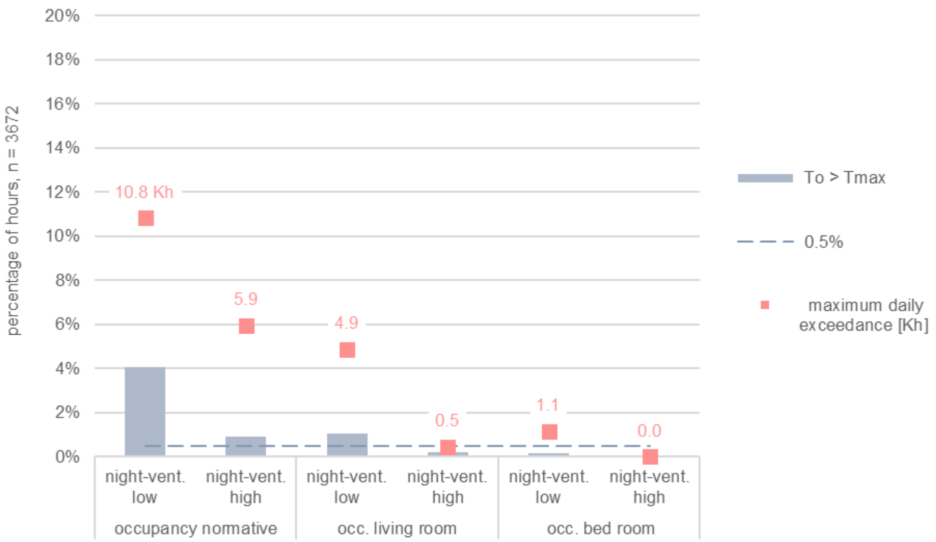


Diagram 7: CS1 - dynamic simulation - adaptive comfort statistics

Both diagrams show the simulation results of *CS 1* and the six *use case* variants with variable occupancy and ventilation modes. Naturally, the **overheating risk decreases with lower occupancy and higher night-ventilation**. The first three variants indicate clear overheating, particularly through a high number of hours with temperatures over 29°C (*Diagram 6*) and also through a high daily exceedance (*Diagram 7*). The other variants could be acceptable despite the rather high maximum temperature of around 29°C. Generally, night-ventilation should be maximized and normative occupancy would not be possible for this case study room.

Diagram 8 shows a detailed analysis of this critical variant with **normative occupancy**. The temperature profiles of the ambient temperature (*Ta*) and the simulated operative temperature (*To*) are shown for a seven days period. Additionally, the air change rate caused by natural ventilation (*V_low*) and the internal gains (*P_int*) from people and electric equipment are presented. There are always high internal gains present, which does not allow to cool the room down anytime. For residential use this is not realistic. Therefore this normative occupancy variant will not be further evaluated.

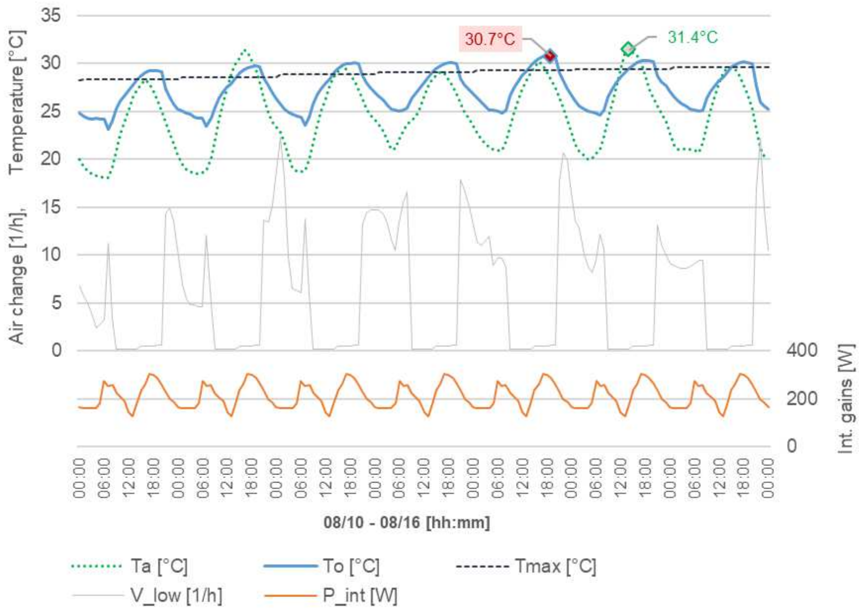


Diagram 8: Dynamic simulation - detailed analysis - normative occupancy

Diagram 9 deals again with the same variant but at another period with an example of **high daily exceedance**. The room heats up continuously during the week and at the end the room temperature exceeds the adaptive threshold temperature. *Diagram 7* showed that higher night-ventilation helps to reduce the maximum exceedance to 5.9 Kh.

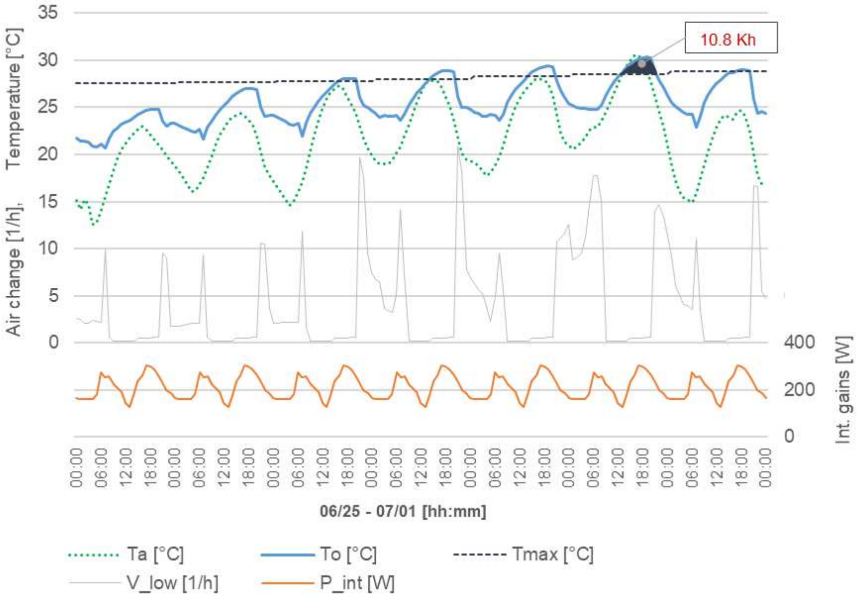


Diagram 9: Dynamic simulation - detailed analysis - daily exceedance

The sixth variant from above without overheating risk is analysed within *Diagram 10*. Because of the **bed room occupancy** schedule the room does not overheat during the day. Even if the maximum room temperature rises to nearly 29°C it is below the adaptive threshold temperature in this case.

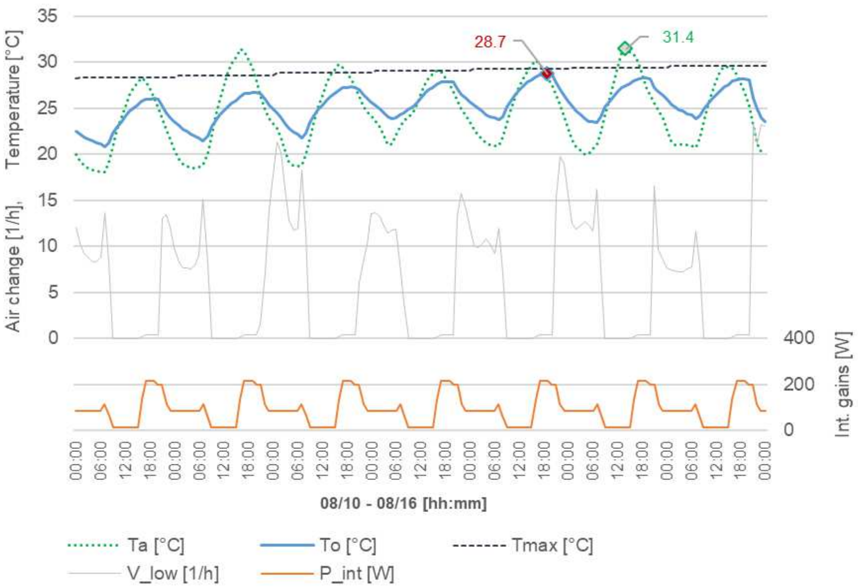


Diagram 10: Dynamic simulation - detailed analysis - occupancy bed room

4.1.4 Comparison

Within this chapter, the results of the detailed normative method and the simulation method are compared for all four case study rooms. The former chapters show the different kind and resolution of input parameters and results for the two methods. Therefore, their results cannot be compared directly. Their differences and conclusions about overheating are discussed in the following.

For the detailed method, the results of the **maximum operative temperature** for three night-ventilation variants (*max*, *med*, *min*) with normative occupancy are shown (see also chapter 4.1.2). Then they are compared to the **statistical evaluation of the simulation results**. Both statistic diagrams, one with adaptive threshold and one with fixed threshold temperature are presented. There are four evaluated *use case* variants, two for occupancy (living room, bed room) and two for night-ventilation (low, high).

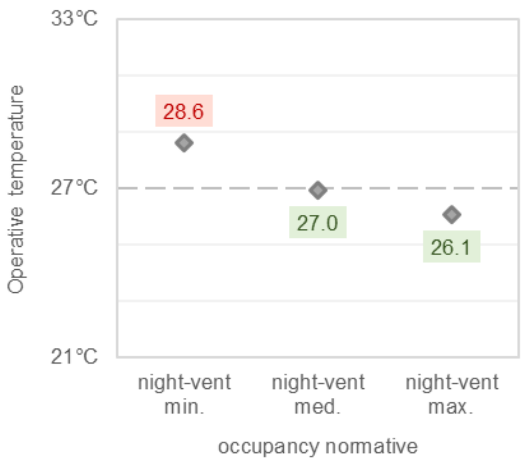


Diagram 11: CS1 - detailed method

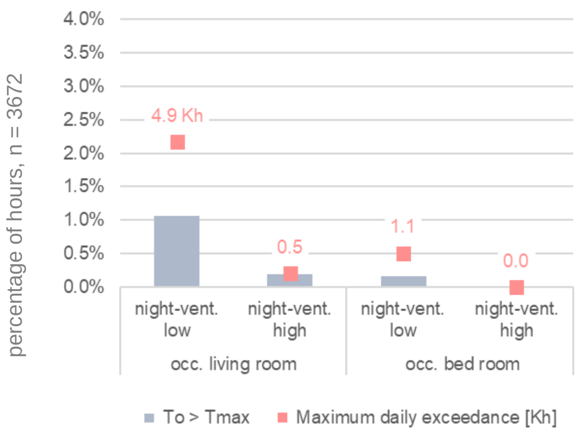


Diagram 12: CS1 - adaptive threshold

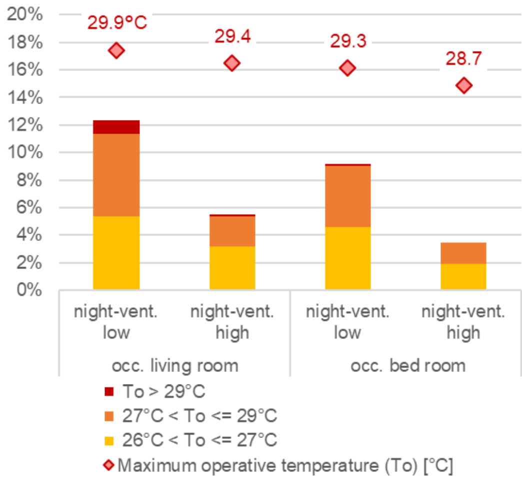


Diagram 13: CS1 - fixed threshold

For the **case study room 1 (CS 1)** the numbers of the maximum operative temperatures from the detailed normative method (*Diagram 11*) and the simulations (*Diagram 13*) differ significantly. Nevertheless, a similar interpretation is possible. Both methods generally conclude that **high night-ventilation can prevent severe overheating** for this case study room. *Diagram 12* also shows that the first *use case* variant with high occupancy and low night-ventilation leads to severe overheating. Only the fourth variant with lower occupancy and high ventilation keeps the room temperature in a comfortable range over the whole summer period.

The design of **case study room 2 (CS 2)** is generally comparable to the design of *CS 1*. Mainly due to a similar floor area and the same window to wall ratio. Only its room height and volume are much larger and the pitch angle of the south orientated façade/roof is more critical.

CS2 - Skylights

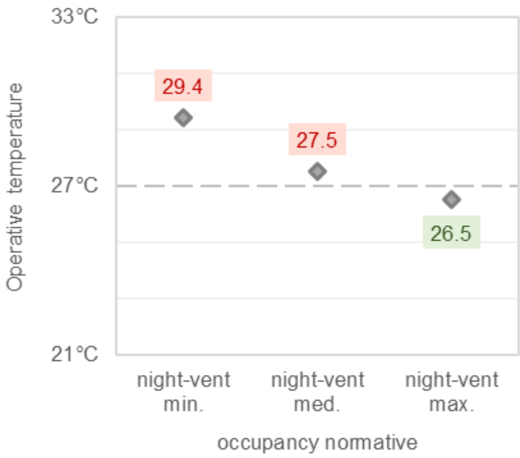


Diagram 14: CS2 - detailed method

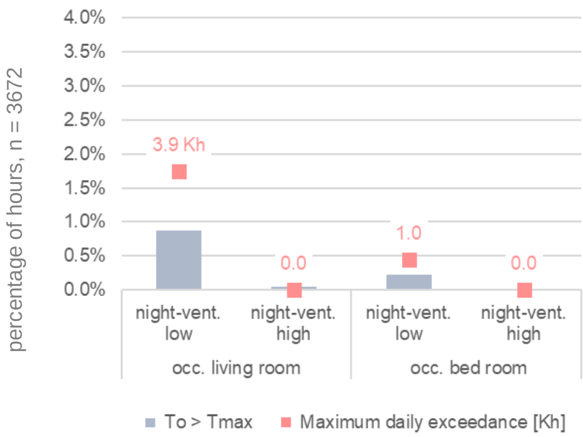


Diagram 15: CS2 - adaptive threshold

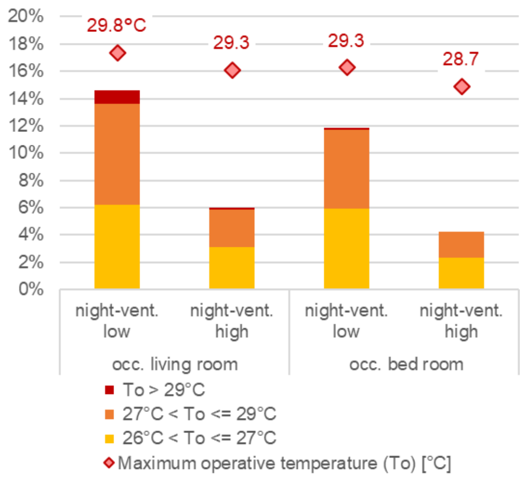


Diagram 16: CS2 - fixed threshold

Diagram 14 shows **slightly higher values** compared to *case study room 1*. Mainly because of the 45° pitch angle of *CS 2*. *Diagram 16* correlates basically to that but the number of hours with very high temperatures (>29°C) is comparable to *CS 1*. This is why *Diagram 15* shows even slightly lower hours with room temperatures exceeding the maximum temperature according to the adaptive comfort theory. This also displays the major difference between the adaptive and the fixed threshold. Additionally, this indicates that the simulation deals differently with the higher volume of *CS 2*, which leads to the same overheating risk as for *CS 1* although the pitch angle of *CS 2* is more critical.

The design of the **case study room 3 (CS 3)** with the overhang and the additional west oriented glazed façade differs from the previous room designs. Due to the generally high shading intensity of all the rooms (g_{tot} = 0.05 for all glazed areas) the differences are not significant. Nevertheless, this room has definitely a **higher overheating risk** than *CS 1* and *CS 2*.

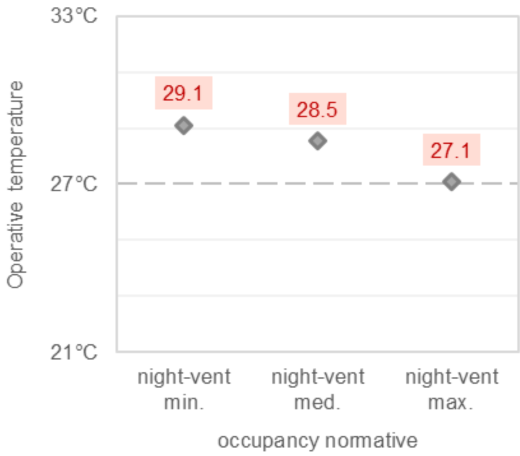


Diagram 17: CS3 - detailed method

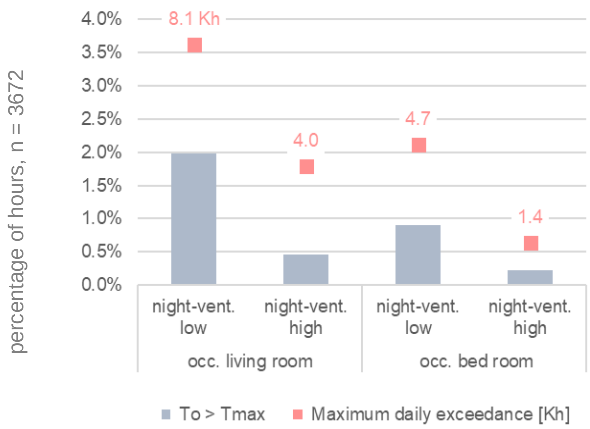


Diagram 18: CS3 - adaptive threshold

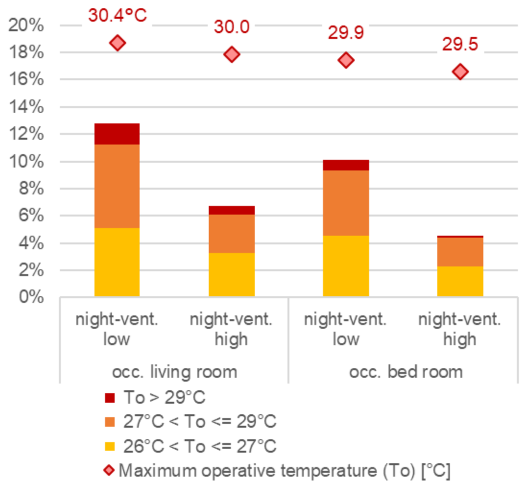
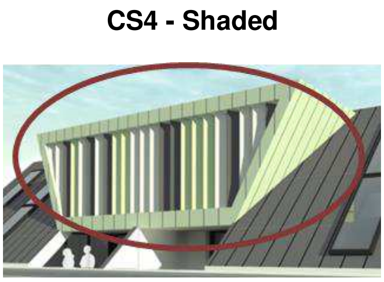


Diagram 19: CS3 - fixed threshold

Diagram 17 and *Diagram 19* both show high maximum room temperatures and critical results regarding overheating risk. Together with *Diagram 18* it can be seen that only high night-ventilation can prevent overheating. Again, the difference of the simulation evaluation methods is illustrated. The number of hours exceeding 26°C is lower compared to *CS 2*. The hours exceeding 29°C is higher, which corresponds to the hours exceeding the adaptive threshold.

Case study room 4 (CS 4) comes with a special design element, which leads to differentiated results. There are fixed shading elements in front of the south orientated façade instead of standard shading directly on the glass plane. For the detailed normative method there is only the possibility to set one shading factor for all external shading elements. In the course of the modeling for the simulation also the geometry of shading elements can be modeled exactly.



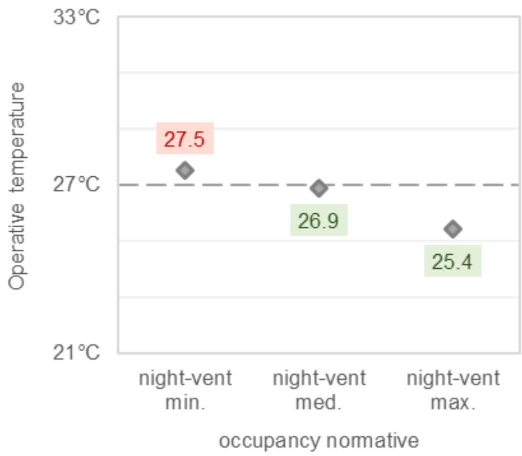


Diagram 20: CS4 - detailed method

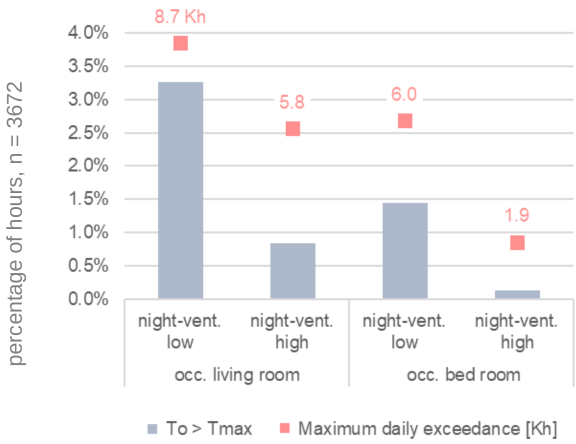


Diagram 21: CS4 - adaptive threshold

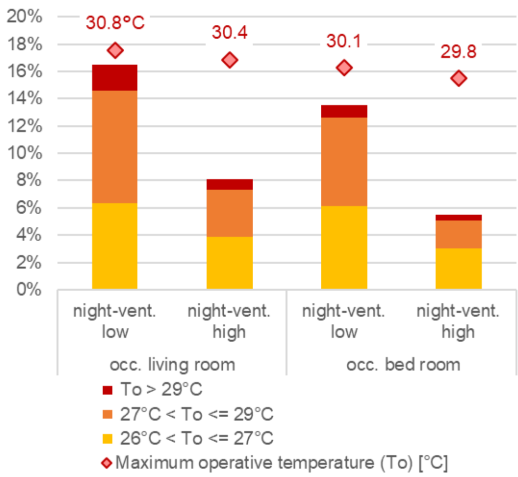


Diagram 22: CS4 - fixed threshold

Diagram 20 indicates a low overheating risk for *CS 4* according to the detailed normative method. The simulation evaluations from *Diagram 21* and *Diagram 22* result in generally high overheating risk. This **significant discrepancy** comes from a misinterpretation of the shading elements from the detailed method, which is verified through the following detailed analysis.

Figure 17 shows the plan of the *case study room 4* and the external shading slats in front of the south orientated windows. *Figure 18* represents the modeling within *SketchUp* for the dynamic simulation with *EnergyPlus*.

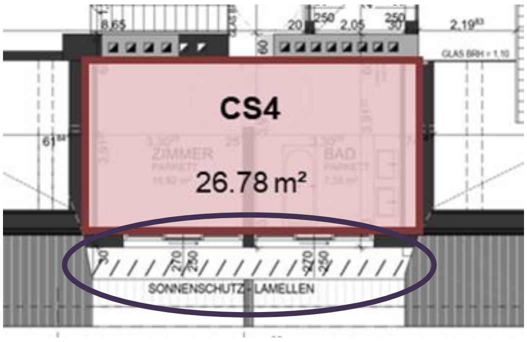


Figure 17: Shading elements CS4 - plan

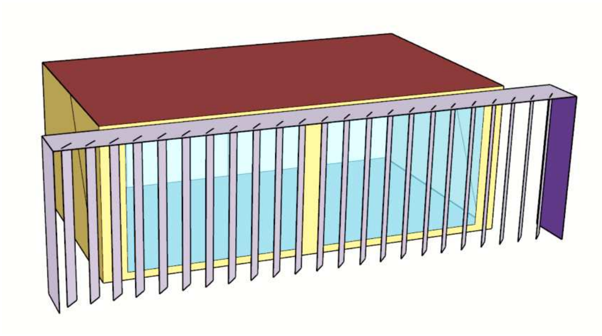


Figure 18: Shading elements CS4 - simulation model

Both pictures show that if the elements are fixed according to the plan, then there is a high shading effect in the morning and a low shading effect in the afternoon. This effect can only be simulated via dynamic simulation. The detailed normative method uses a constant shading factor during the whole day.

Diagram 23 illustrates the effect by comparing the operative room temperatures (*To*) of *CS 4* and *CS 1*. The temperature profiles are mostly parallel but only in the afternoon the room temperature of *CS 4* rises compared to *CS 1*.

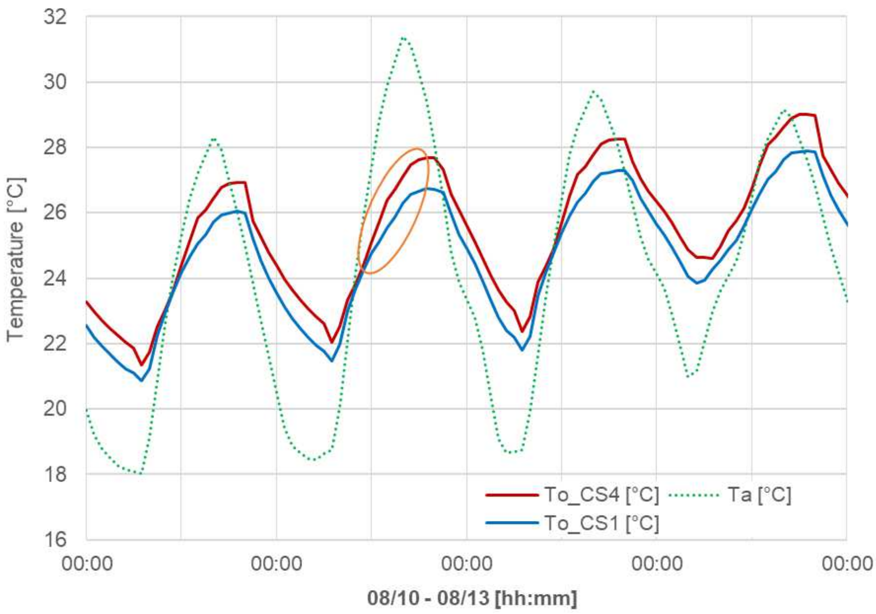


Diagram 23: Detailed analysis - shading elements CS4

4.2 Parametric Study

The parametric study calculations and simulations show the wide variety of possible results. With both methods, the detailed normative method and the dynamic simulation, 48 design variants were investigated. Each design variant was calculated with different *use case* variants and then evaluated based on different criteria depending on the methods.

4.2.1 Detailed Normative Method

For the detailed method two sets of parametric calculations were performed. Both sets imply two *use case* variants, one with *tilted* and one with *opened windows* during the night. The **first set** uses **all openable windows** of the investigated room for night-ventilation. This approach is common for normative overheating evaluation because often this *best-case scenario* is by default the only calculated variant. The **second set** uses only **one window** per design variant independently of the available openable windows. This approach intends to implement more realistic variants for better comparability.

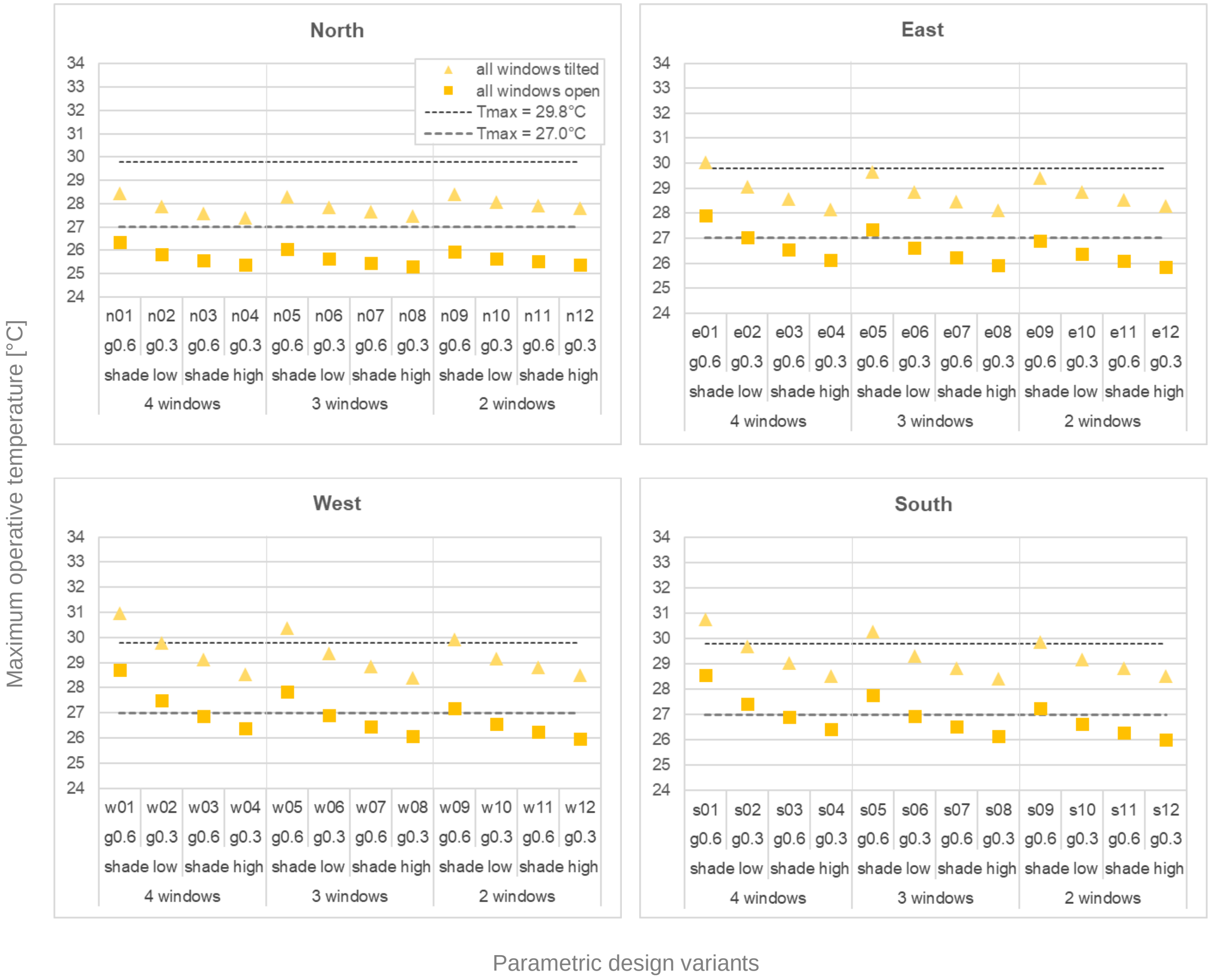


Diagram 24: Parametric study - detailed normative method - all windows tilted/opened

Diagram 24 shows the maximum operative temperature according to the detailed method for all design variants, separated in the four main orientations. There are two *use case* variants were all windows either are tilted or opened during the night. Naturally the variants with tilted windows create higher temperatures compared to the opened windows variants. Here the temperature levels mostly depend on the **orientation** (ΔT_{max} = 2.5 K) and the **shading combination** (ΔT_{max} = 2.3 K), but less on the number of windows (ΔT_{max} = 1.5 K).

For normative overheating evaluation the maximum temperatures have to be compared to the **standard threshold temperature**. The diagrams indicate the two different threshold temperatures. Firstly, the fixed 27°C limit. Secondly, the threshold temperature according to the adaptive comfort theory which is equal to 29.8°C for the investigated location. Especially for the non-standard but more realistically variants with just one opened window and also for the comparison with the simulation results the **adaptive threshold** is more valid.

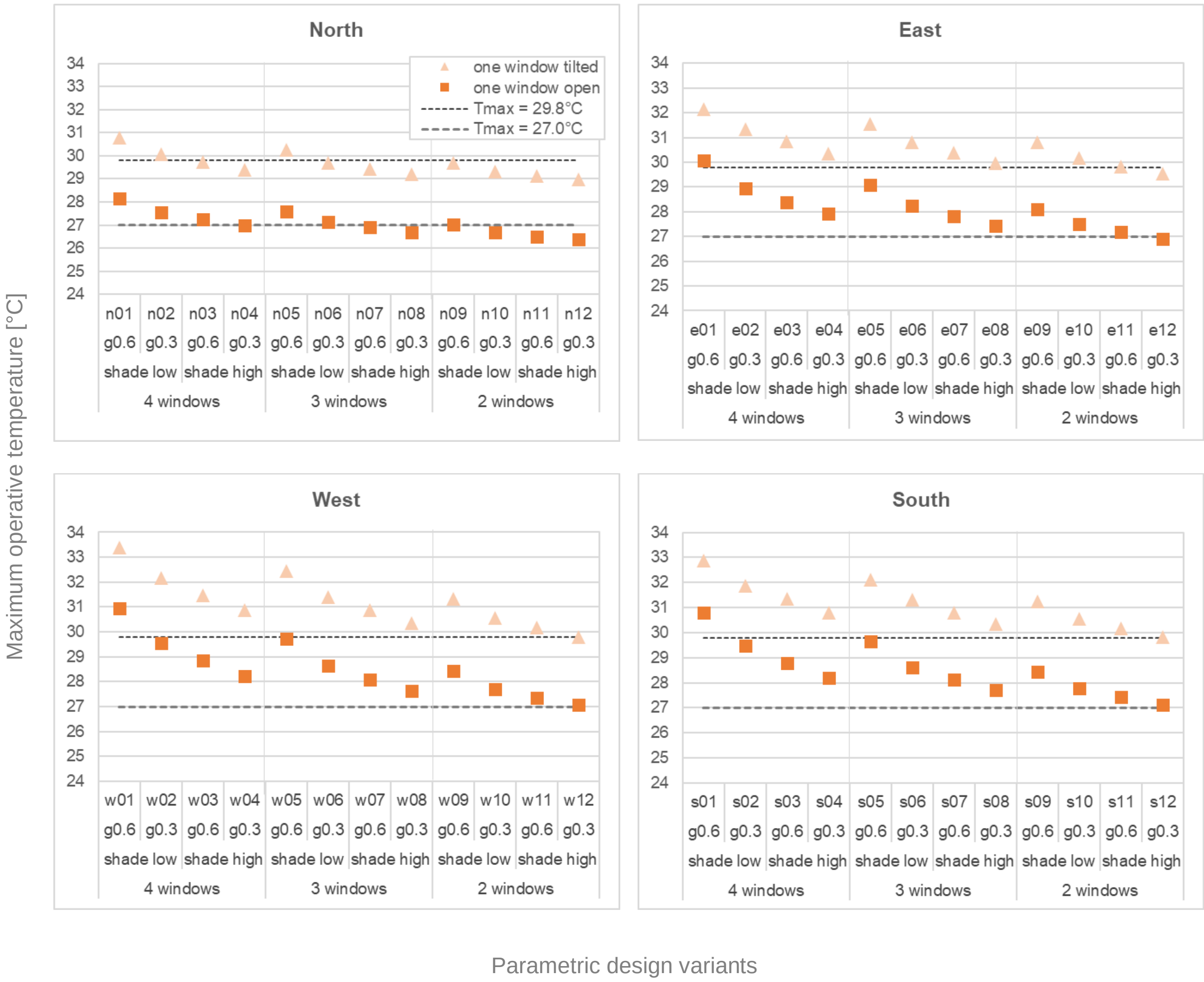


Diagram 25: Parametric study - detailed normative method - one window tilted/opened

Diagram 25 shows a clearly higher temperature level due to the lower night-ventilation effectivity compared to the first set. Again, the **shading combination** (ΔT_{max} = 2.75 K) and the **orientation** (ΔT_{max} = 2.7 K) are crucial, but here also the **number of windows** (ΔT_{max} = 2.55 K) is a main influencing parameter.

If the maximum room temperatures are compared to the fixed 27°C threshold then the only *use case* variant where most temperatures are below this limit is the one with all windows opened (*Diagram 24*). Even for this variant, the west and south orientation with low shading are critical. For the *use case one window opened* there is only the north orientation where temperatures keep below 27°C. So, for standardized normative overheating evaluation most design variants could be declared as *not overheating* if maximum night-ventilation with *all windows opened* is assumed.

Particularly for the evaluation of the more realistic *use case* variants (*Diagram 25*) the adaptive threshold is interesting. Most of the design variants with one opened window show comfortable temperatures. If nigh-ventilation with just *one tilted window* is assumed, then only the north orientated variants show comfortable maximum room temperatures below the threshold of 29.8°C.

4.2.2 Dynamic Simulation

The parametric simulations were again based on the same 48 design variants which were also used for the detailed normative method. There are also four different *use case* variants but here they are defined by the combination of two night-ventilation variants (low, high) and two occupancy variants (bed room, living room). Additionally, the weather data were variated (*standard historical* and *future RCP4.5*) for every design variant. Altogether this leads to 384 simulated variants. Each variant simulates the operative room temperature for the entire summer period from March to September (3672 hours).

Diagram 26 shows the evaluation of all simulated variants together, based on adaptive threshold statistics. Generally, the number of hours where the operative room temperature (*To*) exceeds the adaptive comfort threshold temperature ($T_{max,adapt.comf.}$) is displayed. For every design variant the two climate variants are compared. Every displayed bar represents the range of the different *use case* results, from low occupancy and high night-ventilation to high occupancy and low night-ventilation.

The results show a huge variety of the different variants, in particular for the difference due to weather data. Moreover, the variety within one climate variant and also within single design variants is remarkable. Regarding overheating evaluation, only variants without hours where the adaptive threshold is exceeded can be declared as *low* *overheating risk*. Variants with about 20 critical hours (~0.5% of the summer period) have increased but *acceptable overheating risk*. If more than 40 hourly values exceed the threshold temperature this variant shows *high overheating risk*.

For the standard weather scenario with north and east orientation mainly *low overheating risk* occurs. Increased or even *severe overheating risk* comes mainly with high glazing ratio, low shading and high *g-value*. These variants differentiate strongly due to their *use case* variants (Δh_{max} = 360). Only with the **combination of low occupancy and high night-ventilation**, the overheating risk could be acceptable (see case study results for detailed analysis of *use case* variants).

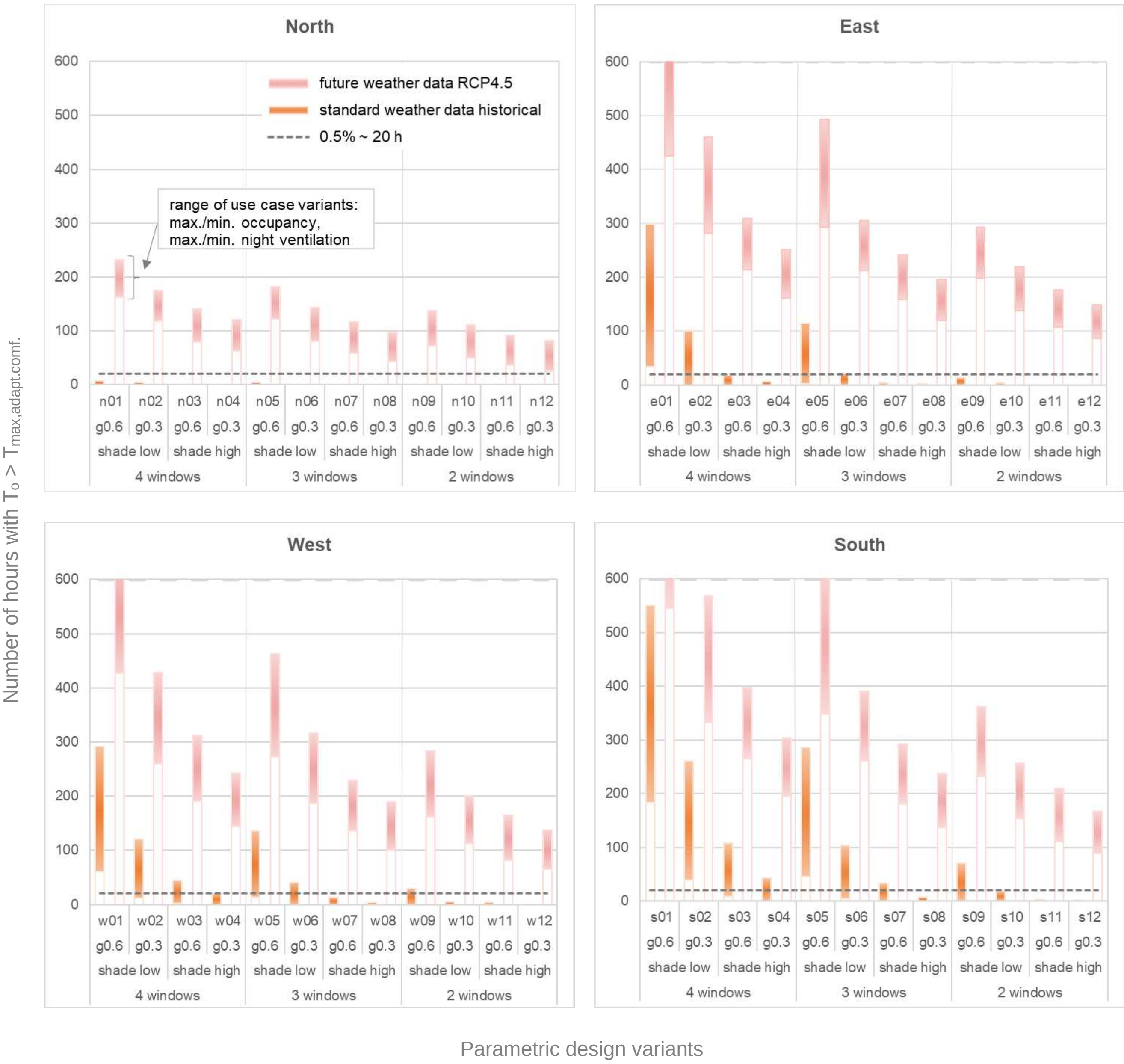


Diagram 26: Parametric study - dynamic simulation - adaptive threshold

The **future climate scenario** shows significantly different results. Only for single design variants with north orientation and small glazing ratio *acceptable overheating risk* is achieved. All other variants show **high or severe overheating risk**.

A detailed view on the *use case* variants, shows that about 50% of the total variants for the standard climate scenario indicate at least *low overheating risk*. For the future climate scenario 100% of the variants lead to overheating.

4.2.3 Comparison

Due to the different definitions of inputs and different variety of outputs, the results of the normative method and the simulation method cannot be compared directly. If the results are compared in terms of overheating evaluation, the following correlations are found. The default variant of the detailed normative method (*all windows open* - *Diagram 24*) and the average of the *use case* variants of the simulation method with standard climate scenario correlate regarding overheating risk.

Table 18: comparison - parametric study results

			4 windows				3 windows				2 windows			
		g_{tot}	0.11	0.08	0.06	0.05	0.11	0.08	0.06	0.05	0.11	0.08	0.06	0.05
detailed method	all win. opened	north	n01	n02	n03	n04	n05	n06	n07	n08	n09	n10	n11	n12
		east	e01	e02	e03	e04	e05	e06	e07	e08	e09	e10	e11	e12
		west	w01	w02	w03	w04	w05	w06	w07	w08	w09	w10	w11	w12
		south	s01	s02	s03	s04	s05	s06	s07	s08	s09	s10	s11	s12
simulation	stand. weather avarage	north	n01	n02	n03	n04	n05	n06	n07	n08	n09	n10	n11	n12
		east	e01	e02	e03	e04	e05	e06	e07	e08	e09	e10	e11	e12
		west	w01	w02	w03	w04	w05	w06	w07	w08	w09	w10	w11	w12
		south	s01	s02	s03	s04	s05	s06	s07	s08	s09	s10	s11	s12

Table 18 shows a similar number of variants resulting in overheating risk (*red*). For the detailed method there are 11 critical design variants (23% of all design variants) and for the simulation method there are 12 overheating variants (25%). The only difference is that for the normative method the west orientation is slightly more critical and for the simulations the south orientated variants are the most critical.

Another correlation arises from the comparison of the normative *one window tilted* variant (*Diagram 25*) with the most critical *use case* variant of the simulations with standard weather. This maximum *use case* variant means high internal gains and low night-ventilation and is represented by the top of the bar in *Diagram 26.* There are 75% of the simulated design variants with temperatures above the adaptive threshold (number of hours > 0). Also 77% of the design variants for the normative *use case one window tilted* show temperatures that exceed the *adaptive comfort threshold*. For an overview over all results with all *use case* variants see *Appendix A: Parametric study results.*

The correlating results show the validity of the detailed method for certain *use cases* and also the partly comparability with the dynamic simulation method. Nevertheless, also significant possible divergences can be observed for example if the different results for specific design variants are compared. *Table 19* shows the different results of one design variant (s03) due to variation of *use cases* and methods.

Table 19: Variance of results - design variant s03

s03	**normative method all windows** tilted/open	**normative method one window** tilted/open	**simulation standard weather**	**simulation future weather**
min.	26.9°C	28.8°C	7 hours 0.2 %	273 hours 7.3 %
max.	29.0°C	31.3°C	109 hours 2.9 %	399 hours 10.6 %

The table presents the variance from nominally *low overheating risk* (green) to nominally *high overheating risk* (red) for the detailed normative method and the simulation with a standard climate scenario. For the simulations with future weather all results indicate *severe overheating (dark red)*. Additionally, the different types of outputs are displayed again. The normative method results in single temperature values for the maximum operative temperature on one summer day. The dynamic simulations result in hourly overheating statistics for the whole summer period.

5 CONCLUSION

5.1 Outcome

Generally, the analysis of the Austrian normative calculation methods and dynamic simulation showed similarities as basis for valid comparisons, but also major differences that lead to discrepancies. One primary divergence is the quantity of input parameters and their level of detail. This leads to very different levels of usability for each method, but also to a different resolution and validity of the outputs. Essential are the general overheating definition and the applied criteria for the overheating assessment with the different methods.

For the practical comparison of the methods and the analysis of their outputs a case study and a parametric study were performed. The case study evaluated four specific designs of a roof top extension for residential use in Vienna. Critical preconditions such as *low thermal mass* and *high glazing ratio* unraveled the limitations of the normative methods. Moreover, the parametric study evaluated a set of 48 design variants with the detailed method and the dynamic simulation. On the one hand the correlation of the results of the different methods could be shown and on the other hand divergences occurred because of special design elements or the use of future weather data for the simulation. Below, more detailed findings regarding all methods and results are presented.

The **simple Austrian normative method** is based on simplified static calculations of thermal mass and solar radiation impact. Due to the few input parameters and only basic calculations it can be performed very quickly within a simple spreadsheet. The only output is the *thermal mass based on the immission area* and the result of the overheating evaluation is only a *yes/no* decision based on a comparison to a minimum value. The main disadvantage is that essential input parameters like outside conditions or internal gains cannot be considered. Therefore, the standard restricts the applicability to certain locations and ventilation variants (ASI 2012). Within the comparison with the detailed method this necessity was verified. A general problem is that these normative restrictions are overruled by the official building guidelines (OIB 2015). These circumstances made it possible that many buildings tend to overheat even if they were planned according to the guidelines. The case study results showed that for example a design without overheating risk according to the simple method, can lead to severe overheating according to the detailed method. Depending on the location and the night-ventilation, the calculated variance of the operative room temperature according to the detailed method is 6 K (24°C - 30°C).

Compared to the simple method, the **detailed normative method** differs mainly regarding the number and the different kind of input parameters. Moreover, a more complex calculation procedure needs to be conducted. Therefore, specific tools are available and a certain expertise is required. Mostly, this tools are integrated into software for normative energy-certification. Ambient temperatures, internal gains and hygienic airflow are examples for normative inputs based on standard values and calculations. The main variable inputs are the shading properties and the window openings for night-ventilation. There is one main output parameter, which is the hourly profile of the operative room temperature for one summer day. For normative overheating evaluation, the maximum value is compared to the fixed threshold temperature of 27°C. As stated above, the case study results show a certain variance depending on the variance of the input parameters, mainly night-ventilation. Due to the critical designs, only variants with high shading intensity and high night-ventilation effectivity result as *not overheating*. So, if in reality for example the windows are only tilted instead of opened completely, then severe overheating can occur. Therefore, realistic inputs should be used instead of only default values like maximum night-ventilation, to avoid severe underestimation of the overheating risk. The comparison with dynamic simulation, also in the course of the parametric study, shows mainly correlation of the outputs and validates the results, but only for the use of historic weather data. Special designs such as fixed shading elements lead to a major discrepancy because of the limitation of the input parameters like shading factors. Another weakness of the detailed method is the lack of variable outside condition definition. Ambient temperature for example is linked to the location but fixed and cannot be adapted. Thus, microclimate conditions and climate change scenarios cannot be analyzed and also simple worst-case analyses cannot be performed. This is a major deficiency because of the rapidly changing climate and the need to react with sophisticated building planning based on reliable evaluation methods.

Dynamic simulation methods differ significantly from normative methods. Mainly due to much more complex and dynamic calculation algorithms, variable calculation periods, vast input variation possibilities as well as due to the variance and resolution of the outputs. Therefore, specialized simulation software programs such as *EnergyPlus* have to be used. They necessarily require certain know-how for the operation and experience for proper interpretation of the results. Regarding overheating evaluation, various outputs could be considered for example different temperatures or energy and comfort parameters. Due to the limitation to residential use and the comparison to the other methods within this thesis, the evaluations focused on the operative room temperature. The simulation period was set to the whole summer period and the output time step to one hour. This leads to huge datasets and the necessity of statistical evaluations. One crucial point for overheating assessment via dynamic simulation is the evaluation criterion. A variable threshold temperature based on the adaptive comfort theory was used, according to different international standards. Despite of the different period and resolution of the outputs also the possible variation of the input parameters distinguishes the simulation method from the normative methods. This leads to the possibilities of very detailed and flexible analysis but also to variances in the results. Thus, even if the simulations are physically more accurate that does not mean that the results are more precise. Therefore, the combination of reasonable definition of the inputs, sophisticated evaluation of the outputs and conscientious interpretation of the results are essential. An advantage of the simulation method is that if the building model and the basic inputs are implemented once, then further variations can be performed very quickly. This was also shown through the parametric study simulations. The variation of window design, orientation, shading type, occupancy, night-ventilation effectiveness and weather data resulted in 384 output variants. It showed the different variations of outputs depending on the combination and influence of the inputs. The most significant finding was the effect of future weather data on the simulation results. Data for a climate scenario based on the *RCP4.5* projection including *Urban Heat Island* effects were used. For comparison, the standard weather data leads to less than 50% of overheating variants. With the future scenario 100% of the simulated variants showed *high overheating risk*. Those extreme results also derive from the worst-case scenario regarding continuous internal gains and single rooms without air- and temperature exchange to other rooms.

In summary it can be said that the simple normative method is only valid if the normative restrictions regarding its feasibility are considered. Moreover, critical design decisions and save planning with the implication of future climate changes are not possible. The detailed normative method produces valid results for standard designs, but only for one summer day with fixed normative climate data. For evaluation of climate change scenarios and heat waves, it would be necessary to adapt the normative inputs and the calculation period. Dynamic simulation shows flexibility for different kinds of overheating assessment but needs certain expertise for proper handling and interpretation. The simulation results of the different climate scenarios show that avoidance of overheating could get much more difficult in close future. Therefore, it will not be sufficient to focus on single parameters such as shading or night-ventilation. For reliable avoidance of summer overheating it will be necessary to consider and optimize all influencing parameters.

5.2 Outlook and Future Research

At the same time as this thesis was written also a new draft document of the standard *ÖNORM B 8110-3* (ASI 2018b) was released. It shows that the simple normative method will presumably no longer be part of the standard, but only the detailed method. This confirms the conclusion regarding the deficiencies of the simple method.

Also the *OIB building guideline 6* was updated (OIB 2019), but did not come into effect within any official building code so far. In the current document the simple normative method is also not mentioned anymore. The updated overheating criterion is the adaptive threshold temperature based on the location-dependent *standard mean temperature* $T_{NAT,13}$. This indicates a change of the evaluation criterion for the detailed method, which also correlates to the conclusion of this thesis.

Generally, the only evaluated output parameter within this contribution (corresponding to most normative methods) is the operative room temperature. According to the majority of studies about thermal comfort, other parameters such as humidity, air velocity, clothing and activity are also essential. For this and other studies about residential buildings in central Europe the operative temperature is clearly dominant, but due to climate change particularly the air velocity will play a bigger role, like it is already the case in warmer climate regions. Therefore, this parameter should also be implemented in overheating evaluations, for example through the adjustment of the definition of the adaptive comfort temperature.

Office buildings also have a high potential for overheating avoidance by sophisticated planning and the implementation of passive or semi-passive methods such as mechanical ventilation, which should also be part of future studies. For office buildings as well as for residential buildings semi-passive methods such as automated night-ventilation and automated shading control could help to avoid overheating in a warming climate.

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(1): Immission area for simple normative method (ASI 2012)

(2): Effective heat storage capacity (ASI 2012)

(3): Specific effective thermal mass (ASI 2012)

(4): Effective thermal mass of one construction component (ASI 2012)

(5): Thermal mass of the furniture and textiles (ASI 2012)

(6): Total effective thermal mass of one room (ASI 2012)

(7): Airflow based on immission area (ASI 2012)

(8): Airflow through opening for night-ventilation (ASI 2012)

(9): Airflow through wind and stack for dynamic simulation (DOE 2016a)

(10): Airflow through wind for dynamic simulation (DOE 2016a)

(11): Airflow through stack effect for dynamic simulation (DOE 2016a)

(12): Maximum adaptive comfort threshold temperature (CIBSE 2013)

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APPENDIX A: PARAMETRIC STUDY RESULTS

Results of detailed normative method; all variants; two different thresholds:

Variants				threshold	27°C		29.8°C		27°C		29.8°C	
					all windows				one window			
					tilted	open	tilted	open	tilted	open	tilted	open
north	4 windows	shade	g=0.6	n01	✗ 28.4	✓ 26.3	✓ 28.4	✓ 26.3	✗ 30.8	✗ 28.2	✗ 30.8	✓ 28.2
		low	g=0.3	n02	✗ 27.9	✓ 25.8	✓ 27.9	✓ 25.8	✗ 30.1	✗ 27.6	✗ 30.1	✓ 27.6
		shade	g=0.6	n03	✗ 27.6	✓ 25.6	✓ 27.6	✓ 25.6	✗ 29.7	✗ 27.3	✓ 29.7	✓ 27.3
		high	g=0.3	n04	✗ 27.4	✓ 25.4	✓ 27.4	✓ 25.4	✗ 29.4	✓ 27.0	✓ 29.4	✓ 27.0
	3 windows	shade	g=0.6	n05	✗ 28.3	✓ 26.0	✓ 28.3	✓ 26.0	✗ 30.3	✗ 27.6	✗ 30.3	✓ 27.6
		low	g=0.3	n06	✗ 27.9	✓ 25.6	✓ 27.9	✓ 25.6	✗ 29.7	✗ 27.1	✓ 29.7	✓ 27.1
		shade	g=0.6	n07	✗ 27.7	✓ 25.5	✓ 27.7	✓ 25.5	✗ 29.4	✓ 26.9	✓ 29.4	✓ 26.9
		high	g=0.3	n08	✗ 27.5	✓ 25.3	✓ 27.5	✓ 25.3	✗ 29.2	✓ 26.7	✓ 29.2	✓ 26.7
	2 windows	shade	g=0.6	n09	✗ 28.4	✓ 25.9	✓ 28.4	✓ 25.9	✗ 29.7	✗ 27.0	✓ 29.7	✓ 27.0
		low	g=0.3	n10	✗ 28.1	✓ 25.6	✓ 28.1	✓ 25.6	✗ 29.3	✓ 26.7	✓ 29.3	✓ 26.7
		shade	g=0.6	n11	✗ 27.9	✓ 25.5	✓ 27.9	✓ 25.5	✗ 29.1	✓ 26.5	✓ 29.1	✓ 26.5
		high	g=0.3	n12	✗ 27.8	✓ 25.4	✓ 27.8	✓ 25.4	✗ 29.0	✓ 26.4	✓ 29.0	✓ 26.4
east	4 windows	shade	g=0.6	e01	✗ 30.0	✗ 27.9	✗ 30.0	✓ 27.9	✗ 32.1	✗ 30.1	✗ 32.1	✗ 30.1
		low	g=0.3	e02	✗ 29.1	✗ 27.0	✓ 29.1	✓ 27.0	✗ 31.4	✗ 28.9	✗ 31.4	✓ 28.9
		shade	g=0.6	e03	✗ 28.6	✓ 26.5	✓ 28.6	✓ 26.5	✗ 30.9	✗ 28.4	✗ 30.9	✓ 28.4
		high	g=0.3	e04	✗ 28.1	✓ 26.1	✓ 28.1	✓ 26.1	✗ 30.4	✗ 27.9	✗ 30.4	✓ 27.9
	3 windows	shade	g=0.6	e05	✗ 29.6	✗ 27.4	✓ 29.6	✓ 27.4	✗ 31.6	✗ 29.1	✗ 31.6	✓ 29.1
		low	g=0.3	e06	✗ 28.9	✓ 26.6	✓ 28.9	✓ 26.6	✗ 30.8	✗ 28.2	✗ 30.8	✓ 28.2
		shade	g=0.6	e07	✗ 28.5	✓ 26.2	✓ 28.5	✓ 26.2	✗ 30.4	✗ 27.8	✗ 30.4	✓ 27.8
		high	g=0.3	e08	✗ 28.1	✓ 25.9	✓ 28.1	✓ 25.9	✗ 30.0	✗ 27.4	✗ 30.0	✓ 27.4
	2 windows	shade	g=0.6	e09	✗ 29.4	✓ 26.9	✓ 29.4	✓ 26.9	✗ 30.8	✗ 28.1	✗ 30.8	✓ 28.1
		low	g=0.3	e10	✗ 28.8	✓ 26.4	✓ 28.8	✓ 26.4	✗ 30.2	✗ 27.5	✗ 30.2	✓ 27.5
		shade	g=0.6	e11	✗ 28.5	✓ 26.1	✓ 28.5	✓ 26.1	✗ 29.8	✗ 27.2	✗ 29.8	✓ 27.2
		high	g=0.3	e12	✗ 28.3	✓ 25.8	✓ 28.3	✓ 25.8	✗ 29.5	✓ 26.9	✓ 29.5	✓ 26.9
west	4 windows	shade	g=0.6	w01	✗ 31.0	✗ 28.7	✗ 31.0	✓ 28.7	✗ 33.4	✗ 30.9	✗ 33.4	✗ 30.9
		low	g=0.3	w02	✗ 29.8	✗ 27.5	✓ 29.8	✓ 27.5	✗ 32.2	✗ 29.6	✗ 32.2	✓ 29.6
		shade	g=0.6	w03	✗ 29.1	✓ 26.9	✓ 29.1	✓ 26.9	✗ 31.5	✗ 28.8	✗ 31.5	✓ 28.8
		high	g=0.3	w04	✗ 28.6	✓ 26.4	✓ 28.6	✓ 26.4	✗ 30.9	✗ 28.2	✗ 30.9	✓ 28.2
	3 windows	shade	g=0.6	w05	✗ 30.4	✗ 27.8	✗ 30.4	✓ 27.8	✗ 32.4	✗ 29.7	✗ 32.4	✓ 29.7
		low	g=0.3	w06	✗ 29.4	✓ 26.9	✓ 29.4	✓ 26.9	✗ 31.4	✗ 28.6	✗ 31.4	✓ 28.6
		shade	g=0.6	w07	✗ 28.9	✓ 26.5	✓ 28.9	✓ 26.5	✗ 30.9	✗ 28.1	✗ 30.9	✓ 28.1
		high	g=0.3	w08	✗ 28.4	✓ 26.1	✓ 28.4	✓ 26.1	✗ 30.4	✗ 27.6	✗ 30.4	✓ 27.6
	2 windows	shade	g=0.6	w09	✗ 29.9	✗ 27.2	✗ 29.9	✓ 27.2	✗ 31.3	✗ 28.4	✗ 31.3	✓ 28.4
		low	g=0.3	w10	✗ 29.2	✓ 26.6	✓ 29.2	✓ 26.6	✗ 30.6	✗ 27.7	✗ 30.6	✓ 27.7
		shade	g=0.6	w11	✗ 28.8	✓ 26.2	✓ 28.8	✓ 26.2	✗ 30.2	✗ 27.4	✗ 30.2	✓ 27.4
		high	g=0.3	w12	✗ 28.5	✓ 26.0	✓ 28.5	✓ 26.0	✗ 29.8	✗ 27.1	✓ 29.8	✓ 27.1
south	4 windows	shade	g=0.6	s01	✗ 30.8	✗ 28.6	✗ 30.8	✓ 28.6	✗ 32.9	✗ 30.8	✗ 32.9	✗ 30.8
		low	g=0.3	s02	✗ 29.7	✗ 27.4	✓ 29.7	✓ 27.4	✗ 31.9	✗ 29.5	✗ 31.9	✓ 29.5
		shade	g=0.6	s03	✗ 29.0	✓ 26.9	✓ 29.0	✓ 26.9	✗ 31.3	✗ 28.8	✗ 31.3	✓ 28.8
		high	g=0.3	s04	✗ 28.5	✓ 26.4	✓ 28.5	✓ 26.4	✗ 30.8	✗ 28.2	✗ 30.8	✓ 28.2
	3 windows	shade	g=0.6	s05	✗ 30.3	✗ 27.8	✗ 30.3	✓ 27.8	✗ 32.1	✗ 29.7	✗ 32.1	✓ 29.7
		low	g=0.3	s06	✗ 29.3	✓ 27.0	✓ 29.3	✓ 27.0	✗ 31.3	✗ 28.6	✗ 31.3	✓ 28.6
		shade	g=0.6	s07	✗ 28.8	✓ 26.5	✓ 28.8	✓ 26.5	✗ 30.8	✗ 28.1	✗ 30.8	✓ 28.1
		high	g=0.3	s08	✗ 28.4	✓ 26.1	✓ 28.4	✓ 26.1	✗ 30.3	✗ 27.7	✗ 30.3	✓ 27.7
	2 windows	shade	g=0.6	s09	✗ 29.9	✗ 27.2	✗ 29.9	✓ 27.2	✗ 31.3	✗ 28.4	✗ 31.3	✓ 28.4
		low	g=0.3	s10	✗ 29.2	✓ 26.6	✓ 29.2	✓ 26.6	✗ 30.6	✗ 27.8	✗ 30.6	✓ 27.8
		shade	g=0.6	s11	✗ 28.8	✓ 26.3	✓ 28.8	✓ 26.3	✗ 30.2	✗ 27.4	✗ 30.2	✓ 27.4
		high	g=0.3	s12	✗ 28.5	✓ 26.0	✓ 28.5	✓ 26.0	✗ 29.8	✗ 27.1	✗ 29.8	✓ 27.1
				percentage	✓ 0%	✓ 77%	✓ 85%	✓ 100%	✓ 0%	✓ 15%	✓ 23%	✓ 94%
					✗ 100%	✗ 23%	✗ 15%	✗ 0%	✗ 100%	✗ 85%	✗ 77%	✗ 6%

Results of dynamic simulations; all variants:

				threshold	Tmax,adapt.comf.: 0% of hours							
					standard weather				future weather			
Variants					occ. bedroom		occ. living room		occ. bedroom		occ. living room	
					V_low	V_high	V_low	V_high	V_low	V_high	V_low	V_high
north	4 windows	shade low	g=0.6	n01	✔ 0.0	✔ 0.0	✘ 0.1	✔ 0.0	✘ 4.6	✘ 4.4	✘ 6.3	✘ 5.7
			g=0.3	n02	✔ 0.0	✔ 0.0	✘ 0.1	✔ 0.0	✘ 3.4	✘ 3.2	✘ 4.8	✘ 4.6
		shade high	g=0.6	n03	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 2.2	✘ 2.2	✘ 3.8	✘ 3.7
			g=0.3	n04	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 1.8	✘ 1.7	✘ 3.3	✘ 3.1
	3 windows	shade low	g=0.6	n05	✔ 0.0	✔ 0.0	✘ 0.1	✔ 0.0	✘ 3.5	✘ 3.3	✘ 5.0	✘ 4.7
			g=0.3	n06	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 2.3	✘ 2.2	✘ 3.9	✘ 3.8
		shade high	g=0.6	n07	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 1.7	✘ 1.6	✘ 3.2	✘ 3.0
			g=0.3	n08	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 1.3	✘ 1.2	✘ 2.7	✘ 2.5
	2 windows	shade low	g=0.6	n09	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 2.1	✘ 2.0	✘ 3.7	✘ 3.6
			g=0.3	n10	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 1.5	✘ 1.4	✘ 3.1	✘ 2.9
		shade high	g=0.6	n11	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 1.1	✘ 1.0	✘ 2.5	✘ 2.4
			g=0.3	n12	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 0.8	✘ 0.7	✘ 2.2	✘ 2.0
east	4 windows	shade low	g=0.6	e01	✘ 5.5	✘ 0.9	✘ 8.1	✘ 2.2	✘ 18.3	✘ 11.6	✘ 20.5	✘ 14.2
			g=0.3	e02	✘ 0.7	✔ 0.0	✘ 2.7	✘ 0.1	✘ 9.5	✘ 7.7	✘ 12.5	✘ 9.3
		shade high	g=0.6	e03	✘ 0.1	✔ 0.0	✘ 0.5	✘ 0.1	✘ 6.3	✘ 5.8	✘ 8.4	✘ 7.2
			g=0.3	e04	✔ 0.0	✔ 0.0	✘ 0.2	✔ 0.0	✘ 4.5	✘ 4.4	✘ 6.8	✘ 6.1
	3 windows	shade low	g=0.6	e05	✘ 1.0	✘ 0.1	✘ 3.1	✘ 0.3	✘ 10.3	✘ 8.0	✘ 13.4	✘ 10.0
			g=0.3	e06	✘ 0.1	✔ 0.0	✘ 0.6	✘ 0.1	✘ 6.3	✘ 5.8	✘ 8.3	✘ 7.2
		shade high	g=0.6	e07	✔ 0.0	✔ 0.0	✘ 0.1	✔ 0.0	✘ 4.5	✘ 4.3	✘ 6.6	✘ 6.0
			g=0.3	e08	✔ 0.0	✔ 0.0	✘ 0.1	✔ 0.0	✘ 3.5	✘ 3.3	✘ 5.3	✘ 4.9
	2 windows	shade low	g=0.6	e09	✘ 0.1	✔ 0.0	✘ 0.4	✔ 0.0	✘ 5.9	✘ 5.4	✘ 8.0	✘ 7.0
			g=0.3	e10	✔ 0.0	✔ 0.0	✘ 0.1	✔ 0.0	✘ 4.0	✘ 3.8	✘ 6.0	✘ 5.4
		shade high	g=0.6	e11	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 3.1	✘ 2.9	✘ 4.8	✘ 4.4
			g=0.3	e12	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 2.4	✘ 2.4	✘ 4.1	✘ 3.8
west	4 windows	shade low	g=0.6	w01	✘ 6.0	✘ 1.7	✘ 8.0	✘ 3.1	✘ 15.7	✘ 11.6	✘ 17.8	✘ 13.4
			g=0.3	w02	✘ 1.5	✘ 0.3	✘ 3.3	✘ 0.7	✘ 9.3	✘ 7.1	✘ 11.7	✘ 9.0
		shade high	g=0.6	w03	✘ 0.4	✘ 0.1	✘ 1.2	✘ 0.2	✘ 6.2	✘ 5.2	✘ 8.5	✘ 6.7
			g=0.3	w04	✘ 0.1	✔ 0.0	✘ 0.5	✘ 0.1	✘ 4.6	✘ 3.9	✘ 6.6	✘ 5.8
	3 windows	shade low	g=0.6	w05	✘ 1.6	✘ 0.4	✘ 3.7	✘ 0.8	✘ 9.7	✘ 7.4	✘ 12.6	✘ 9.3
			g=0.3	w06	✘ 0.3	✔ 0.0	✘ 1.1	✘ 0.2	✘ 6.0	✘ 5.1	✘ 8.6	✘ 6.8
		shade high	g=0.6	w07	✘ 0.1	✔ 0.0	✘ 0.4	✘ 0.0	✘ 4.3	✘ 3.7	✘ 6.2	✘ 5.5
			g=0.3	w08	✔ 0.0	✔ 0.0	✘ 0.1	✔ 0.0	✘ 2.9	✘ 2.7	✘ 5.1	✘ 4.5
	2 windows	shade low	g=0.6	w09	✘ 0.1	✔ 0.0	✘ 0.8	✘ 0.1	✘ 5.2	✘ 4.4	✘ 7.7	✘ 6.3
			g=0.3	w10	✔ 0.0	✔ 0.0	✘ 0.1	✔ 0.0	✘ 3.3	✘ 3.1	✘ 5.4	✘ 4.9
		shade high	g=0.6	w11	✔ 0.0	✔ 0.0	✘ 0.1	✔ 0.0	✘ 2.4	✘ 2.2	✘ 4.5	✘ 3.9
			g=0.3	w12	✔ 0.0	✔ 0.0	✔ 0.0	✔ 0.0	✘ 2.0	✘ 1.8	✘ 3.8	✘ 3.4
south	4 windows	shade low	g=0.6	s01	✘ 13.1	✘ 5.0	✘ 15.0	✘ 7.1	✘ 22.7	✘ 14.8	✘ 25.0	✘ 17.4
			g=0.3	s02	✘ 4.6	✘ 1.1	✘ 7.1	✘ 1.8	✘ 12.4	✘ 9.0	✘ 15.5	✘ 11.1
		shade high	g=0.6	s03	✘ 1.2	✘ 0.2	✘ 2.9	✘ 0.6	✘ 8.3	✘ 7.2	✘ 10.8	✘ 8.6
			g=0.3	s04	✘ 0.2	✔ 0.0	✘ 1.2	✘ 0.2	✘ 6.2	✘ 5.3	✘ 8.3	✘ 7.1
	3 windows	shade low	g=0.6	s05	✘ 5.3	✘ 1.3	✘ 7.8	✘ 2.0	✘ 13.4	✘ 9.4	✘ 16.7	✘ 11.8
			g=0.3	s06	✘ 1.0	✘ 0.1	✘ 2.8	✘ 0.5	✘ 8.1	✘ 7.1	✘ 10.6	✘ 8.4
		shade high	g=0.6	s07	✘ 0.1	✔ 0.0	✘ 0.9	✘ 0.1	✘ 5.8	✘ 4.9	✘ 8.0	✘ 6.9
			g=0.3	s08	✔ 0.0	✔ 0.0	✘ 0.2	✔ 0.0	✘ 4.0	✘ 3.7	✘ 6.5	✘ 5.7
	2 windows	shade low	g=0.6	s09	✘ 0.6	✔ 0.0	✘ 1.9	✘ 0.2	✘ 7.3	✘ 6.3	✘ 9.9	✘ 7.9
			g=0.3	s10	✘ 0.0	✔ 0.0	✘ 0.5	✔ 0.0	✘ 4.7	✘ 4.2	✘ 7.0	✘ 6.1
		shade high	g=0.6	s11	✔ 0.0	✔ 0.0	✘ 0.1	✔ 0.0	✘ 3.2	✘ 3.0	✘ 5.7	✘ 5.0
			g=0.3	s12	✔ 0.0	✔ 0.0	✘ 0.1	✔ 0.0	✘ 2.5	✘ 2.4	✘ 4.5	✘ 4.0
		percentage			✔ 52%	✔ 77%	25%	✔ 56%	✔ 0%	✔ 0%	0%	✔ 0%
					✘ 48%	✘ 23%	75%	✘ 44%	✘ 100%	✘ 100%	100%	✘ 100%

APPENDIX B: PSEUDOCODE DETAILED METHOD

Comprehensive representation of the calculation procedure of the prototype tool for the detailed normative method. (Nackler 2017)

```
/* Außentemperatur; Mittelwert NAT−T13, Schwankung öN B 8110−3 A.1 */
Ermittle_Te();

/* Stündliche solare Bestrahlungsstärken nach öN B 8110−3 A.2 als auch stündl.
   effektive Außentemperatur jeder Außenbauteilfläche für jede Orientierung und
   Neigung: TeEff nach Formeln 4.1 */
Ermittle_ILSol();
Ermittle_TeEff();

/* Stündlich festgelegte Werte int. Lasten für Personen und Geräte einlesen */
Ermittle_ILper_ILger();

/* Wirksame Wärmekapazitäten aller Bauteile Innen und Außen (24h Periode) */
Ermittle_KapBautI();
Ermittle_KapBautE();

/* Wirksame Wärmekapazität der Einrichtung; A_NF = Nettoraumfläche */
KapEinr = A_NF * 38 * 1024.8;

/* Tair = Trad = Top = alle TiSurf = alle TeSurf = 20 */
Initialisiere_StartTemperaturen();

/* Uebergangskoeffizienten innen Konvektion und Strahlung, außen gesamt */
hic = 2.5; hir = 5; he = 25;

/* Verteilungsfaktoren */
CFsol = 0.1; CFger = 0.5; CFper = 0.5;

/* Hauptschleife: Wiederholung bis deltaTrad < 0.0001 und deltaTair < 0.0001 */
WIEDERHOLE im 10s Zeitschritt bis eingeschwungener Zustand {

    /* Summe der über sämtliche Fenster linear interpolierten Globalstrahlung
       zum akt. Zeitschritt unter Berücksichtigung von (Glas−)Fläche, g−Wert
       und entweder Sonnenschutz (Fc) oder Reduktion des Strahlungstransmis−
       sionsgrads per Exponent Epsilon */
    Ermittle_ILsol_akt();

    /* Wärmestrom zuf. Konvektion Innere Lasten (Solar, Geräte, Personen) */
    qILc_akt = ILsol_akt*CFsol + ILger_akt*CFger + ILper_akt*CFper;

    /* Wärmestrom zuf. Strahlung Innere Lasten (Solar, Geräte, Personen) */
    qILr_akt = ILsol_akt*(1-CFsol) + ILger_akt*(1-CFger) +
               + ILper_akt*(1-CFper);

    /* Wärmestrom zuf. Konv. innen; qBautic = hic * ABaut * (Tair−TiSurf),
       für jedes Bauteil durchzuführen; ABaut = Bauteilfläche;
       qBaut = Wärmestrom konvektiver Anteil über alle BT */
    Ermittle_qBautic();
    qBaut = -1 * (SumAll(qBautic));

    /* Wärmestrom zuf. Strahlung innen; qBautir = hir*ABaut*(Trad−TiSurf),
       für jedes Bauteil durchzuführen */
    Ermittle_qBautir();

```

```
    /* Wärmestrom zuf. Konv. und Strahlung außen; für jedes BT durchzuf.,
       qBaute = he*ABaut * (TeEff_akt−TeSurf) oder wenn adiabat
       qBaute = hic*ABaut * (Tair−TeSurf) + hir*ABaut * (Trad−TeSurf) */
    Ermittle_qBaute();

    /* Wärmestrom zuf. Transmission qBautk = KBaut*ABaut*(TiSurf−TeSurf),
       für jedes Bauteil durchzuführen; KBaut = Wärmedurchgangswiderstand */
    Ermittle_qBautk();

    /* Volumenstrom nat. Lüftung nach öN B 8110−3 Anh. B; Wenn ganz geöffnet
       Z.B. 0.7*100*fen_B*fen_H*Sqr(fen_Heff)*Sqr(Abs(Tair−Te_akt))
       Summe über alle Oeffnungen + Infiltration + notwendiger hyg. VolStr;
       dann Wärmestrom zufolge Luftvolumenstrom ermitteln */
    Ermittle_VolStr();
    qVent = 0.34 * VolStr * (Te_akt - Tair);

    /* Effektive Fenster Innentemperatur nach Formel 4.2 */
    TFen_i = Tair + hir / (hir + hic) * (Trad - Tair);
    /* Eff. Fenster Aussentemperaturn nach Formel 4.3; für alle SF durchzuf.
       TFen_e = Te_akt + 0.84 * 5.6/(he) * (SF_W * Tsky_akt +
       + (1−SF_W) * Te_akt−Te_akt); Tsky_akt=Te_akt−10; SF_W=0.5 */
    Ermittle_TFen_e();
    /* Fenstertemperatur für weitere Berechnung des Wärmestroms;
       TFen = TFen_i − (TFen_i − TFen_e) * UFen * (1/(hic + hir)),
       für alle 4 Fensterrichtungen durchzuführen; UFen = Uw−Wert */
    Ermittle_TFen();
    /* Wärmestrom aufgrund Fenstertemperatur; Summe über alle Fenster */
    qFen = SumAll(AFen * hic * (TFen - Tair));

    /* Luftknotentemperatur; Lüftungsanlage weggelassen;  zeitschritt  = 10  */
    Tair = Tair + (qILc_akt+qBaut+qVent+qFen) / KapEinr * zeitschritt;

    /* Strahlungstemperatur, Summe über alle BT */
    Trad = [SumAll(TiSurf * ABaut) + SumAll(TFen * AFen)+
         + qILr_akt/hir] / ABautges;

    /* Bauteilinnentemperatur für nächsten Zeitschritt berechnen (für alle BT)
       TiSurf = TiSurf + (qBautic+qBautir−qBautk) / KapBauti * zeitschritt */
    Ermittle_TiSurf();

    /* Bauteilaussentemperatur für nächsten Zeitschritt berechnen (für alle BT)
       TeSurf = TeSurf + (qBaute + qBautk) / KapBaute * zeitschritt */
    Ermittle_TeSurf();

    /* Operative Temperatur, Mittel aus Luft− und Strahlungstemperatur */
    Top = 0.5 * (Tair + Trad);

} WIEDERHOLE_ENDE
```

APPENDIX C: OUTPUTS ENERGYPLUS

Representative selection of a set of over 400 outputs (DOE 2016c):

Output:Variable,*,Site Outdoor Air Drybulb Temperature,hourly; !- Zone Average [C]

Output:Variable,*,Site Outdoor Air Humidity Ratio,hourly; !- Zone Average [kgWater/kgDryAir]

Output:Variable,*,Site Outdoor Air Relative Humidity,hourly; !- Zone Average [%]

Output:Variable,*,Site Wind Speed,hourly; !- Zone Average [m/s]

Output:Variable,*,Site Wind Direction,hourly; !- Zone Average [deg]

Output:Variable,*,Site Sky Temperature,hourly; !- Zone Average [C]

Output:Variable,*,Site Horizontal Infrared Radiation Rate per Area,hourly; !- Zone Average [W/m2]

Output:Variable,*,Site Diffuse Solar Radiation Rate per Area,hourly; !- Zone Average [W/m2]

Output:Variable,*,Site Direct Solar Radiation Rate per Area,hourly; !- Zone Average [W/m2]

Output:Variable,*,Site Precipitation Depth,hourly; !- Zone Sum [m]

Output:Variable,*,Site Ground Reflected Solar Radiation Rate per Area,hourly; !- Zone Average [W/m2]

Output:Variable,*,Site Ground Temperature,hourly; !- Zone Average [C]

Output:Variable,*,Site Surface Ground Temperature,hourly; !- Zone Average [C]

Output:Variable,*,Site Deep Ground Temperature,hourly; !- Zone Average [C]

Output:Variable,*,Site Simple Factor Model Ground Temperature,hourly; !- Zone Average [C]

Output:Variable,*,Site Outdoor Air Enthalpy,hourly; !- Zone Average [J/kg]

Output:Variable,*,Site Outdoor Air Density,hourly; !- Zone Average [kg/m3]

Output:Variable,*,Site Solar Azimuth Angle,hourly; !- Zone Average [deg]

Output:Variable,*,Site Solar Altitude Angle,hourly; !- Zone Average [deg]

Output:Variable,*,Site Solar Hour Angle,hourly; !- Zone Average [deg]

Output:Variable,*,Site Rain Status,hourly; !- Zone Average []

Output:Variable,*,Site Snow on Ground Status,hourly; !- Zone Average []

Output:Variable,*,Site Exterior Horizontal Sky Illuminance,hourly; !- Zone Average [lux]

Output:Variable,*,Site Exterior Horizontal Beam Illuminance,hourly; !- Zone Average [lux]

Output:Variable,*,Site Exterior Beam Normal Illuminance,hourly; !- Zone Average [lux]

Output:Variable,*,Site Sky Diffuse Solar Radiation Luminous Efficacy,hourly; !- Zone Average [lum/W]

Output:Variable,*,Site Beam Solar Radiation Luminous Efficacy,hourly; !- Zone Average [lum/W]

Output:Variable,*,Site Daylighting Model Sky Clearness,hourly; !- Zone Average []

Output:Variable,*,Site Daylighting Model Sky Brightness,hourly; !- Zone Average []

Output:Variable,*,Site Daylight Saving Time Status,hourly; !- Zone Average []

Output:Variable,*,Site Day Type Index,hourly; !- Zone Average []

Output:Variable,*,Site Mains Water Temperature,hourly; !- Zone Average [C]

Output:Variable,*,Zone Outdoor Air Drybulb Temperature,hourly; !- Zone Average [C]

Output:Variable,*,Zone Outdoor Air Wetbulb Temperature,hourly; !- Zone Average [C]

Output:Variable,*,Zone Outdoor Air Wind Speed,hourly; !- Zone Average [m/s]

Output:Variable,*,Zone Total Internal Radiant Heating Energy,hourly; !- Zone Sum [J]

Output:Variable,*,Zone Total Internal Radiant Heating Rate,hourly; !- Zone Average [W]

Output:Variable,*,Zone Total Internal Visible Radiation Heating Energy,hourly; !- Zone Sum [J]

Output:Variable,*,Zone Total Internal Visible Radiation Heating Rate,hourly; !- Zone Average [W]

Output:Variable,*,Zone Total Internal Convective Heating Energy,hourly; !- Zone Sum [J]

Output:Variable,*,Zone Total Internal Convective Heating Rate,hourly; !- Zone Average [W]

Output:Variable,*,Zone Total Internal Latent Gain Energy,hourly; !- Zone Sum [J]

Output:Variable,*,Zone Total Internal Latent Gain Rate,hourly; !- Zone Average [W]

Output:Variable,*,Zone Total Internal Total Heating Energy,hourly; !- Zone Sum [J]

Output:Variable,*,Zone Total Internal Total Heating Rate,hourly; !- Zone Average [W]

Output:Variable,*,Zone People Total Heating Energy,hourly; !- Zone Sum [J]

Output:Variable,*,Zone People Total Heating Rate,hourly; !- Zone Average [W]

Output:Variable,*,Electric Equipment Electric Power,hourly; !- Zone Average [W]

Output:Variable,*,Electric Equipment Electric Energy,hourly; !- Zone Sum [J]

Output:Variable,*,Surface Outside Face Sunlit Area,hourly; !- Zone Average [m2]

Output:Variable,*,Surface Outside Face Sunlit Fraction,hourly; !- Zone Average []

Output:Variable,*,Surface Outside Face Incident Solar Radiation Rate per Area,hourly; !- Zone Average [W/m2]

Output:Variable,*,Surface Window Total Glazing Layers Absorbed Solar Radiation Rate,hourly; !- Zone Average [W]

Output:Variable,*,Surface Inside Face Absorbed Shortwave Radiation Rate,hourly; !- Zone Average [W]

Output:Variable,*,Surface Shading Device Is On Time Fraction,hourly; !- Zone Average []

Output:Variable,*,Zone Ventilation Sensible Heat Loss Energy,hourly; !- HVAC Sum [J]

Output:Variable,*,Zone Ventilation Sensible Heat Gain Energy,hourly; !- HVAC Sum [J]

Output:Variable,*,Zone Air Temperature,hourly; !- HVAC Average [C]

Output:Variable,*,Zone Thermostat Air Temperature,hourly; !- HVAC Average [C]

Output:Variable,*,Zone Air Humidity Ratio,hourly; !- HVAC Average []

Output:Variable,*,Zone Ideal Loads Supply Air Sensible Heating Energy,hourly; !- HVAC Sum [J]

Output:Variable,*,Zone Ideal Loads Supply Air Latent Heating Energy,hourly; !- HVAC Sum [J]

Output:Variable,*,Facility Total Purchased Electric Power,hourly; !- HVAC Average [W]

Output:Variable,*,Environmental Impact Total CO2 Emissions Carbon Equivalent Mass,hourly; !- HVAC Sum [kg]

Output:Variable,*,Zone Mechanical Ventilation No Load Heat Removal Energy,hourly; !- HVAC Sum [J]

Output:Variable,*,Zone Mechanical Ventilation Cooling Load Increase Energy,hourly; !- HVAC Sum [J]

Output:Variable,*,Zone Mechanical Ventilation Air Changes per Hour,hourly; !- HVAC Average [ach]