ANALYSIS OF ECONOMIC VIABILITY OF PERSONAL CEILING FANS USING BUILDING SIMULATION

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Abstract

The present work addresses the question of economic viability of ceiling fans in comparison to different cooling concepts for office buildings. An office building in southern Germany that had been refurbished and supplied with a night ventilation system and ceiling fans was modelled. This model was used to compute the parameters to evaluate the indoor air. Occupant behaviour for working hours, window opening behaviour, and ceiling fan usage was deduced from available models and monitoring data. The available data for the inside air temperature served the calibration process of unknown parameters and the validation of the whole model. Four different concepts were implemented to the model: night ventilation with ceiling fans, as installed in the examined building, air-conditioning system, night ventilation without ceiling fans, and a system with no cooling or ventilation. Processing the simulation results, thermal discomfort hours due to warm indoor temperatures in the building was assessed. Namely, the predicted mean vote (PMV) and thermal sensation vote (TSV) were calculated and compared amongst the different concepts. A productivity evaluation depending on the indoor air climate served the overall economic assessment. Together with the simulation results for the cooling energy demand and the costs related to the component installations and maintenance, the four concepts were compared by means of the monetary value of each. The results show a positive impact on the monetary costs of night ventilation in comparison to the system without cooling or ventilation, as the productivity improvement outweighs the costs of components and electricity. The benefits of an additional ceiling fan installation are limited due to the relatively low outdoor temperatures in summer observed at the analysed location. The positive effect is diminished further by the high investment costs that result from the ceiling fan as custom-made solution. Future work should assess the economic viability of ceiling fans for warmer environments.

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List of abbreviations

ACS	*Air-Conditioning System*
AMV	*Actual Mean Vote*
AV	*Air Velocity*
BRS	*Building-Related Symptoms*
CAPEX	*Capital Expenditures*
CF	*Ceiling Fan*
CFD	*Computational Fluid Dynamics*
CO_2	*Carbon Dioxide*
COP	*Coefficient of Performance*
DVU	*Decentralised Ventilation Unit*
E+	*EnergyPlus*
EMS	*Energy Management System*
GHG	*Greenhouse Gas*
HVAC	*Heating, Ventilation, Air Conditioning*
IAQ	*Indoor Air Quality*
IEQ	*Indoor Environmental Quality*
KIT	*Karlsruhe Institute of Technology*
Mio	*Million*
NPV	*Net Present Value*
NV	*Night Ventilation*
O & M	*Operation & Maintenance*
OPEX	*Operational Expenditures*
PAQ	*Perceived Air Quality*
PCS	*Personal Comfort System*
PEC	*Primary Energy Consumption*
PMV	*Predicted Mean Vote*
POC	*Profit-Oriented Company*
PPD	*Predicted Percentage Dissatisfied*
PS	*Public Service*
PTS	*Predicted Thermal Sensation*
RH	*Relative Humidity*
RP	*Relative Performance*
SET	*Standard Effective Temperature*
TMY	*Typical Meteorological Year*
TSV	*Thermal Sensation Vote*

1 Introduction

1.1 Motivation

In the national “Climate Protection Plan”, Germany declares to cut their greenhouse gas (GHG) emissions until 2050 by 80 to 95% compared to 1990 (dena 2016). The subdivision of this aim defines more specified goals as summarized by dena: Until 2030, emissions must decrease by 55%, with a reduction of 67% within the building sector. In absolute numbers, these values represent more than 130 Mio. t CO_2-equivalent for the building sector. The share of Germany’s total emissions accounts for 13% for direct emissions and 30% for indirect emissions from the building sector. Another indicator that shows the energetic relevance of the building sector in Germany is the primary energy consumption (PEC). Until 2050 the PEC must decrease by 80%, down to 243 TWh compared to 1217 TWh in 2008 as set within the climate protection plan 2050. Heating, cooling and hot water accounts for more than 90% of the building-related energy usage in Germany (dena 2019). Even though only 36% of the buildings are non-residential buildings, and within these buildings cooling sums up to less than 3% (9 TWh) of the overall energy usage, the number of cooling devices is constantly rising due to the increase of hot days per year and a reduction of energy consumption and cooling emissions is necessary (dena 2019).

While decarbonisation of heating and cooling systems impacts emissions but not inevitably the PEC, efficiency improvements of heating and cooling systems, innovative HVAC concepts (heating, ventilation, air conditioning) and building insulation contribute to lowering the energy demand. Ecological aims and regulations are of great importance. Nevertheless, economic considerations must be handled equally since a lack of economic viability can be a criterion for exclusion.

The costs of an HVAC system are composed of capital and operational expenditures (CAPEX and OPEX), which are part of the position owning and maintaining a building. These costs sum up to approximately 3% of the total costs associated with a building (Brager 2013) and are often neglected. What is not taken into consideration is the impact of HVAC systems on the actual and perceived room climate, which may affect the productivity of the employees. Salaries constitute 80 – 90% of the building associated costs and which makes the indirect costs of HVAC systems significantly higher than the direct costs (Brager 2013). Room climate influences health and comfort and can be evaluated within an Indoor Air Quality (IAQ) assessment. Since most people spend more than 90% of their time indoors, many diseases and sick leaves (e.g. asthma, allergies or sick building syndrome) are directly linked to the IAQ, which is therefore a powerful lever to improve health and working efficiency (Olesen 2005). The IAQ does not represent the perception of comfort that depends on several physical and psychological factors, such as air movement, personal preferences, clothing, and outdoor temperature. The impact from additional parameters can be evaluated for example with the Perceived Air Quality (PAQ) assessment (Rawal et al. 2020; de Dear and Brager 2001).

A range of the issues mentioned above is faced in a district office in Dillingen, Germany, aiming to a reduction of the energy consumption while improving the comfort of the employees. Within the framework of a building refurbishment, night ventilation was implemented and within the research project "Deck-in-Vent", personal comfort systems (PCS) in form of ceiling fans were installed individually at each workplace. Complementary to the air temperature reduction with night ventilation, ceiling fans improve the thermal comfort in hot weather periods.

1.2 Project Deck-In-Vent

In the planning phase of the building renovation, a simulation study was conducted, investigating different cooling concepts. Evaluation of the simulation results showed that the temperature is higher than 26 °C for 8% of the usage time without an active cooling system. This leads to an exceedance of the recommended temperature limits according to DIN EN 16798-1 (2019). The possibility to relax the thermal boundaries for a comfortable room climate with an increased air velocity through the application of ceiling fans aroused based on the results of the project “Passiv Kühl” (Wagner and Voss 2014).
As a result, project “Deck-In-Vent” aims to the preservation of a comfortable room climate on hot days, while maintaining low energy consumption and installation costs by providing every workplace with an acoustic ceiling panel and an integrated personal ceiling fan. This project proposes the analysis of the cost-benefit ratio in terms of economic, energetic, and socio-cultural aspects of the panel-integrated fans. To shed light on this issue, including among others, room temperature, energy measurements, and interactions with the ceiling fan, several variables regarding the indoor environmental quality and the cooling strategy components were monitored for three months in 2020 and supported with an employee questionnaire. The results from the questionnaire are not analysed within this work.

1.3 Thesis objective

The objective of this thesis is the assessment of efforts and benefits of ceiling fans in terms of energy demand, costs, and comfort in comparison to alternative active and passive cooling solutions by way of an example. Additionally, the energy demand of ceiling fans and the user satisfaction in connection with the latter will be determined. Simultaneously, comfort evaluation results will be transferred into economic costs, which is the unique feature of this work. While the comfort of PCS was assessed in various studies, the economic viability of the PCS was not investigated sufficiently (Rawal et al. 2020).

1.4 Methodology

This chapter describes the methodology that was chosen to achieve the thesis objective. The overall concept is pictured in Figure 1. In the introductory part, basic information was provided about motivation, background, and thesis objective. As described in section 1.3, different cooling concepts are compared to each other regarding comfort, economic and ecological considerations. The concepts are:

- Concept NoCooling: No ventilation or air-conditioning (situation before renovation)
- Concept NV: Night ventilation
- Concept NVandCF: Night ventilation (NV) and ceiling fans (CF) (situation after renovation)
- Concept ACS: Air-conditioning system (decentralised, ideally modelled)

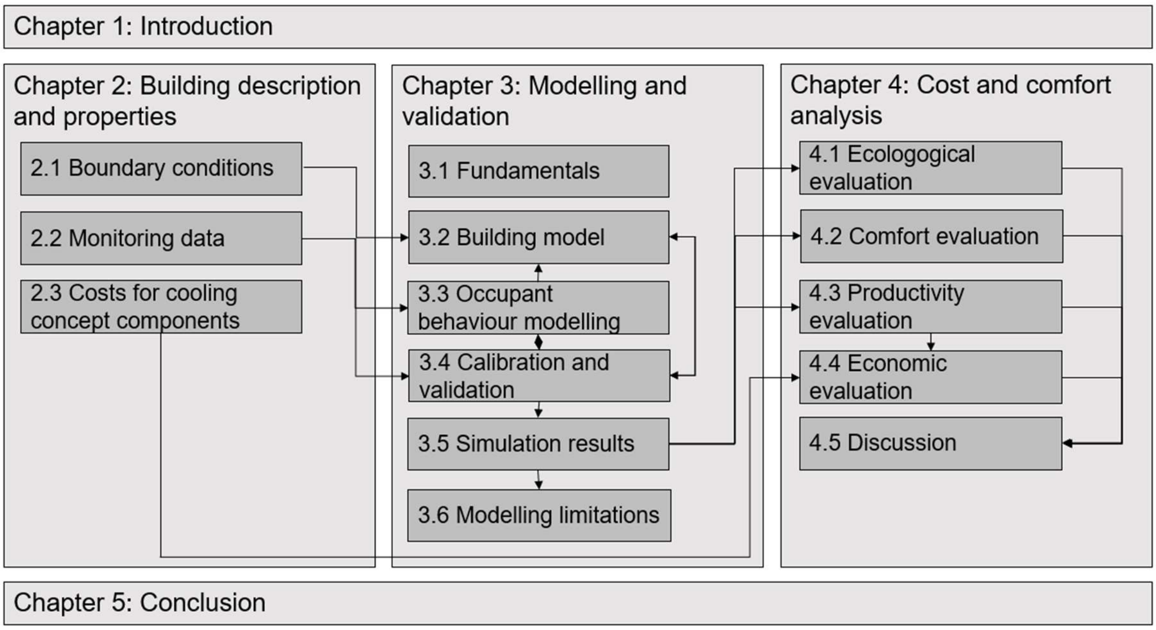

Figure 1: Methodology overview

Chapter 1 served the introduction, the outline of the thesis objective and the methodology. Subsequently, the state-of-the-art will be summed up. In the next chapter, fundamentals for building simulation, building data, building control schedules, and other boundary conditions, which will be used for the modelling of the building in chapter 3, will be explained. Assessment of the monitoring data is another point in chapter 2 and will be used for the occupant behaviour modelling and the validation in chapter 3. Not all parameters for the building model are known, which makes a calibration of model parameters necessary. The validation process is vital to make sure that project information and processing of the monitoring data (e.g., ceiling fan usage) is directly applicable to the used model and to render further adaptations. With the building model, temperature and energy usage were calculated. The model provides the foundation for the economic assessment in chapter 4. The economic evaluation is based on costs for different cooling strategy components (chapter 2.3) and the productivity calculation (chapter 4.3), which requires, amongst others, the room air temperature as a variable. The electricity usage has an ecological (chapter 4.2) and an economic (chapter 4.4) aspect. The comfort evaluation (chapter 4.1) can be used as standalone criteria or as a basis for a productivity analysis. Only for the concept with night ventilation and ceiling fans there is available data. This data neither includes monitoring data for the energy usage of the building, nor is it covering the whole cooling season. As both factors are necessary for the economic evaluation, a building model was created to provide the temperature distribution and the cooling energy demand for the building for all concepts over a whole cooling period.

1.5 State-of-the-art

1.5.1 Cooling strategies

To maintain a comfortable room climate during summer, air-conditioning systems (ACS) are one possible solution for new buildings. Independent from fluctuations of the outdoor temperatures, ACS can preserve temperatures constant at a desired setpoint. However, negative aspects are the expensive installation and the high energy usage during operation, especially for refurbished buildings that rely on decentral devices. Moreover, ACS can lead to overcooling of buildings which might lead to building-related symptoms (BRS) (Mendell and Mirer 2009).

Night ventilation is a useful tool to reduce cooling loads during summer, especially in high-mass buildings with a high thermal inertia (Darmanis et al. 2020). They measured a single room of a high-mass earthen building in Istanbul. Based on the results, they calculated a reduction of the cooling loads of 27% with night ventilation and discovered an explicitly high effectiveness for hot days. Another research conducted by Pfafferott et al. (2004) shows that the usage of night ventilation leads to an improvement of thermal comfort without the necessity of electricity usage. Especially in the case of renovated buildings, overheating is a potential source of discomfort (Földváry et al. 2017), which can be tackled by night ventilation. Additional to night ventilation or as an alternative concept, fans can improve the thermal comfort by elevating the air speed.

1.5.2 Comfort

The perceived air quality was already introduced as an important indicator for thermal comfort. Therefore, many studies were dedicated to creating models that predict the actual comfort. The most popular comfort model is based on the research findings from Fanger.

Fanger (1967)

The model uses air temperature (T_{air}), radiant temperature (T_{rad}), relative humidity (RH), air velocity (AV), metabolism rate (met) and clothing (clo) to calculate the Predicted Mean Vote (PMV). It is only applicable to controlled environments which means conditioned buildings with permanent compliance with room climate setpoints. The PMV gives information about the perception of the room temperature on a 7-point scale from – 3 (cold) to 3 (hot). It is calculated with the equation:

$$PMV = [0.303 * \exp(-0.036M) + 0.028]L\,,$$

where M is equal to the metabolic activity and L describes the difference between internal heat production and heat loss. The PMV can be used to calculate the Predicted Percentage Dissatisfied (PPD) that provides information about the percentage of people that would feel uncomfortable at the given air condition. The minimum PPD occurs at a PMV of 0 and is 5%,

$$PPD = \ 100 - 95 * \exp[-(0.03353 * PMV^4 + 0.2179 * PMV^2)] \ .$$

DIN EN ISO 7730 (2005) defines different comfort classes based, amongst others, the PPD:

Comfort Class	PPD
A	< 6
B	< 10
C	< 15

Table 1: Different comfort classes depending on PPD

Nicol et al. (2002)

For a building with natural ventilation and no active cooling, adaptation to the environmental conditions is a natural tendency and results in a higher thermal comfort than predicted by Fanger's model. Therefore, an alternative model must be used that includes the adaptive measures from the occupants. This can be, for example, a change of clothing to discharge thermal loads from the body, elevated air speed to embrace convective heat loss, or personal access to ventilation controls. Nicol et al. defined the comfort temperature (T_c) as a function of the outdoor temperature (T_o) with a comfort zone of ± 2 °C for limited adaptative measures:

$$T_c = 13.5 + 0.54\,T_o \ .$$

Yao et al. (2009)

The adaptive model from Yao et al. is based on the results from a survey that was conducted in China. They complemented Fanger's PMV-model with an adaptive coefficient λ. The adaptive coefficient differs for warm environments with a PMV > 0 and cold environments with a PMV < 0:

$$aPMV_{warm} = \frac{PMV}{1 + \lambda_{\mathrm{warm}} * PMV} \ ,$$

$$aPMV_{cool} = \frac{PMV}{1 - \lambda_{\mathrm{cool}} * PMV} \ .$$

To define λ, the least square method was applied to the monitored onsite environment and to the Actual Mean Votes (AMV) from a questionnaire in comparison to the calculated PMV.

Gao et al. (2015)

Elevated air speed caused by fans was not considered by Yao et al. Therefore, the model from Gao et al. complements the listed models. Besides the adaptive measures, the convective heat loss is considered using Standard Effective Temperature (SET) (Gagge et al. 1972) instead of the room air temperature. The results are not indicated as PMV or adapted PMV, contrary to Fanger's or Yao's model, but as Predicted Thermal Sensation (PTS) and Thermal Sensation Vote (TSV_{sa}), which is shown in the following equation:

$$\mathrm{PTS} = 0.25\ \mathrm{SET} - 6.03 \ ,$$

$$TSV_{sa} = \frac{PTS}{1 + \lambda_{\mathrm{s}} * PTS} \ .$$

Comparing the discrepancy between the measured TSV values from a survey and the calculated PTS, the adaptive coefficient λ_{s} was calculated, the same way Yao et al. did. λ_{s} is given as -0.195 to -0.213. The index "sa" gives information about the calculation approach. The inclusion of adaptive measures is indicated by "a". The dependency on the SET is indicated by "s". The same scale is employable for PMV and TSV. In contrast to Yao's model, the TSV calculation is identical for cool and warm environments.

Gagge et al. (1972)

The SET from Gagge et al. "considers a human [being] as two concentric thermal compartments that represent the skin and the core of the body" (ASHRAE 2017, p. 198). It can be used to calculate the air temperature in a standard environment that "exchanges the same total sensible and insensible heat as in the actual test environment" (Nishi and Gagge 1977). The standard environment is defined with a relative humidity of 50%, still air and a clothing of 0.6. Besides the air temperature, the SET considers radiant temperature, air velocity, relative humidity, clothing, metabolic rate, exposure times, body height, body weight, turbulence intensity, driving coefficient for regulatory sweating, driving coefficient for vasolidation, and driving coefficient for vasoconstriction. In addition, they used the SET as part of their “2-node-model” to predict thermal comfort (Gagge 1973). This model considers air speeds higher than 0.2 m/s but no adaptive measurements.

Shipworth et al. (2016)
The calculation of the PMV is a viable method to determine the perceived air quality. Nevertheless, it does not take other mainly psychological factors into account, such as personal control and responsiveness (Haynes 2008). The personal control regarding ventilation refers to the possibility to affect natural ventilation (e.g., possibility to open windows) or to PCS like desk or ceiling fans, where the effects of adjustment are directly perceptible. Shipworth et al. outlined the impact on thermal comfort due to different biological and psychological properties and the variation of background and experience. They propose a moving from mean responses and centrally managed environments to individual drivers and satisfaction by personal devices.

1.5.3 Personal comfort systems

PCS can appear in the form of personal fans, personal ventilation, revolving comfort systems, seat systems, radiant, evaporative or wearable systems (André et al. 2020). One way of categorising PCS is heating, heating and ventilation, cooling, cooling and ventilation, and ventilation (Rawal et al. 2020). Ventilation PCS "function by reducing the subjects’ skin temperatures by increasing the air movement around the subjects’ bodies and facilitating increased evaporation of sweat, inducing a ‘cool’ sensation without using any compressor-based cooling" (Rawal et al. 2020, p. 11). Advantages of ceiling fans over desk fans are space-saving on the desk, less noise, and a higher efficiency. Personal fans address individual differences in PAQ and thermal comfort and are a viable approach to reach higher rates of satisfaction. Many studies show that ceiling fans can be an energy efficient technology to improve thermal comfort in the context of office buildings (Rissetto et al. 2021; Rohles et al. 1982).

1.5.4 Productivity and cost calculations

From the economic point of view, two aspects must be examined. On the one hand, the capital and operational expenditures (CAPEX and OPEX) of a certain cooling strategy system have to be considered (Rosenquist et al. 2004; Darmanis et al. 2020). On the other hand, the influences of thermal comfort on the productivity of the employees must be evaluated. It is often argued that the costs of a new HVAC system are not compensated

by a higher thermal comfort, without taking into consideration that productivity and thermal comfort are linked (McCartney and Humphreys 2002; Seppänen et al. 2003).
Many studies tried to quantify the effects from thermal sensation on productivity. Haynes (2008) outlines the positive correlation between productivity and satisfaction. He suggests that “by improving the office environmental conditions, occupant productivity could be increased by 4-10 percent” (Haynes 2008, p. 41). McCartney and Humphreys (2002) present the results of a questionnaire that was conducted in 25 buildings around Europe with the result that productivity does not necessarily correlate with indoor air temperature but with thermal preference. In addition to the improved productivity, an increase of the indoor environmental quality (IEQ) leads to fewer cases of sickness and therefore less costs for sick leaves (Brager 2013). Productivity models serve a quantification of the worker’s performance regarding the indoor environmental conditions. Models were developed, amongst others, by Seppänen et al. (2006), and Lan et al. (2011).

Seppänen et al. (2006)

The productivity model estimates the relative performance (RP_{Sepp}) of an office worker as a direct function of the indoor temperature (T_{Air}). The correlation is based on a study review and the productivity maximum occurs at an air temperature of 21.75 °C and is 99.912%.

$$RP_{Sepp} = 0.1647524 * T_{Air} - 0.0058274 * T_{Air}^2 + 0.0000623 + T_{Air}^3 - 0.4685328 \ .$$

Lan et al. (2011)

The second research used within this work leads to the relative performance (RP_{Lan}) as a function of the thermal sensation vote (TSV), which is comparable to the PMV. It is the result from a study where volunteers performed neurobehavioural tests and answered questionnaires in different thermal conditions. The maximum RP_{Lan} occurs at a TSV of -0.2074 and is 99.88713%.

$$RP_{Lan} = -0.0351 * TSV^3 - 0.5294 * TSV^2 - 0.215 * TSV + 99.865 \ .$$

The relation between relative performance (RP) and TSV is shown Figure 2. Seppänen’s model suggests a significantly higher loss in RP for worse TSV, compared to Lan’s result.

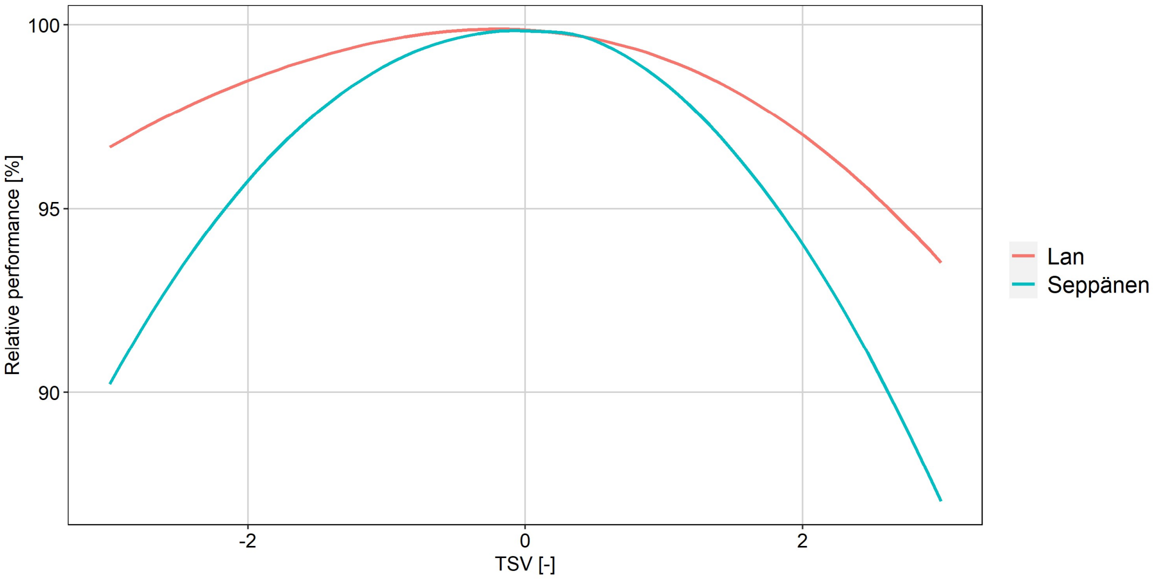

Figure 2: RP depending on TSV (Lan et al. 2011, p. 1061)

2 Building description and properties

2.1 Boundary conditions

This chapter describes the building and the boundary conditions. The studied office building in Dillingen serves as a basis for modelling, simulation, and calculation. After a presentation of the building characteristics, such as heat transfer coefficients, floor area and segmentation of the building, the ceiling fans are introduced. Afterwards, the building control system is described and conditions for internal loads are presented.

2.1.1 Building characteristics

The studied district office is in Dillingen an der Donau, Bavaria (Germany) (Figure 3). The building has five floors (including the basement) with more than 90 service and office rooms from ground floor to third floor, and a gross floor area of 5500 m². During the attachment of a new building to the existing one, the old building was refurbished. This refurbishment includes an improvement of the thermal transmittance of the façades and new windows with a control system for night ventilation and a decentralised ventilation unit. As a result, a reduction of the end energy consumption from 206 kWh/m² to 87.2 kWh/m² according to DIN 18599 (2016) was estimated.[1] For further improvement of the thermal comfort, ceiling fans were installed at every workplace.

Figure 3: Main district building east façade (DBW-Architekten)

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[1] This information originates from the project proposal

Since the renovation, most of the offices provide space for one or two employees and have an area of around 20 m² with two window and blind systems. The new building is located at the south side of the existing building and is equipped with an ACS. The window-system consists of a fixed glazing (middle), a window that can be opened and tilted manually (left) and an opaque window for night ventilation (right), which can be opened either manually or automatically (Figure 4).

Figure 4: Inside view of an office room. The window system and the integrated personal ceiling fan are shown (Bergische Universität Wuppertal)

Additional data (building data, floor plan, zoning, maximum occupancy etc.) can be found in Annex 1 and Annex 2 and was implemented accordingly. In short:

- Gross area (basement to 3rd floor): 5500 m²
- Net floor area (ground floor to 3rd floor): 3488 m²
- Building orientation: North wall is oriented 345° from true north
- Thermal transmittance south and west façade: 0.1 W/m²*K
- Thermal transmittance north façade: 0.74 W/m²*K
- Thermal transmittance roof: 0.713 W/m²*K

- Thermal transmittance inner walls: 0.68 W/m²*K
- Air exchange rate through infiltration (assumed): $\frac{0.1}{h}$
- Glazing size: 0.991 m²
- Manual window size: 0.478 m²
- Night ventilation window size: 0.239 m²
- g-value window and glazing: 0.55
- Window/wall ratio: 0.22
- Number of employees: 157

2.1.2 Ceiling fans

The ceiling fans were integrated into the acoustic panels that were installed during refurbishment at every office workplace. This process includes a bore through the panel because the ceiling fan is positioned on top of it facing downwards. The axial fan has a rotating area with a diameter of 300 mm and an installation depth of 92 mm. A custom fabricated grill is mounted below and has manually adjustable blades to manipulate the air directions. The composition of these components is a prototype based on existing parts. The design is shown in Figure 5. The fans are manually adjustable from 0 (off) to 100 (maximum power) providing elevated air speed to the occupants.

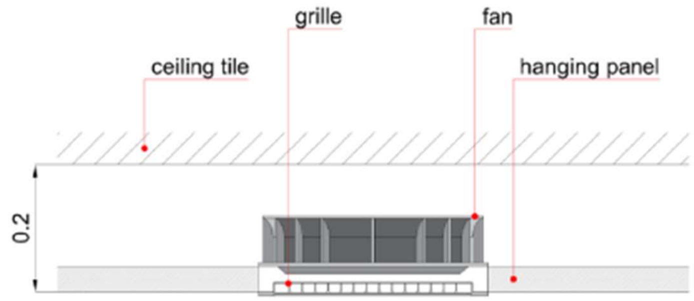


Figure 5: Acoustic panel and ceiling fan (Rissetto et al. 2021)

2.1.3 Shading device

The position of the blinds is manually adjustable. An additional central building control intends to lower the external heat loads when the sun is shining. The shading automatic control strategy is depicted in Figure 6. The control is different for the east and west façade because of the different intensity of solar radiation over time. The blinds are closing at 06:30 am and 00:30 pm for the east façade and at 11:30 am and 05:00 pm for the west façade if the illuminance on the window sensor is higher than the illuminance setpoint. At 08:00 pm for east façade, respectively 10:00 pm for west façade, closed blinds are opened. The illuminance value where the blinds are closing is not known.

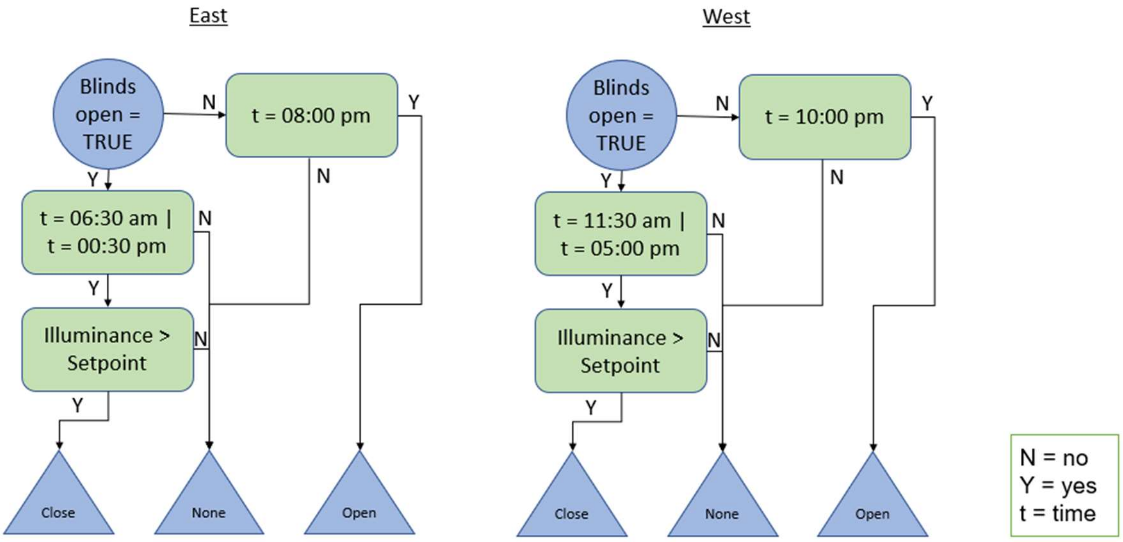


Figure 6: Shading building control strategy

2.1.4 Decentralised ventilation unit

The decentralised ventilation unit (DVU) with heat recovery is located at the top side of the windows and can be used manually or automatically. The purpose of this unit is to provide the required air change when night ventilation is deactivated, and during the heating period when the recovery of thermal energy is desired. The DVU has three settings with a mass flow of 21, 37 or 56 m³/h. The control strategy is set according to Figure 7. The control system sets the device to level „2“ (37 m³/h) at 07:00 pm and at 06:00 am. The ventilation units are deactivated whenever windows are opened or night ventilation is active, or when the ambient temperature is above 30 °C.

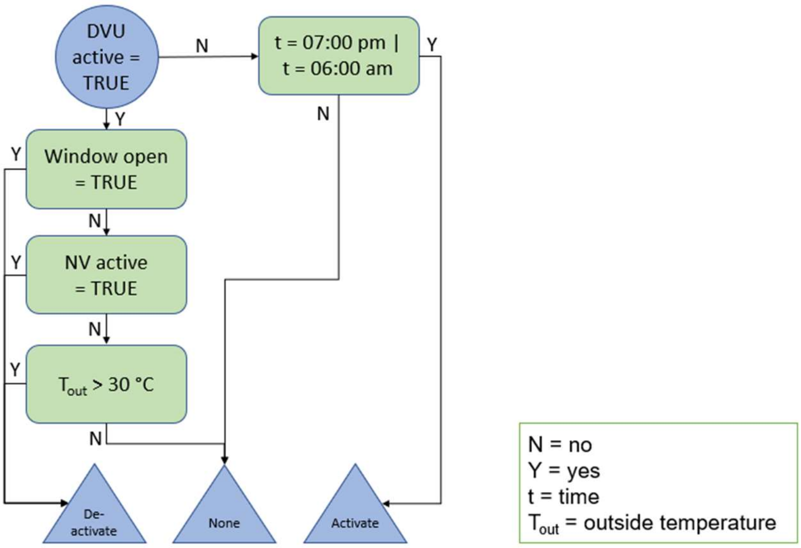


Figure 7: Building control DVU

2.1.5 Night ventilation

Besides the ceiling fans of the project “Deck-in-Vent”, the usage of night ventilation is a focal point for the cooling concept. The control strategy activates night ventilation between 7:00 pm and 7:00 am. Conditions for the opening is an indoor air temperature at least 2 °C higher than the setpoint temperature and 2 °C higher than the outdoor air temperature. The control closes the night ventilation windows at 07:00 am or when either the indoor air temperature is 2 °C below the temperature setpoint, the windspeed is higher than 8 m/s, or the outdoor air temperature falls below 10 °C (Figure 8). Further unfavourable conditions (like a blocking of the window) are not considered.

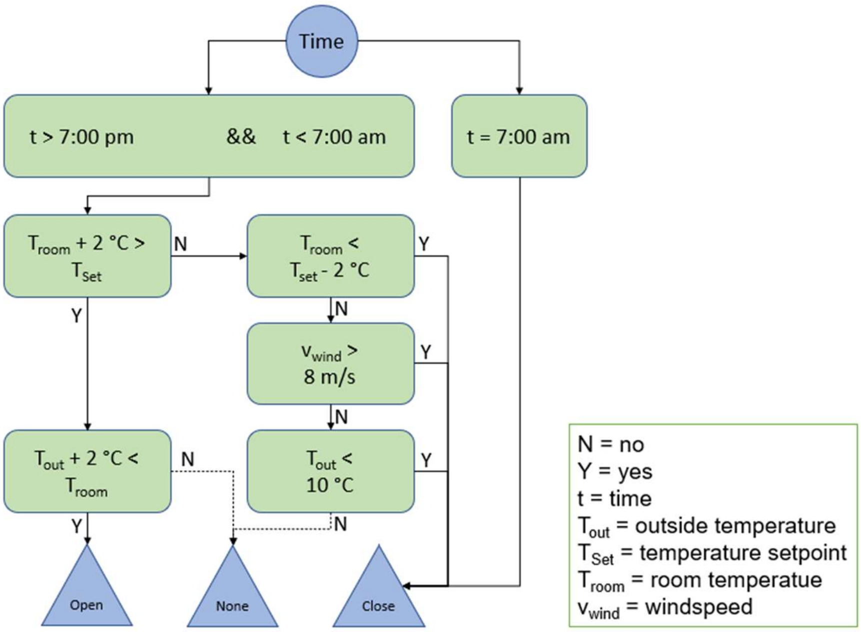


Figure 8: Flow chart night ventilation control

2.1.6 Internal loads

Another important property for the model is internal loads. Heat gains originate from artificial lighting, electrical equipment, and the metabolic heat release of humans. The activity in the building is office work in a sitting or standing position. Therefore, the heat gain from employees is set to $115\ W/Person$ (ASHRAE 2017, p. 473).

For lighting internal loads, ASHRAE suggests an approach that determines a maximum *Lighting Power Density* (LPD) multiplied with a *Space Fraction (SF)*, which describes the fraction of lighting heat gain that goes to the room and is different for every room usage type or luminaire category respectively (ASHRAE 2017, p. 474). This results in a heat gain density of

$$\dot{q}_{lighting} = LPD * SF \quad .$$

The results for the different usage types can be found in Table 2. For usage types other than offices an average value was calculated. The space fraction corresponding to a recessed fluorescent luminaire with lens was applied.

Usage type	**LPD [W/m²]**	**SF [-]**	**Heat gain density [W/m²]**
Office	12	0.45	5.4
Stairway	7	0.45	3.15
Restroom	10.6	0.45	4.77
Lobby	9.7	0.45	4.365
Corridor	7.1	0.45	3.195
Average w/o office	8.7	0.45	3.9

Table 2: Heat gain density for lights

Information about further electrical equipment in the offices is not available. Such being the case, the average heat gain for laptops with docking station is assumed for the model: $61\ \mathrm{W/Person}$ (ASHRAE 2017, p. 481).

The internal loads from metabolic heat release depend on the presence of employees. It is assumed that both, lighting and electrical equipment, are turned on during occupancy and turned off during absence. The occupancy schedule will be determined in later steps of this thesis (3.3.1). It is assumed that one lighting and one laptop is assigned to every employee. Therefore, the heat gain from lighting within the offices must be converted to a heat gain density depending on the number of employees. Most of the offices consist of an area of around 20 m² which leads to:

$$\dot{q}_{lighting} = 5.4\frac{W}{m^2} * 20\ \frac{m^2}{Office} = 108\frac{W}{Office} \quad .$$

With an average of 2 employees per office this results in:

$$\dot{q}_{lighting} = \frac{108\ \frac{W}{Office}}{2\ \frac{Employees}{Office}} = 54\frac{W}{Employee} \quad .$$

As both, lighting and electrical equipment, are linked to the occupancy profiles, internal loads are zero with the departure of the employees.

2.2 Monitoring data

This chapter provides an overview of the data that was monitored. Data processing was carried out with R (R Core Team 2020). Monitoring was carried out for ground floor to third floor from the 12th of August 2020 to the 11th of November 2020. In total, data for 92 rooms was gathered. This data includes:

- Room temperature
- Inside humidity
- CO_2-concentration
- Room temperature setpoint
- Valve setting
- Blind position
- Position of the windows (opened, tilted)
- Ceiling fan setting
- Decentralised ventilation unit setting
- Position of the ventilation windows
- Temperature of outdoor air, inlet air, outlet air, exhaust air (at ventilation unit)
- Electricity usage for lighting, ceiling fan and decentralised ventilation unit

Data was either monitored every 5 minutes (e.g., room temperature), every 30 minutes or whenever changes occurred. In this work, a timestep is defined to be 5 minutes. Weather data was recorded for:

- Outdoor temperature
- Humidity
- Precipitation
- Wind speed
- Illuminance

Data gaps can be noticed from the 10th to the 13th of September, on the 19th and the 20th of September, the 19th of October, and from the 2nd to the 4th of November. Table 3 provides an overview of the quality and quantity of the available data. Annex 3 shows the number of days with corresponding data for the technical devices and measuring points for each room. Rooms 107, 124, 207, 227, 307 and 327 were preselected as representative rooms for floor 1, 2 and 3 and both, east and west orientation. Therefore, these are the only rooms with values for indoor humidity, CO_2-concentration, electricity usage and temperatures at the decentralised ventilation unit installation (Table 3).

Monitoring Objective	**# Rooms**	**Range**	**Usability**
Air temperature	All		Yes
Humidity	6		Yes
CO2-concentration	6		Yes
Temperature setpoint	Ground Floor		Limited
Valve setting	Ground Floor	0-1	Limited
Blind setting	All	0-1	Yes
Window state	All	0/1	Limited
Ceiling fan setting	All	0-100	Yes
Ventilation unit setting	All	0.39/0.78/1.18	Yes
Position of night ventilation window	All	0-255	Yes
Temperature at DVU	6		Limited
Electricity usage (lighting, CF, DVU)	6		Yes (Lighting)

Table 3: Overview monitoring data quality

The measurements for the air temperature are the most complete for all rooms compared to the other parameters. It is also the most important parameter as it is used for the validity of the building model in section 3.4. Humidity measurements are used to doublecheck the temperature profile on possible inconsistencies. Based on the CO_2-concentration, the occupancy profile will be assessed in section 3.3.1. The valve setting is not used. The same goes for the temperature setpoint because it is limited to the ground floor and is also very changeful throughout the day. This makes a generalization to the building difficult and would also bring the risk of overfitting. The measurement of the blind setting is continuous from 0 (open) to 1 (closed). Tilting and opening of the windows (both 0) was metered with separate sensors. Some inconsistencies were found which will be explained in section 2.2.5. The ceiling fan can be adjusted continuously from 0 to 100 (maximum power). This data will be used to evaluate the user behaviour of the employees (section 2.2.6 and 3.3.3). It is unclear, what exactly is stated with the three different values for the DVU. Nevertheless, it can be assumed, that the values are representative for the three possible settings of the DVU. Anyway, measurements for the DVU will not be used. The position of the night ventilation window is discrete from 0 to 255. The upper limit is equivalent to a completely open window. The monitoring values for the electricity usage of the lights will be used complementary to the CO_2-concentration for the assessment of the occupancy profile.

2.2.1 Room temperature

Figure 9 shows the daily mean temperature over the whole monitoring period for the 6 reference rooms. Monitoring results for rooms 207 and 327 show a constant temperature value for the first two weeks of monitoring, which indicates a measuring or processing error. Regarding room 227, the first two weeks of temperature monitoring were 32,767, which is not logical. This was excluded in Figure 9. The orange line displays the outdoor temperature. The similarity of the temperature profiles is distinctive. Nevertheless, a slight variation is visible. Especially in later stages of the monitoring, where the difference of the room temperatures is up to ~ 2 °C.

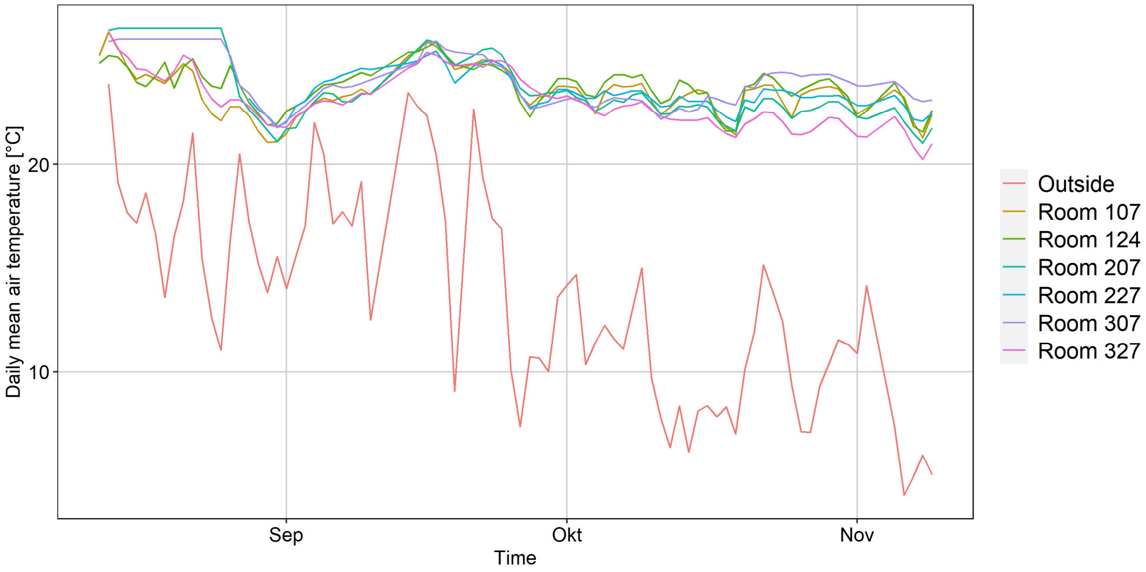


Figure 9: Daily average temperatures for the monitoring period for preselected rooms

2.2.2 Humidity

Figure 8 shows the daily average humidity for the monitoring period for the 6 reference rooms. With an average relative humidity between 40-60% over the day, the monitoring data for the humidity inside the six rooms is within the expected values. The decrease from August to November, which can be observed in Figure 10, is expected, since the heating of the outdoor air leads to a lower relative humidity inside. The values for the outdoor humidity are inexpressive because the data is only available for 11 of 84 days of the monitoring period. The weekly periods are depictable, similar to the measurements for room temperature.

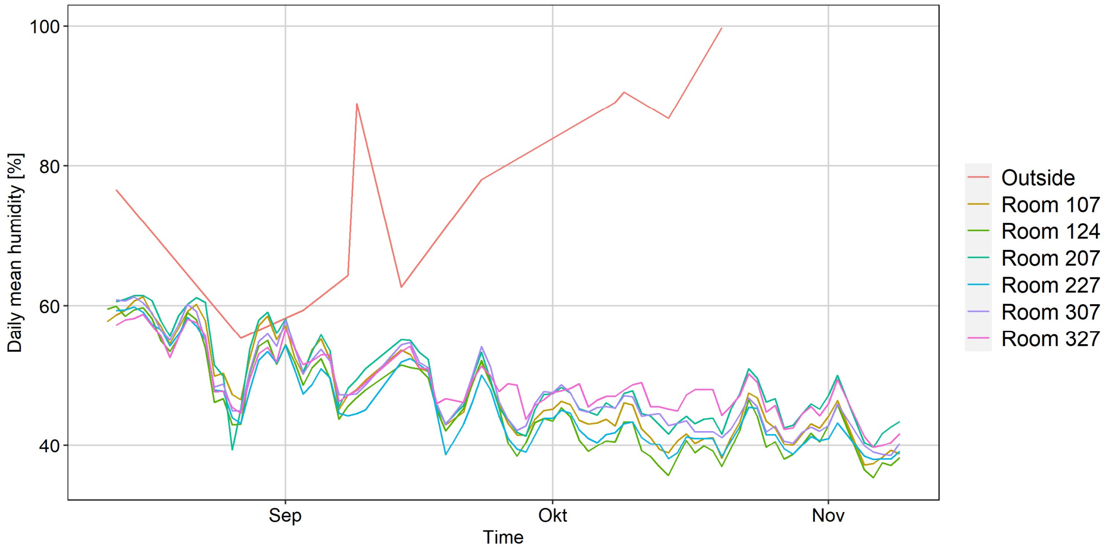


Figure 10: Daily average humidity for the monitoring period for preselected rooms

2.2.3 CO_2-concentration

The CO_2-concentration in the atmosphere is currently around 400 ppm on average and is assumed to be constant. A concentration like the outdoor condition is expectable for times of no occupancy. This can be seen in Figure 11 where the CO_2-concentration for the 6 rooms is depicted for the monitoring period. The downward peaks occur at the weekend with a minimum concentration around 400 ppm.

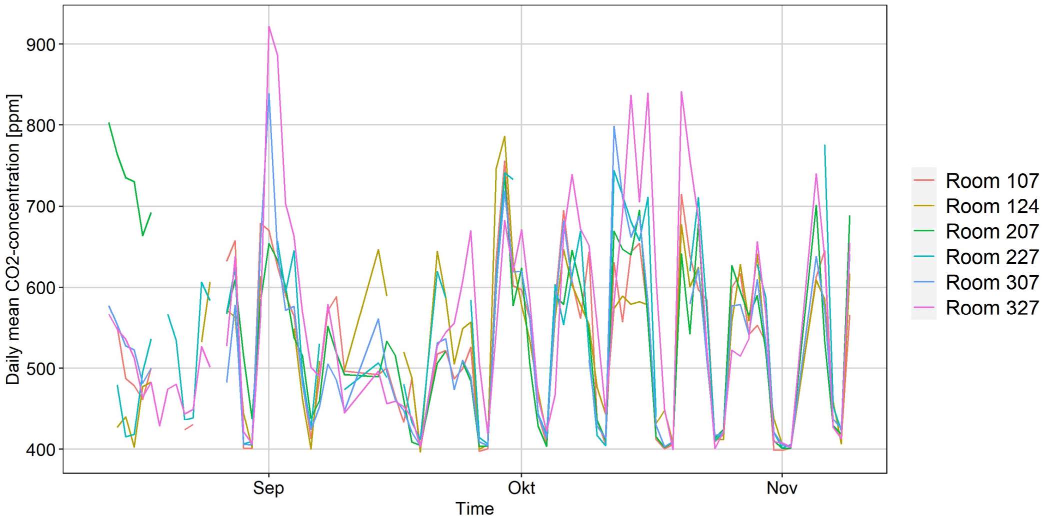


Figure 11: Daily average CO_2-concentration for the monitoring period for preselected rooms

2.2.4 Night ventilation

The use of the night ventilation is shown in Figure 12. For all days during the monitoring period, the rooms with active night ventilation are summed up. For most of the nights and rooms, the night ventilation is in use during August. It is not clear but very likely, that the activations after the 1st of September are monitoring errors and the night ventilation is deactivated after August.

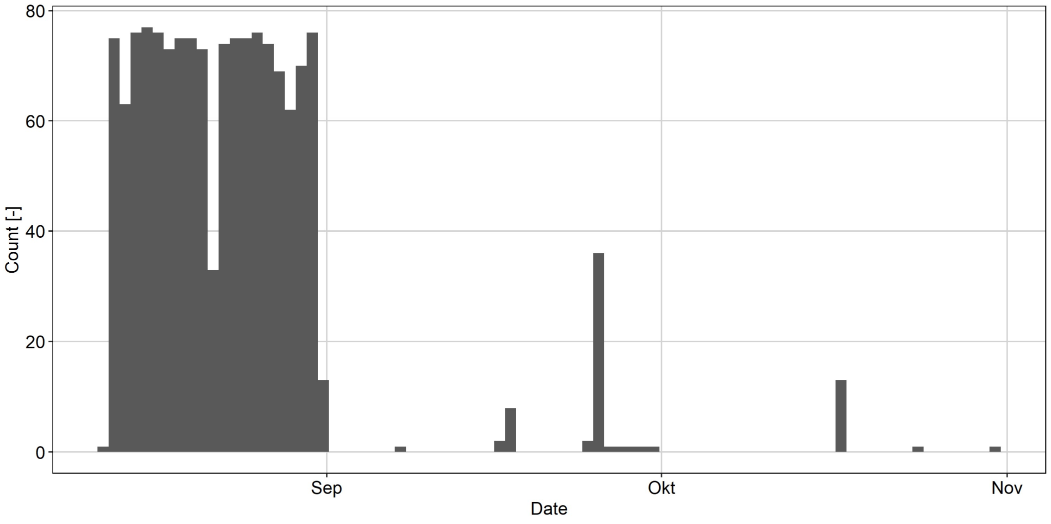


Figure 12: Days with use of night ventilation (92 rooms)

Figure 13 illustrates an example of the use of night ventilation. The data shows room 134 on the 31st of August. The date was chosen because at that time night ventilation was active, and there is monitoring data available for the outdoor temperature. The room was chosen as it is one of the few rooms where the room temperature setpoint is available on that date. The consequence of the room temperature setpoint was explained in Figure 8. For a better visualization of the figure, the state of the window (red line) was plotted in reference to the y axis on the left, where a unit of 10 means open and a unit of 0 means closed. The room air temperature setpoint is constant at 21 °C (blue line).

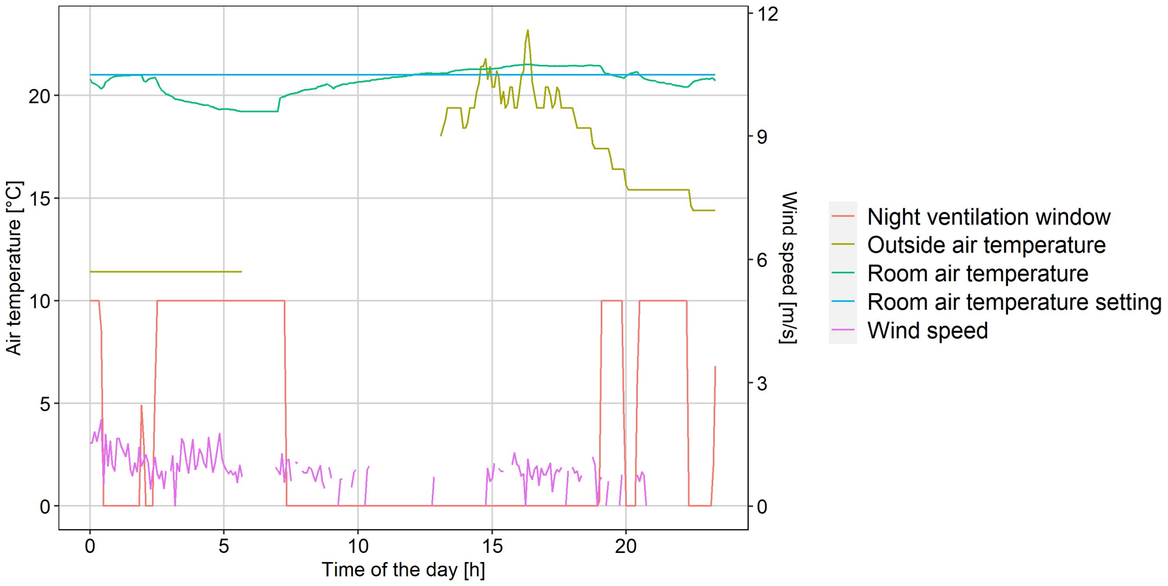


Figure 13: Room 134 on the 31st of August

The outdoor temperature in the morning was not properly monitored but it was in the evening. When the night ventilation windows are open, a decrease in room temperature (green line) is recognisable from 2:00 am to 7:00 am. The same behaviour can be observed in the evening, although it is not clear why the NV windows are closing around 8:00 pm and 10:30 pm. The wind speed has a maximum of 2 m/s. Therefore, it should not be the cause for the windows closing. Nor is the indoor air temperature 2 °C below the setpoint temperature, or the outdoor temperature below 10 °C. Even with this single event to remain unexplained, the effect of the night ventilation is visible.

2.2.5 Window opening

Figure 14 shows the monitoring value for the opening of the left window on a daily average as an example. Rooms 107, 207, 227 and 327 show a reasonable window opening behaviour whereas room 307 has no useful data, due to a data processing error, and is therefore excluded. Usual values for the positions of the windows would be a majority of "1" for closed, and some opening periods ("0") during office occupancy. As it becomes colder outside in the later stages of the monitoring, fewer time periods with open windows are expected. This trend is visible in Figure 14 with smaller downward peaks for October and November compared to August and September.

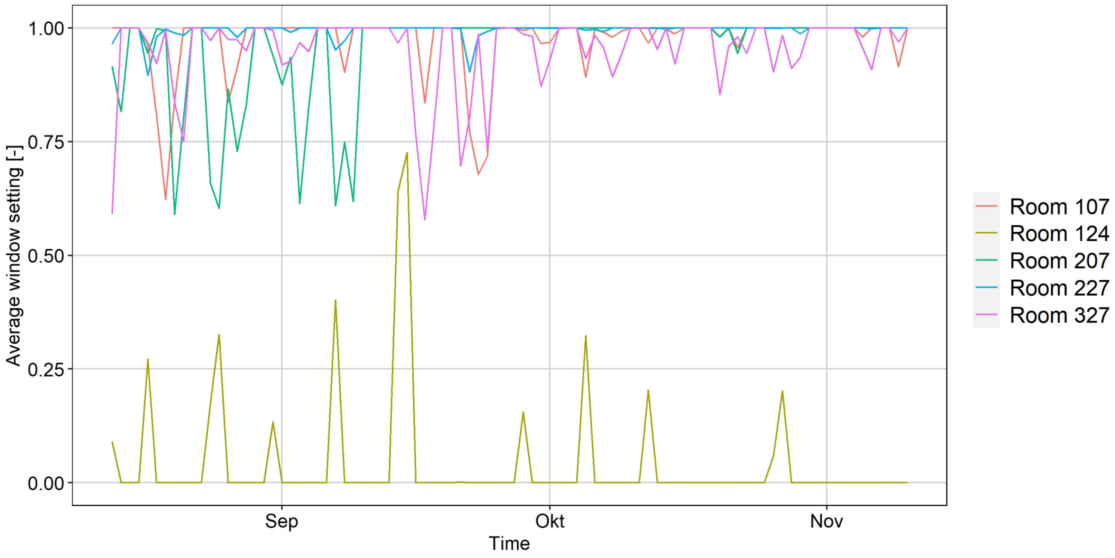


Figure 14: Daily average window setting for the monitoring period for preselected rooms, 0: open, 1: closed

A single inconsistency appears for room 124. As explained in section 2.2, monitoring data is either "1" or "0". When the measured value is "1", the window is closed since the electricity circuit of the measuring device is closed. When the value is "0", the window is either open/tilted, or a technical error occurred. Almost permanent opening of the window, as the curve of room 124 suggests, is not probable in cold weather periods because it would lead to low temperatures in the corresponding room. This does not correspond to the monitored values for the indoor air temperatures in Figure 9. Another indicator for open windows would be a decrease of CO_2-concentration, which is not the case (Figure 11).

2.2.6 Ceiling fans

The ceiling fans are almost exclusively operated manually except for an automatic deactivation at 7:00 pm. Monitoring data for the ceiling fans is especially important to evaluate the user behaviour in later steps of the thesis. The maximum setting for ceiling fans is “100”. The active condition was categorised into “air speed levels”, being:

- “Off” ($0 \leq x < 5$),
- “Low” ($5 \leq x < 35$),
- “Medium” ($35 \leq x < 65$) and
- “High” ($65 \leq x \leq 100$),

and was counted for all ceiling fans. Most of the measurements are “0”. The results can be seen in Figure 15, where the usage of all ceiling fans was added up, divided into the three different active states, and plotted in steps of 0.2 °C. The ceiling fans were used at temperatures higher than 21 °C. The most frequent temperature with ceiling fan usage can be observed at indoor temperatures between 23 and 23.5 °C, which can be explained due to the temperature distribution in Dillingen. No temperatures higher than 28 °C were measured while ceiling fans were in use. It can be observed from the diagram, that higher temperatures lead to the desire of a higher air speed. This can be noticed in a higher setting of the ceiling fans (level “medium” and “high”).

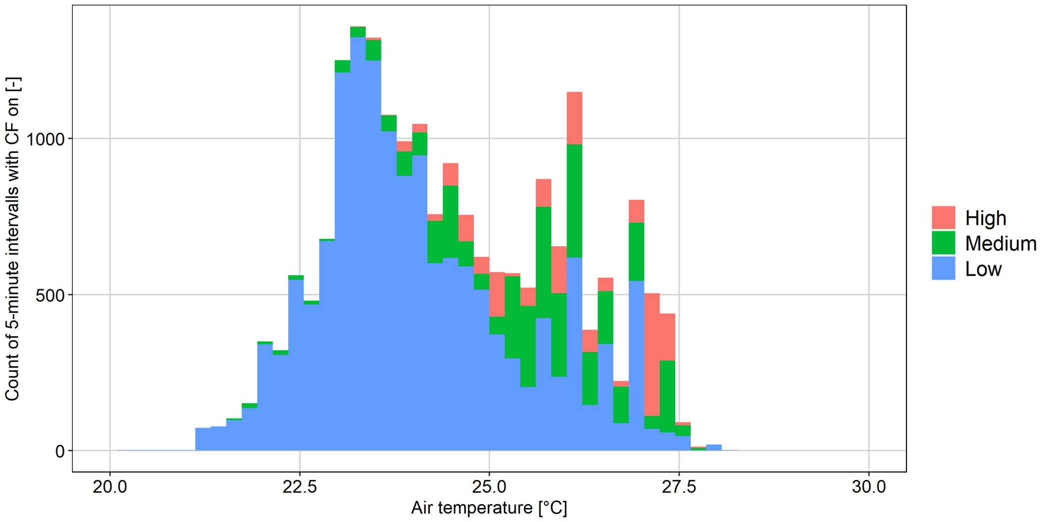


Figure 15: Active states ceiling fans for all rooms, histogram

A cumulative distribution of the ceiling fan usage is depicted in Figure 16. Almost half of the ceiling fan usage occurs at temperatures between 22 and 24 °C.

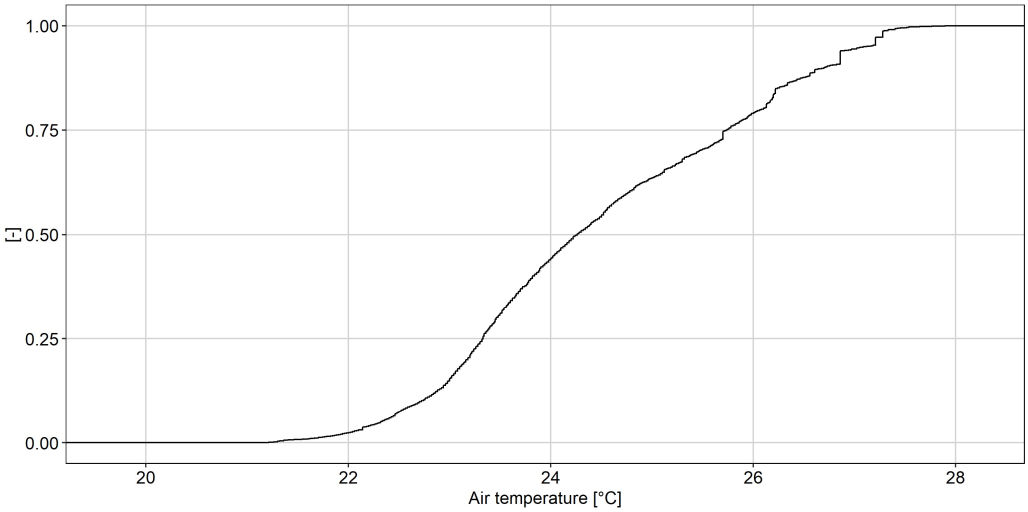


Figure 16: Active states ceiling fans for all rooms, cumulative

2.3 Costs for cooling concept components

In this chapter, the basis for the economic evaluation (section 4.4) is provided considering CAPEX and OPEX for the different concepts.

The expenditures for the night ventilation and the ceiling fans were obtained from the planning documentation of “Deck-In-Vent”. Since the DVU does not inevitably come with night ventilation, corresponding costs are not considered within this calculation. Planning expenses run on the whole project. For this reason, it is necessary to proportionally allocate them to the investment costs of building control and automation, acoustic panel, ceiling fans and night ventilation with the share of the DVU left out. Costs for ACS are not available and were assumed according to literature values. The focus of this work lies on measures for refurbishment; thus, decentralized ACS are presumed instead of a central ACS. As the building (ground floor to third floor) has 92 rooms, the same number of split ACS must be purchased and installed. Out of the available range of costs, the mean values below, based on a web page for ACS (vetall.de 2021), were used for the subsequent calculations:

- Investment: 1300 €
- Operation and maintenance: 170 €/a
- Installation: 1325 €
- Commissioning: 575 €

Installation costs for the concepts exclusive of ACS add up to approximately 15% (based on the project planning data). Operation and maintenance (O & M) costs are not available and were assumed to run up to 5% of the investment costs (Djukanovic et al. 2002). The planning costs for the ACS were presumed to follow the same investment/planning ratio as the other cooling strategy components (ratio = 4.1). Investment costs for one acoustic panel are approximately 100 € (daemmisol.de 2021). Costs for operation and maintenance are neglected as no moving parts are involved and a low maintenance effort is expected. All costs are summarised in Table 4.

	Building Control	**Acoustic Panel**	**Ceiling Fans**	**Night Ventilation**	**Air Conditioning**
Investment [€]	24,900	15,700	73,790	34,750	119,600
Installation [€]	3,735	2,355	11,069	5,213	174,800
Planning costs [€]	6,077	3,829	11,355	8,480	29,171
O & M [€/a]	1,245	0	3,690	1,737	15,640

Table 4: Component costs overview

Building control

The building control is included in every concept. In addition to the hardware for controlling the shading, for instance, software implementations must be pursued.

Acoustic panel

Acoustic panels are also necessary for all concepts due to their positive impact on acoustic and lights. They are mounted with an adjustable ceiling suspension.

Ceiling fans

The integration of the ceiling fans into the acoustic panels is a custom-made solution. For installation, the acoustic panels need to be bored up so the fans can be inserted. Besides the ceiling fan, a grill is installed that manipulates the air flow direction. These tasks comprise a high installation effort that leads to high overall costs. Considering the progression into a standard solution, investment and installation effort would decrease significantly.

Night ventilation

For night ventilation, sensor technology is needed (REED contacts) as well as the actuation for the window opening.

ACS

To install the split air-conditioning device, the outer wall must be holed, and one part of the device must be installed on the outer façade. Additionally, a refrigeration technician is obligatory when dealing with split devices. This results in high investment and installation costs.

3 Modelling and validation

This chapter gives an overview of the physical fundamentals of a modelling process and simulation (3.1), the building model that was created based on section 2.1 (3.2), the occupant behaviour modelling for occupancy, window opening, and ceiling fan usage (3.3), and both, calibration and validation of the model (3.4). During the validation process, the simulation results are compared to the monitoring data of the air temperature inside the office rooms. This is followed by a presentation of the simulation results (3.5) and the limitations of the model (3.6).

3.1 Fundamentals

Some important building parameters were already introduced in section 2.1, such as heat transmission (U) or the solar heat gain coefficient (g). In this chapter, the physical relevance of these values is described as well as further fundamentals regarding modelling and simulation. Heat transfer is composed of conduction, convection, and radiation.

Conductive heat transfer describes the transfer of internal thermal energy on a molecular scale without bulk motion. It can be calculated using the first law of thermal conduction, Fourier's law:

$$q_{Conduction} = -\lambda \; gradT \quad .$$

The heat flux q [W/m²] is a vector proportionally to a temperature gradient (gradT) across a unit surface. λ [W/(mK)] is the thermal conductivity. It depends on the material conditions (e.g., temperature) and, for anisotropic materials, on the heat flow direction. For simplicity, λ is mostly assumed to be a scalar and a constant material property. The negative sign indicates that heat flux is always from the warmer to the colder. Figure 17 shows temperature distribution and heat flux direction for a homogeneous wall with constant λ.

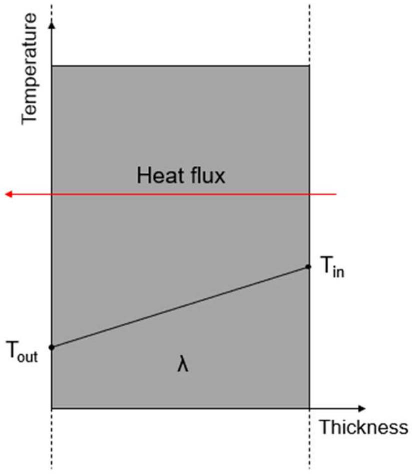


Figure 17: Heat flux and temperature distribution through a wall

The second law of conductive heat transfer is the implementation of the first law into the conservation of energy expression:

$$div(\lambda\ gradT) = \frac{\partial \rho c T}{\partial t} - \boldsymbol{\phi} \quad ,$$

with specific heat capacity c [J/(kgK)], density ρ [kg/m³] and heat flow ϕ [W].

Convective heat transfer describes the heat transfer between fluids and surfaces that is induced by motion of the fluid. The following equation is used to calculate the heat transfer:

$$q_{Convection} = \alpha(T_s - T_f) \quad ,$$

with α [W/(mK)] as convective heat transfer coefficient and the temperature difference between surface (T_s) and fluid (T_f). α depends, amongst others, on element properties and wind speed. Convective heat transfer can be either natural or forced. One example for forced convection is elevated air because of wind. Convection that is induced by a buoyant force is defined as natural convection. This results, for example, from the ascension of cold air that is heated on a surface with a higher temperature.

The first law of heat conduction is used to calculate the collective thermal transmittance through building elements such as walls or roofs. Different λ for the single layers and the respective material thicknesses are collectively described by the U-value. Additionally, the convective heat transfer on the inner and outer side of the building's element is included. The second law of heat conduction shows that a higher material density and a higher specific heat capacity increase the temperature gradient. These variables are characteristics of the building mass respectively the internal mass, which indicate the heat storage capacity of the building. The possibility to store thermal energy is specifically useful for night ventilation, where the internal mass of the building is cooled down by window opening during the night, which diminishes overheating throughout the day.

Radiative heat transfer comes from electromagnetic waves and does not rely on matter, which is fundamentally different to conduction and convection. Every surface with a temperature higher than 0 K emits radiation (E_s). The radiation from a "black body" to the half space is calculated according to the Stefan-Boltzmann law:

$$\dot{E_s} = \sigma T^4 \quad ,$$

with the Stefan-Boltzmann-constant σ ($5.67 * 10^{-8}$ W/(m²K)). For "grey bodies", this formula is modified using the emissive coefficient ε:

$$\dot{E}_S = \varepsilon\sigma T^4 \quad .$$

The heat transfer by radiation applies to every surface and is especially important for high temperature applications. The high temperature object that is relevant for building simulation is the sun, which induces solar gains through windows or other light-transmissive elements. The intensity of the sun irradiance is defined with the solar constant i_{solar} = 1.367 kW/m². This radiation intensity is reduced during the transition of the atmosphere. Aside from that, only a fraction of the radiance is transmitted through the windows, the residual radiation is either reflected or absorbed, according to the conservation of energy:

$$\alpha + \varepsilon + \tau = 1 \quad ,$$

with transmissive coefficient τ and absorbance α.

The solar heat gain coefficient g describes the heat gain through windows and combines the transmissive heat gain and the energy that is absorbed and subsequently released into the building.

The *first law of thermodynamics* applies to a closed thermodynamic system:

$$Q_{12} + W_{12} = \Delta U \quad .$$

This means, that thermal energy (Q) and energy due to work (W), that are added to a closed system, are converted to internal energy (ΔU). Figure 18 provides an example for a single office room with cooling loads and no internal work.

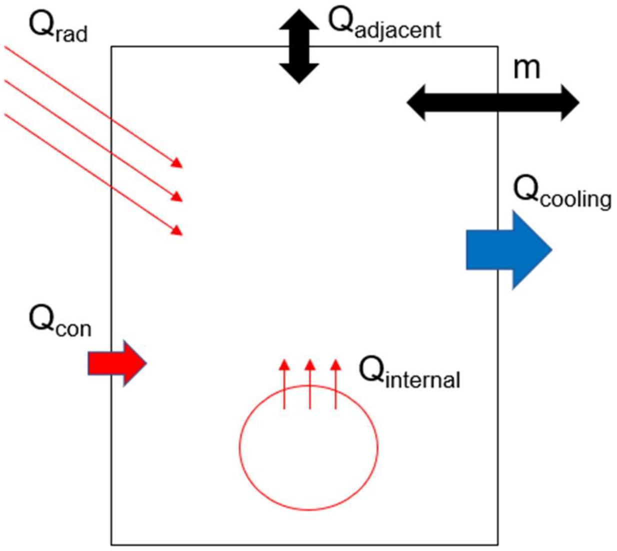


Figure 18: Heat flow for a single room

Q_{rad} is the thermal energy from solar radiation through windows, Q_{con} is the heat gain by convection and conduction through the outer walls, $Q_{adjacent}$ is the heat flow from and to other rooms in the same building and $Q_{internal}$ are internal loads that result from metabolic heat release of the occupants or from electrical devices. Without $Q_{cooling}$, the heat gains lead to an increase of the internal energy and therefore an increase of the room temperature. To conserve a constant room temperature, the same energy amount that is added to the room must be discharged ($Q_{cooling}$). For an open system, enthalpy differences in the context of mass flows (m) are considered (kinetic and potential energy are neglected):

$$Q_{12} + W_{12} = H_2 - H_1 \quad .$$

This occurs by infiltration, ventilation systems, or open windows and doors.

RC-model

For simulation purposes, state space modelling can be used to calculate heat flow through walls and the capacitance of the latter. Figure 19 shows an example for a single layer. Convective heat transfer results in the difference from the outer air temperature (T_o) to the temperature at the outer wall (T_1). The same goes for the inner air temperature (T_i) and the temperature at the inner wall (T_2). The thermal capacitance of the building element is divided into two equal compartments with temperatures T_1 and T_2. The boundaries for the heat conduction resistance (R) are the wall temperatures. This model is also named 3R2C-model, as two capacitances and three resistances represent conductive and convective heat transfer and the thermal capacitance.

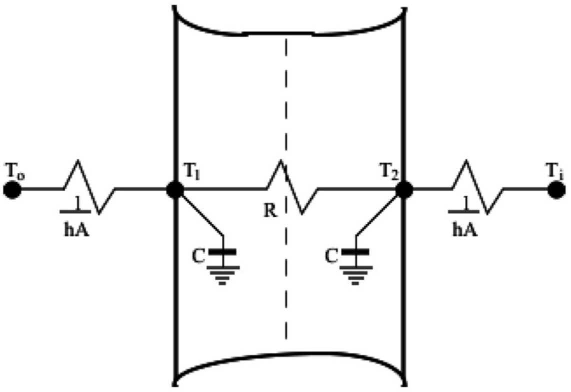


Figure 19: State space model (U.S. Department of Energy 2018, p. 61)

Nodal method

Three approaches for physical modelling are state of the art: CFD (computational fluid dynamics), zonal and nodal (Foucquier et al. 2013). While CFD is the most thorough approach that considers thermal transfer on a microscopic scale, the nodal approach simplifies each building zone into a homogenous volume with uniform state variables. The zonal approach lies in between and divides every room into small zones.

For the nodal model (also called multizone), every zone as well as every wall is assumed as one node with unique conditions and represented by an RC-model. One advantage is the computation of a multizone building for a large time period within a short amount of time. In contrast to this is the limitation to unique states that do not differentiate local variances and their impact on thermal comfort.

3.2 Building model

This chapter provides a description of the building model, the software that was used, and the modelling procedure. Boundary conditions and building properties (section 2.1) as well as adaptations that were made are explained. The purpose of the building model is the computation of the energy usage for cooling and, amongst others, the parameter of the indoor air that will be used for comfort calculations in section 4.2.

For this thesis, the air movement and temperature distribution within the single rooms is not of interest which makes the nodal approach well-suited for this modelling approach. EnergyPlus (E+) is a suitable software to follow this approach. Using SketchUp, a building model of the district office in Dillingen with thermal zones was modelled and exported to EnergyPlus.

3.2.1 Building envelope and zonal distribution with Sketch-Up

Sketch-Up is a 3D-modelling program. After drawing the floor layout, the rooms can be extracted floor wise. Doors and windows are added afterwards. In combination with OpenStudio-PlugIn, thermal zones are applied to every room. Thermal zones are air volumes with homogenous values for the indoor air parameters. The boundary conditions for the heat transfer of every zone (adjacent thermal zone, outside, ground) are set automatically. Figure 20 shows a visualization of the building model (west side). The basement was omitted in the model because the rooms serve other purposes than office or service and no ceiling fans are installed. Considering this, the boundary condition for the ground temperature is the setpoint temperature for the night ventilation respectively the average of cooling and heating setpoint for the ACS. For model simplicity, the manual window and the glazing of the window systems were combined into a single glazing object (Figure 4, left: manual window, middle: fixed glazing) and have an area of 1.47 m². As seen on the right edge of Figure 20, a part of the building model has no windows. This part represents the new building that was added to the existing building. In this part, an ACS was installed to prevent overheating, therefore the temperature was assumed to be constant for the modelling purpose. Energy usage for this part is not of interest. Nevertheless, the volume was included to model the heat transmittance on the south side of the existing building.

Figure 20: Visualization of the district office Dillingen in Sketch-Up

Similar to the approach from Klein et al. (2016), the building was divided into zones that merge some of the office rooms on the same floor with the same orientation. This simplification is viable because the effects on the building's energy usage and the indoor air parameters that affect every employee individually is marginal. For this building, it resulted in 51 zones with one thermal zone each. Offices at the edge of the building were modelled separately, while offices on the same floor with only one outer wall in the same orientation, were modelled as one zone. Additionally, rooms that do not function as workspace (e.g., staircases, bathrooms, lobby) are modelled separately from the office rooms. This is necessary because thermal loads from employees and equipment emerge only in the offices. In Figure 21, the thermal zones of the ground floor are shown. Zones 6, 9, 12 and 13 represent one room, whereas zones 5, 10 and 11 combine several offices in one zone. These zones are highlighted in grey in the figure. Zones 2 (Restroom), 3 and 4 (Lobby/Foyer), 7 (Staircase), 8 (New Building), and 14 (Corridor) were mostly neglected for the analysis.

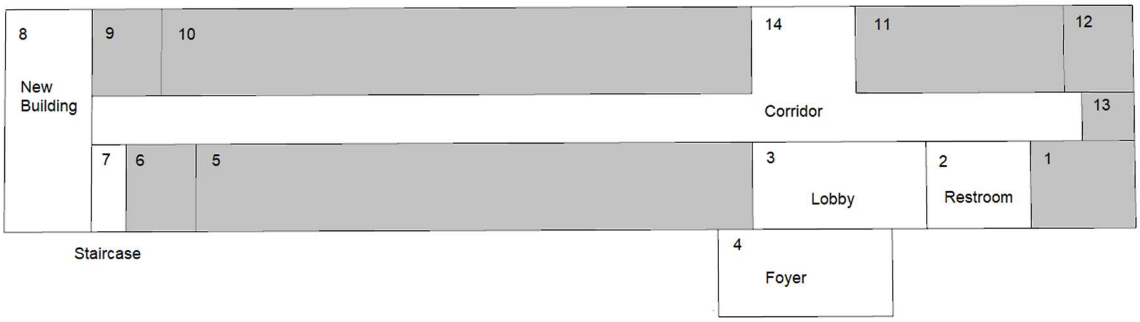


Figure 21: Zone plan ground floor

Omitted internal walls were modelled as thermal mass. Thermal mass from furniture is small compared to the building envelope with internal walls (Johra and Heiselberg 2017) and was neglected. Floors 1 to 3 have a similar layout. More detailed information to zoning can be found in Annex 4. The building plan can be found in Annex 5.

3.2.2 Modelling with EnergyPlus

EnergyPlus (U.S. Departement of Energy 1996-2021) is an open-source whole building energy simulation program that is based on zonal modelling and follows the nodal approach. Thermal zone conditions and heat balance can be simulated as well as HVAC systems and energy usage. A model in EnergyPlus is a composition of individual objects and their interaction. For example, a window-object is linked to the wall-object it refers to and consists of further objects, amongst others, the shading control, or the material the glazing consists of. Building properties and elements were already introduced in section 2. Further implications for the model are described in this section. This includes the presentation of the used weather data (3.2.2.1), the assumptions for shading devices (3.2.2.2) as well as ventilation and windows (3.2.2.3).

3.2.2.1 Weather data

Weather data was monitored at the district office building. To model the weather profile in E+, a specific file type is required (EnergyPlus WeatherFile (.epw)). As some of the required variables to create an epw file in E+ were not part of the monitored data in Dillingen, a comparable weather profile was used for the simulation. The weather data for a typical meteorological year (TMY) for Ulm, which is 40 km west and 10 km south from Dillingen, was chosen. To prove the applicability of the selected weather file to the building in Dillingen, the monitored temperatures were compared. Although the temperature profile is not equal for the whole monitoring period, certain weeks with similar temperature distributions were found. Weeks 36, 37 and 42 were chosen due to the relatively high similarity in air temperature and the differences in temperature between the beginning of September (weeks 36 and 37) and the middle of October (week 42). The profile for weeks 35 to 37 can be found in Figure 22.

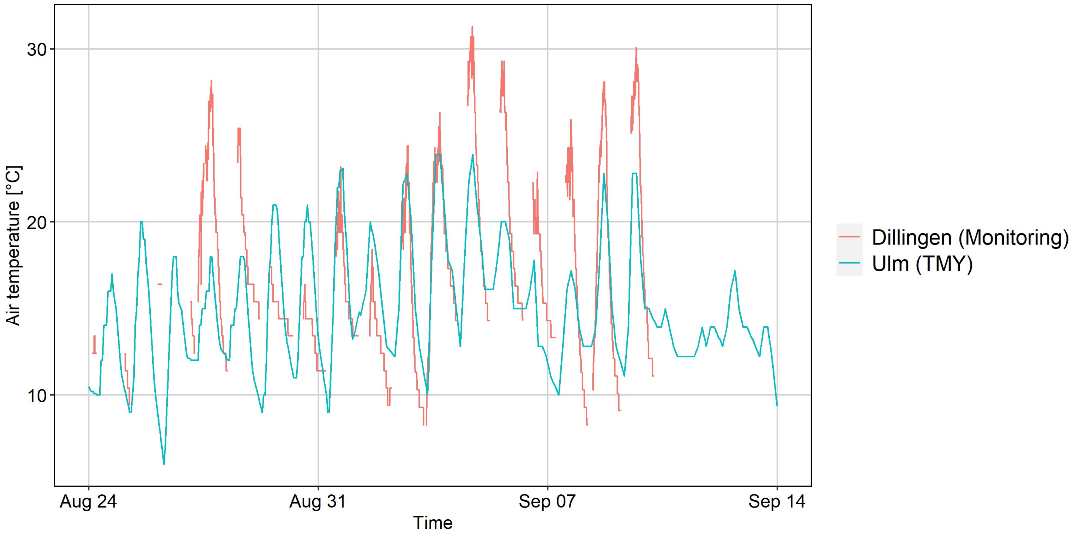


Figure 22: Temperature monitoring and EPW-File for weeks 35 to 37

Figure 23 shows the monitored air temperature and the air temperature from the weather file for Ulm for week 42. While the data from the EPW-file is complete (blue line), the weather profile for Dillingen (red line) has some missing data points.

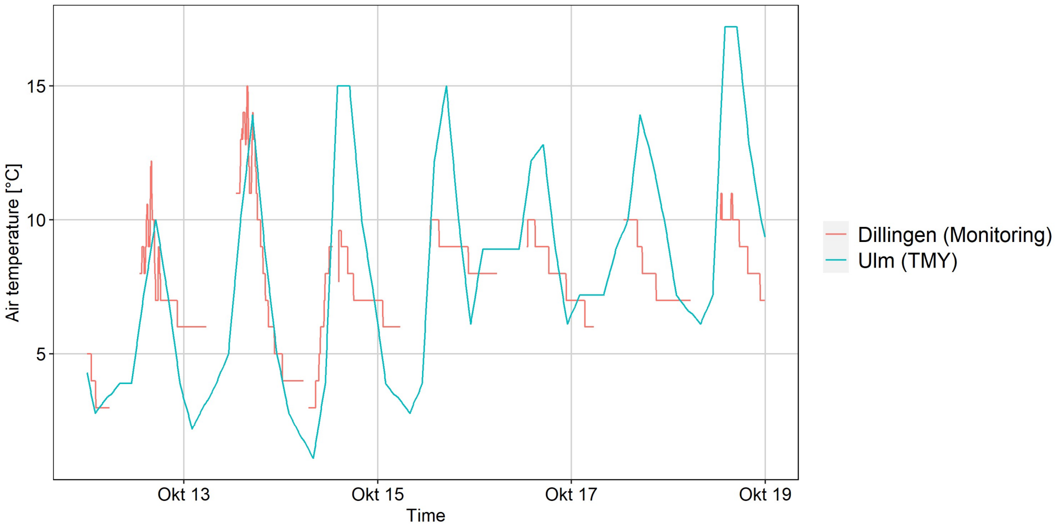


Figure 23: Temperature monitoring and EPW-File for week 42

Figure 24 shows the cumulative monitoring data for the outdoor air temperature compared to the data that was used for the simulation (TMY). The temperatures for the TMY are slightly lower than those of the monitoring data with a maximum temperature around 28 °C. Nevertheless, the overall accordance between both temperature distributions is high.

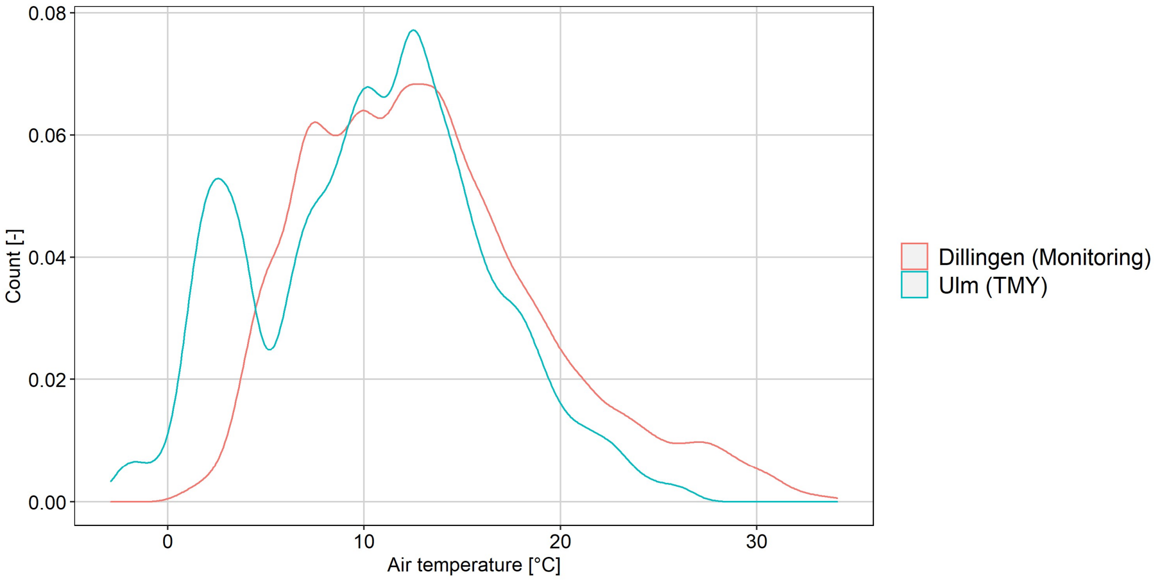


Figure 24: Cumulative outside air temperature monitoring/TMY

Figure 25 shows the distribution of the available monitoring data throughout the day. The data between 7 am and 1 pm is less sufficient than for the rest of the day, which possible influences the average air temperature. The effect was not analysed in detail.

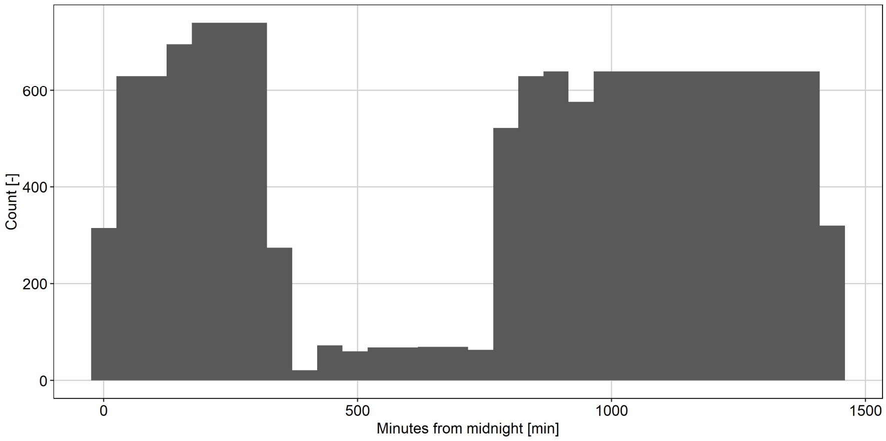


Figure 25: Histogram available monitoring data outdoor air temperature

The climate in Germany is moderate. This means, no extreme temperatures, neither cold nor hot, are experienceable. The average temperature in Europe for the months June to August is shown in Figure 26 for the years 1961 to 1990. Due to climate change, this looks possibly different today, but the tendency is likewise. While the average air temperatures for this three months period is around 20 °C in Germany, countries like France, Italy or Spain have average air temperatures as high as 30 °C. For TMY of Ulm, the average temperature is only 16.46 °C for the same period. This moderate temperature influences the results of this thesis.

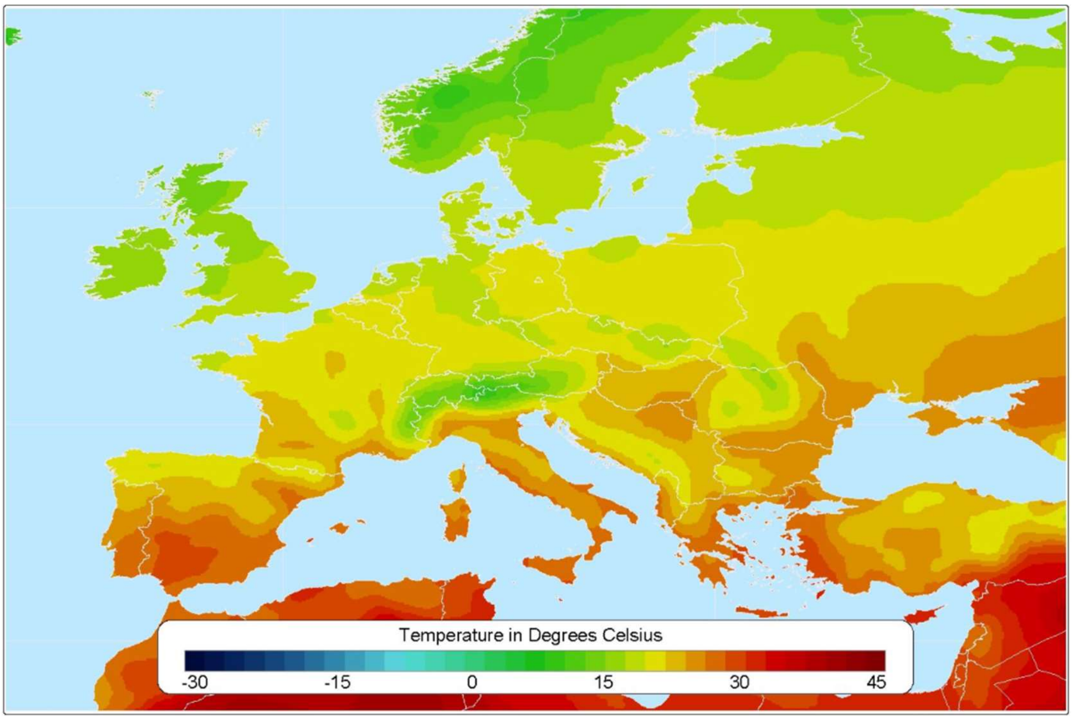


Figure 26: Average temperature in Europe, June to August (1961 to 1990) (University of East Anglia, CRU 2021)

3.2.2.2 Shading

The control strategy for the shading device was implemented in the model as described in section 2.1.3. The setpoint for the activation of the shading devices is based on illuminance levels. Since the threshold value is unknown, a value was taken from the literature. Based on the work from Arnesano et al. (2019), a threshold value of a radiance of $192\ W/m$ on the windows was defined. Indoor temperature as condition was not used because it is no part of the control strategy in Dillingen.

3.2.2.3 Decentralised ventilation unit, night ventilation and window opening

Decentralised ventilation units (DVU), night ventilation (NV) and manual window opening constitute the air exchange for the building model. User behaviour for the ventilation unit was not analysed. For this reason, the DVU is only in use following a determined building automation control. The building control that was described in Figure 7 activates the DVU at 7:00 pm and does not include a lower temperature limit where the DVU is turned off. This can cause an undesired cool down during the night. To prevent this, the control for the DVU is implemented like the building control for night ventilation, including temperature limits. This means, it is activated at 6:00 am and 7:00 pm and deactivated when the temperature limits are exceeded. Besides this, the DVUs are deactivated whenever windows are opened, or night ventilation is active.

The decentralised ventilation units, window opening, and night ventilation were implemented as one object in E+ for each window-system. The flow rate is proportional to the employees occupying the office. It is adjusted accordingly if DVU or NV are activated, or windows are opened. Only one of the three technical devices can be active/open at a time. The control system was implemented to EnergyPlus by means of an Energy-Management-System (EMS).

Mass Flow Rates

Mass flow rates were defined for open windows, NV and DVU. Information for the mass flow rate of the DVU was extracted from the product data sheet, being 37 m^3/h (0.01 m^3/s) at setting “2”.

Flow rates for open windows and night ventilation were calculated according to Wang et al. (2017). With CFD simulations, they investigated flow rates for single-sided ventilation at different opening types and angles of windows. They suggest a formula for the mass flow (M) depending on a normalized mass flow rate (M_{Norm}) and the difference between the outdoor air temperature and the room temperature (ΔK):

$$M = M_{Norm} * \sqrt{\Delta K}$$

M_{Norm} differs for different window types and the opening area. The boundary conditions that were used within their research is different to the room properties in Dillingen. The room size they used is around half the size of an average office in the main district building:

$$V_{Wang} = 2.5\,m * 3.5\,m * 3.2\,m = 28\,m^3 \text{ compared to}$$

$$V_{Dillingen} = 5\,m * 4\,m * 2.7\,m = 54\,m^3.$$

The window, that was analysed by Wang et al, is bigger than the area of the manual window and the night ventilation window of the office building combined:

$$A_{Wang} = 1.23\,m * 1.48\,m = 1.82\,m^2 \text{ compared to}$$

$$A_{Dillingen\_NV} = 0.239\,m^2 \text{ for NV and } A_{Dillingen\_Window} 0.478\,m^2 \text{ for the manual window.}$$

For the EnergyPlus model it was assumed that manual window opening is equivalent to a complete opening of the window because the difference of the mass flow rates is small until an opening area of around 1/3 of the maximum area. With an opening area of 50% of a complete opening, the mass flow rate is still approximately 90% of a complete opening. From the diagram that illustrates the computed mass flow rates (Wang et al. 2017, p. 9), the flow rate M_{Norm} for an open window can be extracted and is approximately:

$$\mathrm{M_{Norm}} = 150\frac{kg}{h}/K^{-0.5}.$$

The impact of the different room size is unknown. For this work, it is assumed to have a neglectable impact on the mass flow. The scaling depending on the window size is unknown as well and is assumed to be linear. M is:

$$\mathrm{M_{Window}} = \frac{150\frac{kg}{h}}{K^{-0.5}} * \frac{0.478m^2}{1.82m^2} \sim \frac{40\frac{kg}{h}}{K^{-0.5}} \quad \text{for the manual window, and}$$

$$\mathrm{M_{NV}} = \frac{150\frac{kg}{h}}{K^{-0.5}} * \frac{0.239m^2}{1.82\ \ ^2} \sim \frac{20\frac{kg}{h}}{K^{-0.5}} \text{ for the night ventilation window.}$$

The mass flow rate is a function of the temperature differences and was calculated in steps of 2 °C (Table 5). This was preferred over a calculation for every occurrent temperature to minimise the simulation effort. For these calculations, the indoor temperature is assumed to constantly be at 26 °C.

T_out	M_{Window} [m³/h]	[m³/s]	M_{NV} [m³/h]	[m³/s]
$T_{Out} > 24$	40	0.011	20	0.006
$T_{Out} < 24$	57	0.016	28	0.008
$T_{Out} < 22$	80	0.022	40	0.011
$T_{Out} < 20$	98	0.027	49	0.014
$T_{Out} < 18$	113	0.031	56	0.017
$T_{Out} < 16$	126	0.035	63	0.018
$T_{Out} < 14$	138	0.038	69	0.02
$T_{Out} < 12$	150	0.042	75	0.021

Table 5: Mass flow rates for different ΔK for manual window and NV

The manual window has double the area of the NV window. Due to the assumption, that M_{Norm} scales linearly with the window size, the mass flow for night ventilation is half the mass flow for the manual window. For each simulation-timestep, the temperature difference is calculated, and the mass flow rates are set accordingly. With a temperature difference of 2 °C, the mass flow rate for the manual window is the same as for the DVU.

3.3 Occupant behaviour modelling

Chapter 3.2 describes the model that was applied for the window opening behaviour. Additionally, the transfer from the ceiling fan data analysis, that was described in section 2.2.6, to a user behaviour model is explained.

3.3.1 Occupancy modelling

For the modelling process and validation purposes, the occupancy of the office rooms needs to be assessed. As occupancy data is not available, occupancy profiles cannot be modelled individually, but indirectly through the analysis of the available parameters. An approach similar to the work from Candanedo and Feldheim (2016) was used. They developed algorithms that determine the occupancy based on indoor thermal conditions or other parameters such as lighting usage and verified the results with data from a survey. A first approach using the monitoring values for lighting and CO_2-concentration as indicators was pursued analogous to Figure 10 from the introduced work. The results led to multiple arrival and departure processes during the day with no apparent pattern or evidence for the start and the end of working hours. One example is shown in Figure 27. No lighting was used at this day which makes the CO_2-concentration the only condition for occupancy. These results show an unreasonably high amount of departure events throughout the day, which might be caused by a decline of the CO_2-concentration based on window openings instead of absence.

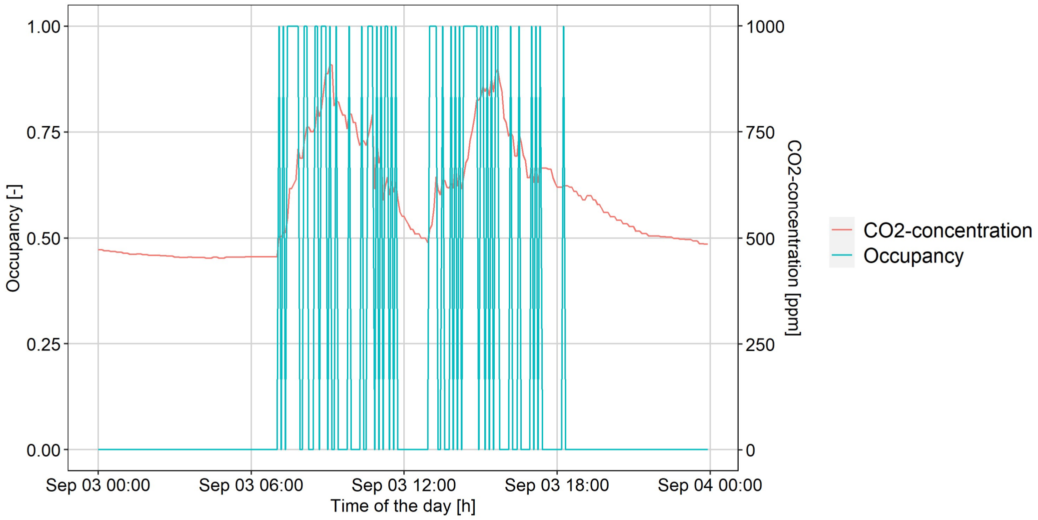


Figure 27: Room 107, occupancy and CO_2-concentration over the day

From this example, the impression arises, that it is useful to determine arrival events in the morning and departure events in the evening. Looking at the results for all 6 rooms, these times are very changeful and working hours are exceeded. The second approach was the evaluation of arrival times in the morning and departure times in the afternoon, neglecting the proceedings during the day. Over the whole monitoring period, no week with empty offices was detected for the monitored rooms, which can be seen in Figure 11 (CO_2-concentration rises every week for all rooms). The scheme to evaluate the arrival and departure times can be seen in Figure 28:

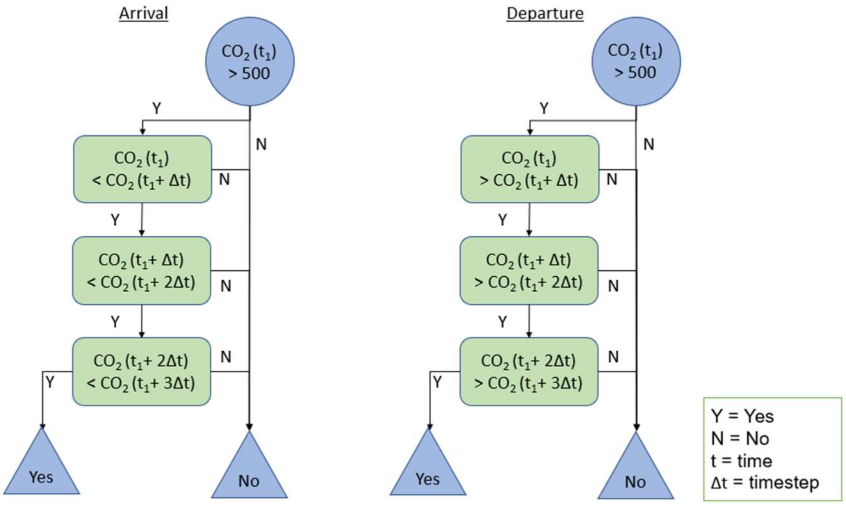


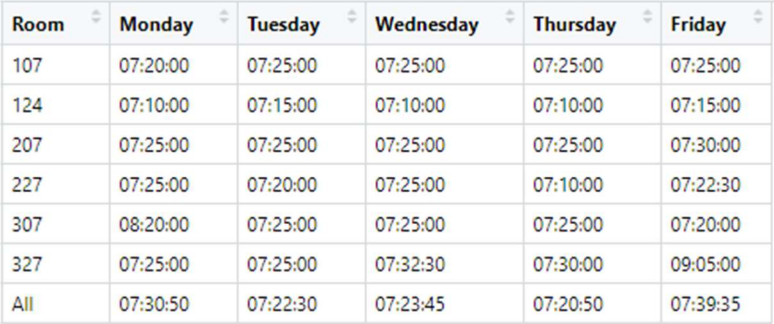
Figure 28: Arrival/departure algorithm

For each day, the first timestep that fulfilled the algorithm for arrival and the last timestep that fulfilled the algorithm for departure was calculated. The process was executed with CO_2 concentration only and with lights as additional sufficient condition. The CO_2-condition implies an increase or decrease of the CO_2-concentration over three timesteps. This was done to assure that single measuring errors do not affect the results. A minimum condition of 500 ppm is used. Otherwise, the natural variation in CO_2-concentration of the outdoor air would be detected as arrival or departure occurrences. With this algorithm, it is not possible to estimate the number of people inside the office, but only whether the office was occupied or not. However, due to safety and hygienic measures implemented in the office district because of the global Covid-19 Pandemic, it is unlikely that more than one person occupied an office on a regular basis.

The difference of the occupancy times for the different rooms and weeks is not important for the modelling process and it could even lead to overfitting of the model. On that account, the median for the start and end of work was defined for all six reference rooms from Monday to Friday over the whole monitoring period. Here, the median was chosen over the mean value to reduce the impact from single measuring errors or anomalies in the outside CO_2-concentration. To achieve one occupation profile for all rooms in the building, the mean value of the results was calculated for the six rooms combined.

The results for arrival and departure time for all workdays and all six rooms after applying both algorithms (with and without lighting) can be seen in Table 6. Even when subtracting a 90-minute daily lunchbreak, the results with light usage as sufficient condition for occupancy are not reasonable because working time would add up to more than 41 hours a week. Working hours for the algorithm assuming solely CO_2-concentration as the condition add up to around 38 hours a week, considering a 45-minute lunch break from Monday to Thursday. Therefore, the approach without lighting as condition was used.

a)

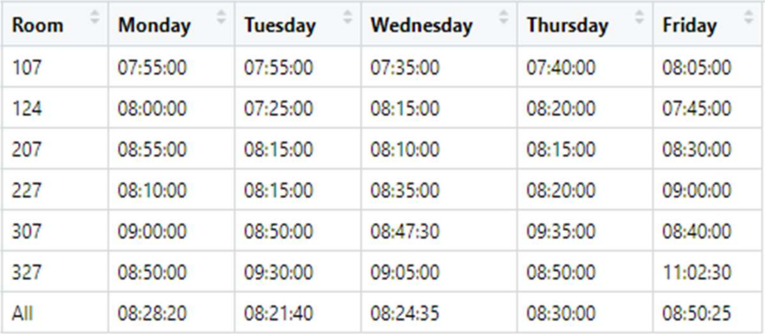


Room	Monday	Tuesday	Wednesday	Thursday	Friday
107	07:20:00	07:25:00	07:25:00	07:25:00	07:25:00
124	07:10:00	07:15:00	07:10:00	07:10:00	07:15:00
207	07:25:00	07:25:00	07:25:00	07:25:00	07:30:00
227	07:25:00	07:20:00	07:25:00	07:10:00	07:22:30
307	08:20:00	07:25:00	07:25:00	07:25:00	07:20:00
327	07:25:00	07:25:00	07:32:30	07:30:00	09:05:00
All	07:30:50	07:22:30	07:23:45	07:20:50	07:39:35

b)

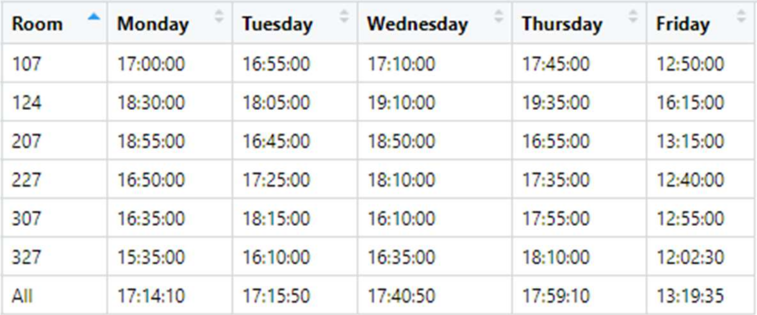
Room	Monday	Tuesday	Wednesday	Thursday	Friday
107	17:25:00	17:55:00	18:25:00	18:30:00	13:50:00
124	19:30:00	19:55:00	19:10:00	19:50:00	16:30:00
207	19:00:00	16:45:00	18:50:00	17:25:00	15:25:00
227	18:50:00	17:25:00	18:10:00	17:40:00	12:55:00
307	17:00:00	18:20:00	16:50:00	18:20:00	13:05:00
327	16:20:00	18:20:00	16:35:00	18:30:00	12:10:00
All	18:00:50	18:06:40	18:00:00	18:22:30	13:59:10

c)



Room	Monday	Tuesday	Wednesday	Thursday	Friday
107	07:55:00	07:55:00	07:35:00	07:40:00	08:05:00
124	08:00:00	07:25:00	08:15:00	08:20:00	07:45:00
207	08:55:00	08:15:00	08:10:00	08:15:00	08:30:00
227	08:10:00	08:15:00	08:35:00	08:20:00	09:00:00
307	09:00:00	08:50:00	08:47:30	09:35:00	08:40:00
327	08:50:00	09:30:00	09:05:00	08:50:00	11:02:30
All	08:28:20	08:21:40	08:24:35	08:30:00	08:50:25

d)



Room	Monday	Tuesday	Wednesday	Thursday	Friday
107	17:00:00	16:55:00	17:10:00	17:45:00	12:50:00
124	18:30:00	18:05:00	19:10:00	19:35:00	16:15:00
207	18:55:00	16:45:00	18:50:00	16:55:00	13:15:00
227	16:50:00	17:25:00	18:10:00	17:35:00	12:40:00
307	16:35:00	18:15:00	16:10:00	17:55:00	12:55:00
327	15:35:00	16:10:00	16:35:00	18:10:00	12:02:30
All	17:14:10	17:15:50	17:40:50	17:59:10	13:19:35

Table 6: a) arrival time with light and CO_2 as condition, b) departure time with light and CO_2 as condition, c) arrival time only CO_2 as condition, d) departure time only CO_2 as condition

The resulting time periods for occupancy can be taken from Table 7. As the arrival and departure times were similar from Monday to Thursday, the same schedule was applied for all four days. A later arrival and an earlier departure time were implemented for Friday.

	Mo - Thu	**Fri**
Arrival	08:25	08:50
Departure	17:30	13:20

Table 7: Mean arrival and departure times

The occupancy schedule results were implemented according to the table. This schedule implies approximately 41 working hours per week, which does not reflect the average working hours per employee and week for Dillingen. To consider absence due to vacation or sick leaves, and employees that do not work full-time, only a fraction of the maximum number of workers is present during the working hours. The average working hours originate from the results of the questionnaires, which were carried out to investigate user behaviour and occupant satisfaction within the building:

$$(1)\quad Working\ hours\ (without\ breaks) = 41,$$

$$(2)\quad Average\ working\ hours = 27,$$

$$(3)\quad Vacation = 10\%,$$

$$(4)\quad Sick\ leaves = 5\%,$$

$$\rightarrow Fraction = \frac{27}{41} * 0.9 * 0.95 = 0.56.$$

This fraction refers to conditions with an absence of the Covid-19 Pandemic. For the validation process, a lower fraction is applicable due to the home office restrictions during the monitoring period that led to a lower attendance. This will be discussed in chapter 3.4.

3.3.2 Window opening behaviour and sensitivity

For the window opening behaviour, the model by Haldi et al. (2009) was used. Based on several years of monitoring, they created a window opening behaviour profile depending on indoor air temperature, outdoor temperature, precipitation, and occupancy. As part of their findings, they stated that most of the window opening actions take place when arrival or departure events occur (Figure 29).

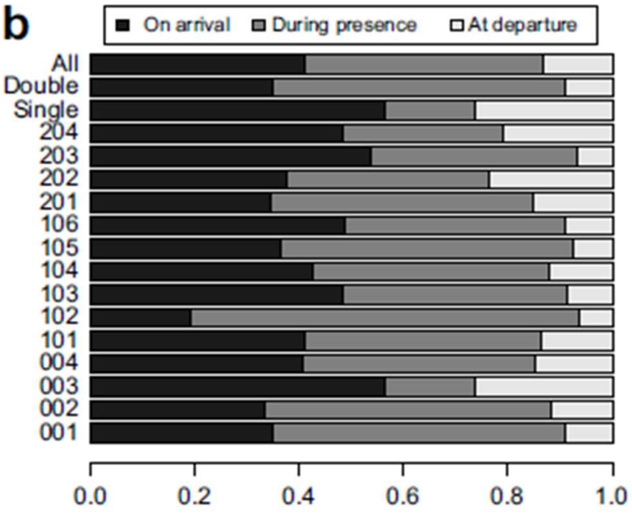
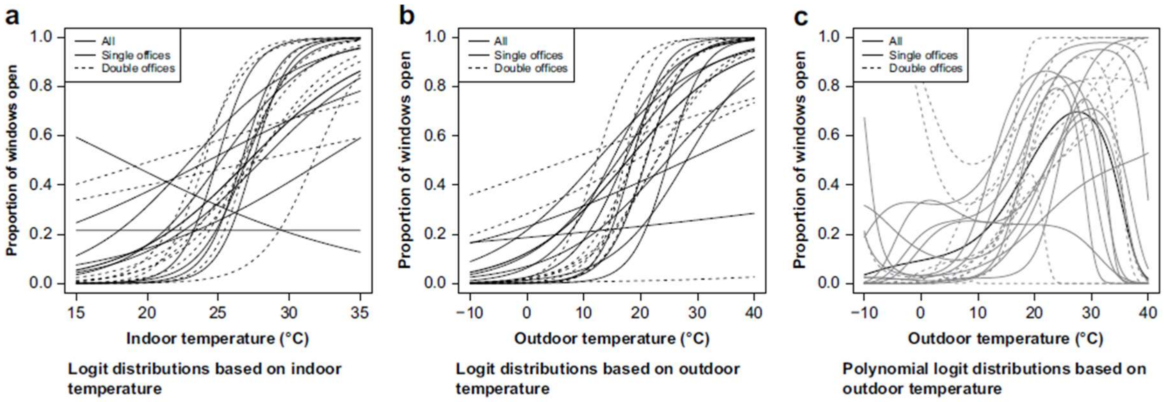


Figure 29: Window openings for different occupancy situations (Haldi and Robinson 2009, p. 2383)

The proportion of windows open increased with a rising indoor temperature (Figure 30, a). This is also the case for a rising outdoor temperature until a certain temperature, where the trend reversed (Figure 30, c).



Logit distributions based on indoor temperature

Logit distributions based on outdoor temperature

Polynomial logit distributions based on outdoor temperature

Figure 30: Occupant specific probability distributions (Haldi and Robinson 2009, p. 2389)

With logit regression (formula) they calculated the probability of a window opening or closing action:

$$p(x_1, \dots, x_p) = \frac{\exp\left(\beta_0 + \beta_1 x_1 + \dots + \beta_p x_p\right)}{1 + \exp\left(\beta_0 + \beta_1 x_1 + \dots + \beta_p x_p\right)} \ ,$$

where β_i are constants estimated through regression and the variables x_i are thermal parameters. The constants were determined using the results of their survey and define a certain behaviour. The resulting model includes random numbers so that personal preferences are determined randomly. The probability is not only depending on the thermal conditions but also on the occupancy status (absence, arrival, ongoing presence, or departure). Logistic regression is useful to determine variables with a concrete state, in this case 1 or 0 for closed or open windows. After calculating the probability of a certain state, a random number between 0 and 1 is created and compared to the probability.
Example at the fourth timestep:

$$WindowState_4 = 1\ (Closed)\ ,$$

$$p_{Opening_4} = 0.24\ ,$$

$$RandomNumber_4 = 0.1382\ ,$$

$$WindowState_4 = 0\ (Open)\ .$$

The only adaptation that had to be made to Haldi’s model to fit the boundary conditions for the simulated building was the integration of a window closing event after departure time, which is not considered in Haldi’s model. The latter is necessary to fulfill the office building’s safety requirements. All open windows are closed at 6:00 pm.

Sensitivity analysis

The building model contains more than 200 windows in total whereof 192 are office manual windows. Most of the windows are used by different employees. It is very time-consuming to simulate a different behaviour for every occupant. Additionally, it is unknown, whether an approach with 192 different behaviours is a better representation of the opening processes in the office building than using the same behaviour for all occupants. Because of that, it is necessary to investigate the changes resulting from different opening behaviours and therefore different constants. Four cases were simulated:

1. All windows are operated with the same opening behaviour.
2. 10 different behaviours, randomly allocated to the windows.
3. 50 different behaviours, randomly allocated to the windows.
4. All windows are operated with a different opening behaviour (192 profiles).

The four cases were compared and analysed, looking for noticeable differences between the thermal conditions, which are influenced by the state of the windows. For these simulations, NV and DVU were not activated so the results are not influenced by other air change than that by manual window opening. To indicate the difference between the four different quantities of window behaviours, the mean air temperature difference between case 1 and cases 2 to 4 were calculated. Secondly, the squared difference was calculated according to the following formulas:

$$\Delta T = \frac{1}{N} * \sum_{t_0}^{t_N} (T_{Occu1}(t_n) - T_{Occu_i}(t_n)) \quad ,$$

$$\Delta T^2 = \frac{1}{N} * \sum_{t_0}^{t_n} (T_{Occu_1}(t_n) - T_{Occu_i}(t_n))^2 \quad .$$

The results are depicted in Figure 31:

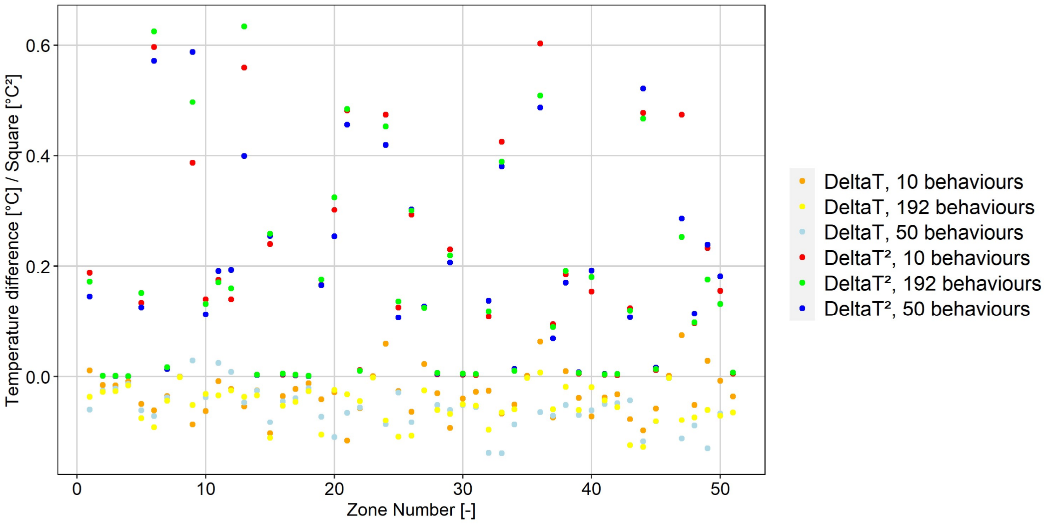


Figure 31: Difference in T and T² between case 1 and case 2 to 4

The different zones are plotted over the x-axis. The difference in air temperature for case 2, 3 and 4 compared to the same behaviour for all windows (case 1) is plotted over the y-axis. The temperature differences for the zones with no occupancy are marginal. The mean temperature difference is less than 0.2, the squared mean temperature difference is less than 0.6 for all cases and all zones. Two examples for different weeks and thermal zones are shown with the air temperature as thermal indicator (Figure 32 and Figure 33).

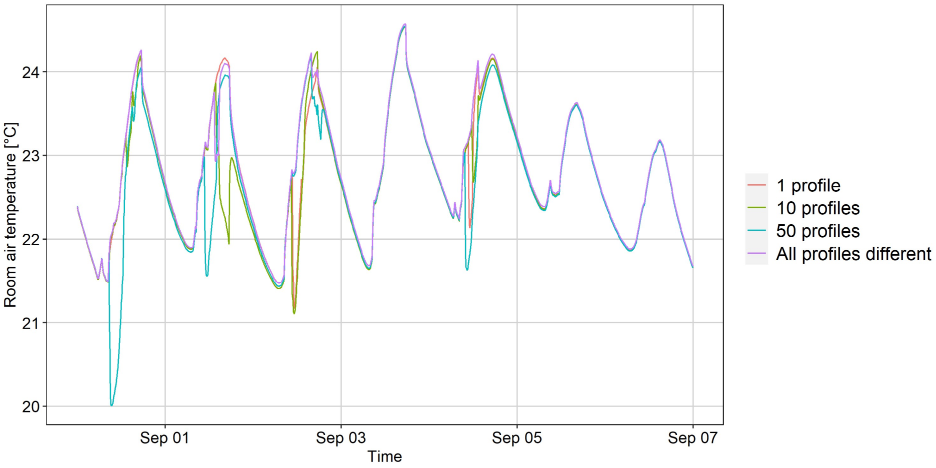


Figure 32: Window opening behaviours, Zone 1, week 36

The only differences between the cases are some downward peaks as the window opening and closing times are not the same. After the temperature drops, the windows are close, and the profiles converge. Apart from that, the behaviour profiles generally are like each other. Based on these results, the same window opening behaviour for all windows in the office was used.

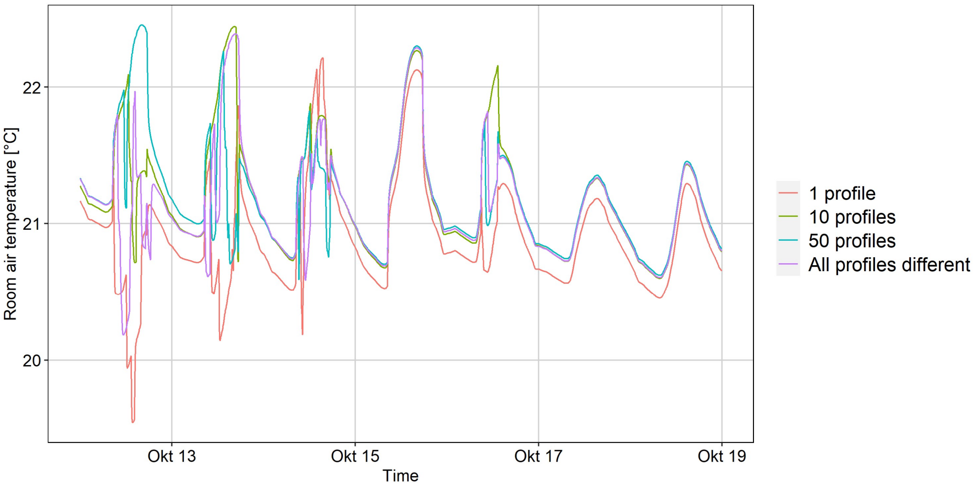


Figure 33: Window opening behaviours, Zone 32 week 42

3.3.3 Ceiling fans

The monitoring data was used to model the occupant behaviour towards the ceiling fan usage. As observed in Figure 16, the distribution of the ceiling fan usage is similar to a logit function and can be described with an “on/off behaviour” with two state conditions (section 3.3.2). Because of that, logistic regression was used, analogous to previous user behaviour research (Liu et al. 2012). The probabilities of the ceiling fan usage were calculated depending on indoor air temperature. An occupancy fraction of 0.2 was used to determine the occupancy of the offices. This means that 20% of the maximum occupancy is reached during the working hours. The determination of the occupancy is shown in Figure 34. From all measured data points (D_1) the periods that are outside of the working hours are excluded (p_1). From the remaining set of data (D_2), the data points with active ceiling fans (D_3, p_2) are separated from the data points with deactivated ceiling fan (D_4, p_2). For D_3 it is assumed that the office is occupied. For the data set without active ceiling fans, the remaining data points with occupation to make an occupancy fraction of 0.2 are determined randomly (D_5, p_4). These data sets (D_3 and D_5) are the basis for the logit regression.

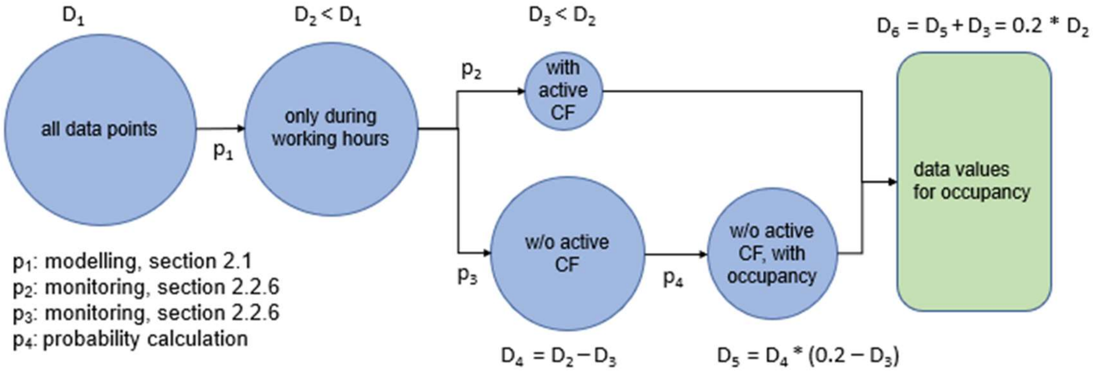


Figure 34: Occupancy determination for ceiling fan usage

Logit regression was explained in section 3.3.2. With the according R-function, the probability of ceiling fan usage depending on the indoor air temperature was computed. Exemplary probabilities for different indoor temperatures are shown in Table 8. At 22 °C, 5% of the employees use the ceiling fan to improve their thermal comfort. More than 62% make use of the ceiling fan at 30 °C.

	22 °C	**24 °C**	**26 °C**	**28 °C**	**30 °C**
P (Fan = On)	0.05	0.111	0.228	0.411	0.623

Table 8: Exemplary probabilities for ceiling fan activation

3.4 Calibration and validation

This chapter presents a description of how the missing parameters were calibrated, and an explanation of the validation process. This is vital to assure the validity of the simulation results.

During validation of the computed temperature distributions, three factors, which entail adaptations to the model and the choice of weeks, were identified. Firstly, even though week 42 has a similar temperature profile, outdoor temperatures observed in week 41 were much colder in the TMY in Ulm than in Dillingen in 2020 (Figure 35). Since no heating was implemented in the building model at this point, the simulation results for the temperature in the building are considerably colder compared to the monitoring results.

Therefore, they were not usable for validation purposes. Secondly, as described in section 2.2, there is a data gap for the second half of week 37, which negatively influences the viability of the validation results for this period. Thirdly, during validation it arose that night ventilation was deactivated on the 1st of September (section 2.2.4). Therefore, a period before the deactivation must be chosen to calibrate the temperature setpoint for night ventilation.

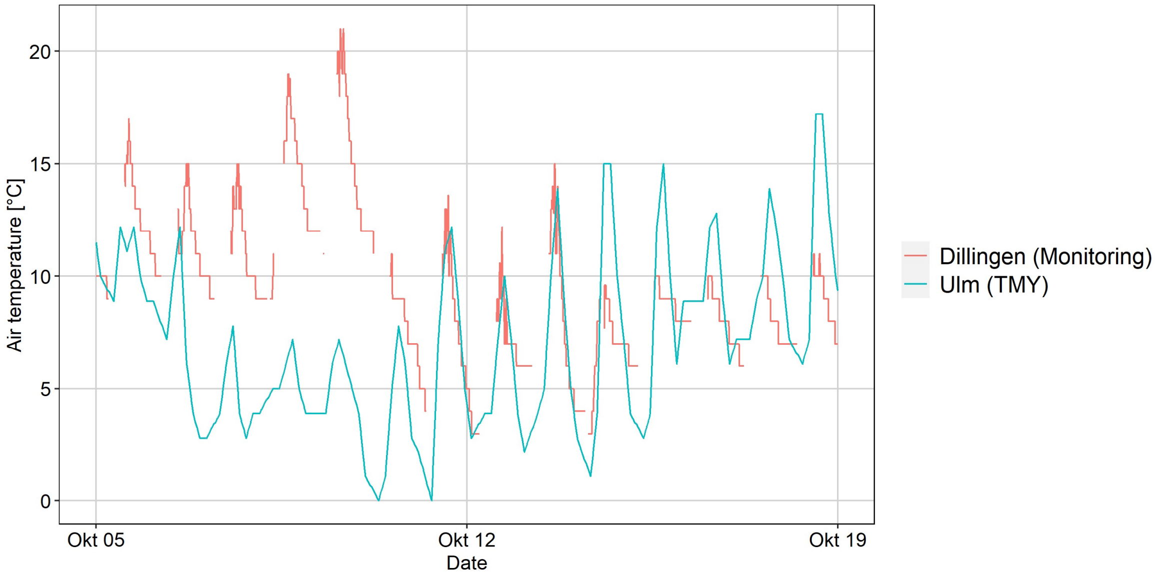


Figure 35: Difference in air temperature for Dillingen (Monitoring) and Ulm (TMY)

As a result, a heating was added to the model so that colder periods are considered. The energy demand for heating is neglected for the evaluation of the simulation results. For the validation, the night ventilation works according to the building control and is deactivated on the 1st of September. Lastly, week 35 was used additionally to week 36, 37, and 42 for validation and calibration of the temperature setpoint because in this week, the monitoring of the air temperature is the most complete in August (section 2.2.1) and the air temperature for the TMY of Ulm is closest to the monitoring data for Dillingen.

3.4.1 Sensitivity analysis to unknown parameters

As already described in section 2.1.6, internal loads result from employees, lighting, and electric equipment, and are calculated based on a fraction of the maximum number of employees per zone. As already mentioned in section 3.3.1, it is unlikely that the calculated occupancy fraction of 0.56 in the building is reached due to Covid-19 restrictions and home office recommendations. This makes a calibration of the occupancy necessary.

The second unknown parameter is the setpoint temperature at which the windows for night ventilation are opened/closed and at which the DVUs are activated/shut-off (section 2.1.5).

To define, which occupancy fractions and setpoints deliver the results closest to the monitoring values, a parameter variation was performed. The selected values, both for occupancy fraction and temperature setpoint (Table 9) are based on the results of the monitoring data analysis.

	Fraction of People [-]	**Setpoint [°C]**
Value 1	0.1	21
Value 2	0.2	22
Value 3	0.3	23

Table 9: Parameter variation values

For each of the nine different combinations of these parameters, a simulation was performed according to the monitoring conditions:

- Timestep: 5 minutes
- Period: 12th of August until 11th of November
- Ventilation: Natural ventilation and night ventilation until the 1st of September
- Heating setpoint: 20 °C

The heating system was implemented in the model as an ideal system to overcome the cool weather in week 41 (Figure 35). With the obtained results, the squared mean temperature differences between monitoring and simulation were calculated for week 35, 36 and 37 as well as for week 42 for each of the office zones:

$$\Delta T^2 = \frac{1}{N} * \sum_{t_0}^{t_n} \left(T_{Monitoring}(t_n) - T_{Simulation}(t_n)\right)^2 \quad .$$

The results for week 35 suggest that a setpoint of 22 °C for night ventilation delivers the outcome that fits the monitored air temperature the most (quadratic difference is lower than at 21 °C or 23 °C). Albeit, it is not clear, which occupancy fraction fits the most. Weeks 36 and 37 were calculated as one period as the conditions are the same (no night ventilation and the weeks are coherent). ΔT^2 was calculated for a setpoint of 22 °C only because this temperature setpoint was defined using week 35 and the setpoint is not relevant after this week due to the deactivation of night ventilation.

Week		**35**			**36 & 37**			**42**		
	Setpoint	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3
ΔT^2 [°C²]	21 °C	4.485	4.472	5.023						
	22 °C	3.39	3.327	3.322	1.554	1.687	1.871	5.826	5.137	4.497
	23 °C	3.69	3.79	4.03						

Table 10: Parameter variation results for four different weeks

Results for the single zones can be found in Annex 6. Based on the results from Table 10, 22 °C is used as temperature setpoint for the building model due to the lowest discrepancy between monitored and simulated air temperature. Figure 36 shows the indoor temperatures for the different occupancy fractions. Further reduction of the temperature difference could be reached with a variable setpoint. However, this would lead to an overfitting of the model and would not be constructive.

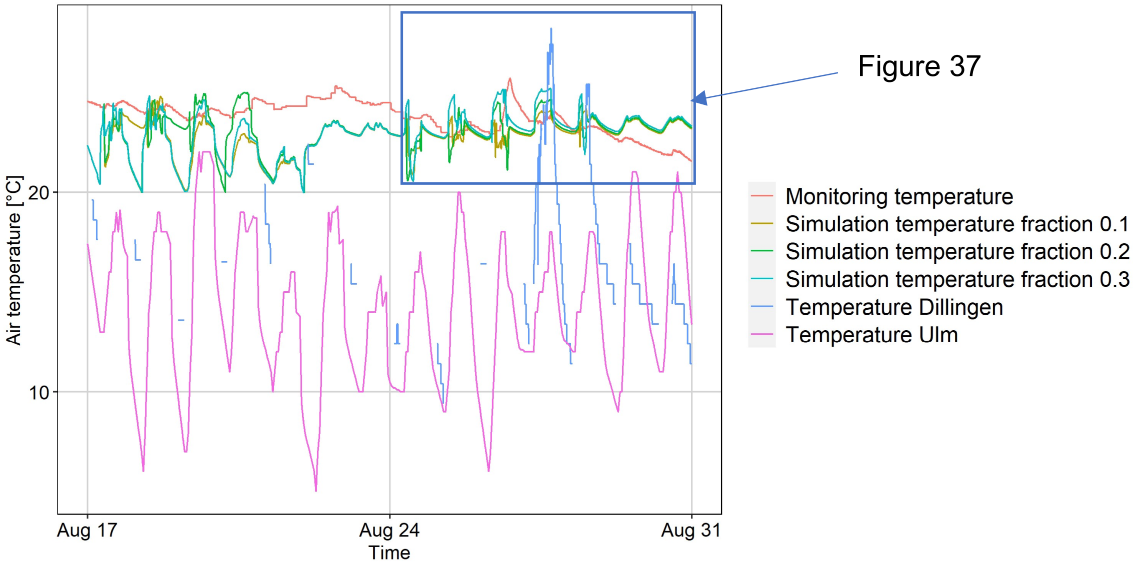


Figure 36: Temperature for different occupancy fractions (Zone 24)

Upward peaks are higher for a larger fraction (Figure 37, cut-out of Figure 36), which indicates the higher internal loads. Nonetheless, it is not distinctive, which fraction comes closest to the occupancy during monitoring.

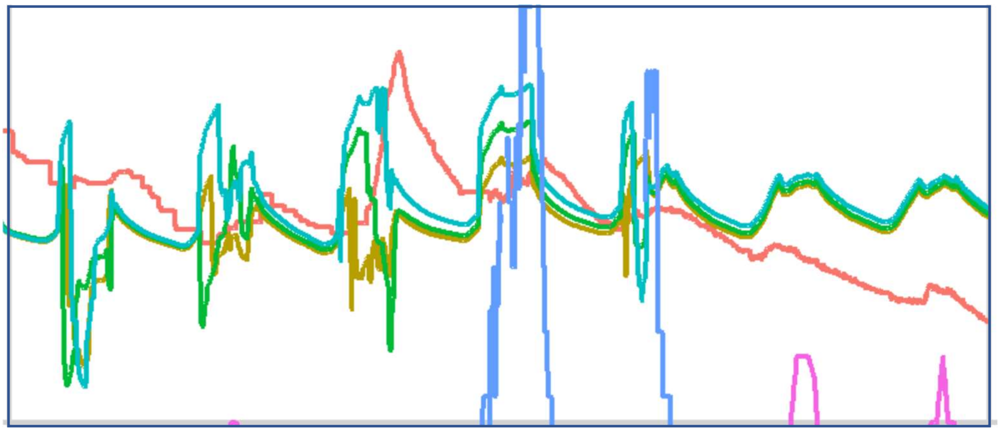


Figure 37: Temperature for different occupancy fractions (Zone 24), cut-out

The cumulative temperature distribution for week 35 is depicted in Figure 38. The values from the individual zones were proportionally weighted to the maximum office occupancy, both for monitoring data and for simulation results. This means that the air temperatures that every employee experiences are depicted, so the value for a zone with 10 employees appears 10 times. The values differ only marginally. There is hardly a difference in the cumulative distributions between the different fractions, although higher fractions logically lead to higher temperatures. The impact from the fraction is low though and a fraction of 0.2 will be used for the validation process.

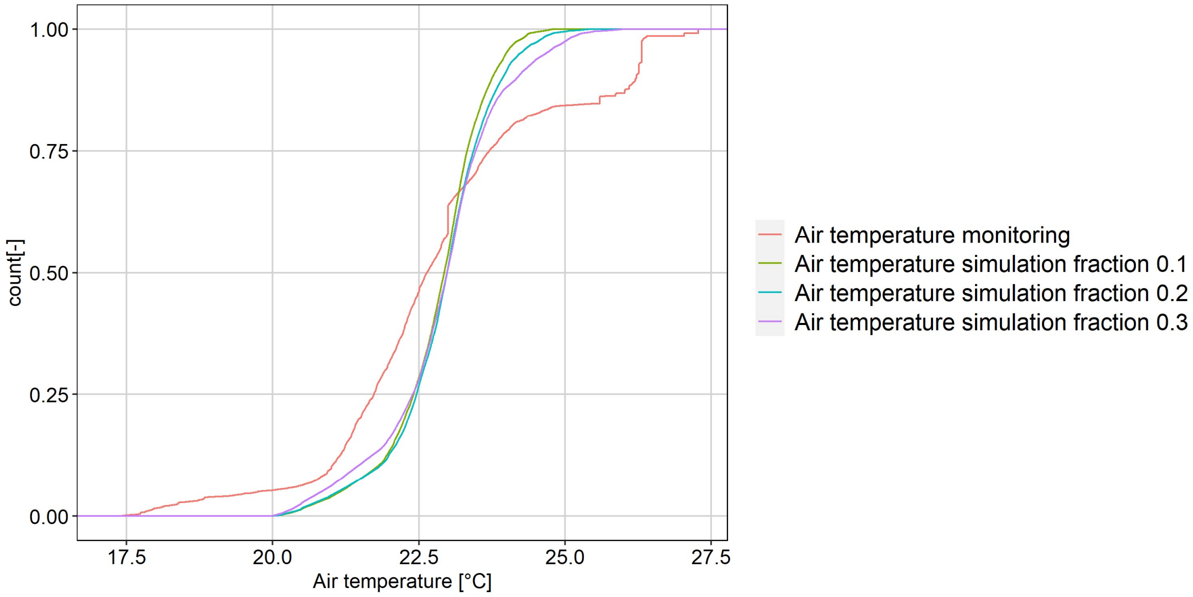


Figure 38: Cumulative temperatures all zones for week 35

3.4.2 Validation

Figure 39 shows the room temperature profile for zone 24 for an occupancy fraction of 0.2 and a temperature setpoint of 22 °C (for night ventilation) for the whole monitoring period as example. At the end of the period, a heating system ensures that the room temperature does not fall below the setpoint of 20 °C.

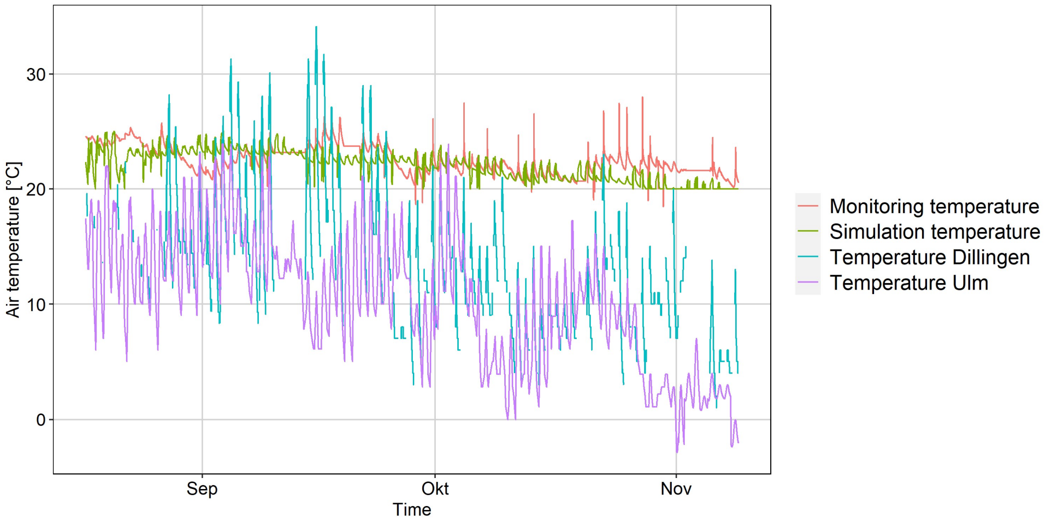


Figure 39: Temperature profile for the whole monitoring period (Zone 24)

The accordance of the monitoring and simulation results for certain weeks was already evaluated within section 3.4.1 indicated by ΔT². Another indicator for the whole simulation period is the weekly average of the outdoor and room air temperatures (Figure 40) and the cumulative distributions of the room air temperature (Figure 41), both for simulation and monitoring.

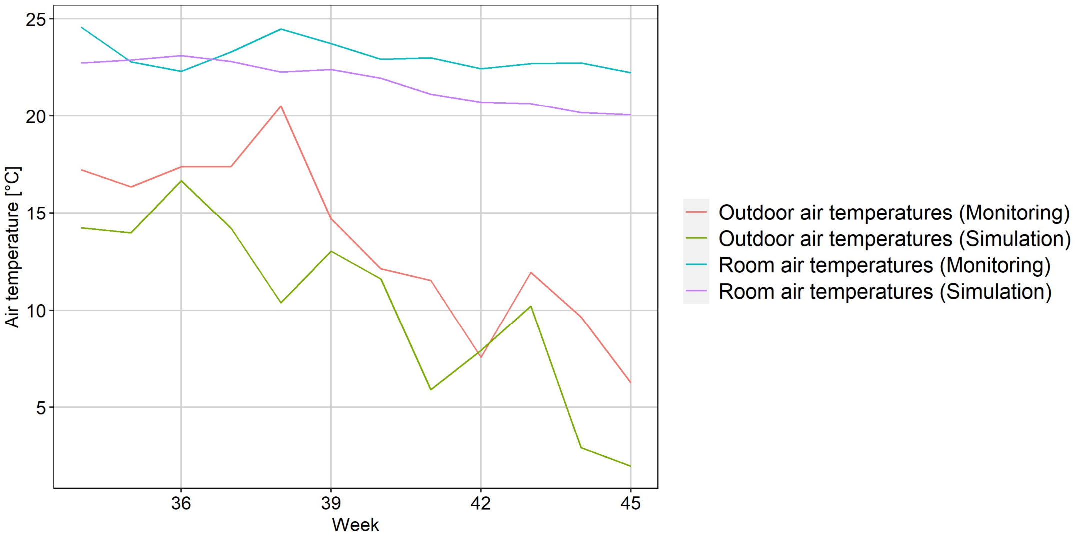


Figure 40: Weekly average of outdoor and room air temperatures for monitoring and simulation

The temperatures for the simulated room air temperatures are slightly lower than the monitoring data. This results from the difference of the outdoor air temperatures that was already explained in section 3.2.2.1 and is visible in Figure 40. The peak at 20 °C for the simulated room air temperatures results from the deactivation of night ventilation at 20 °C and a heating setpoint of as well 20 °C. Besides these variations, the accordance is high.

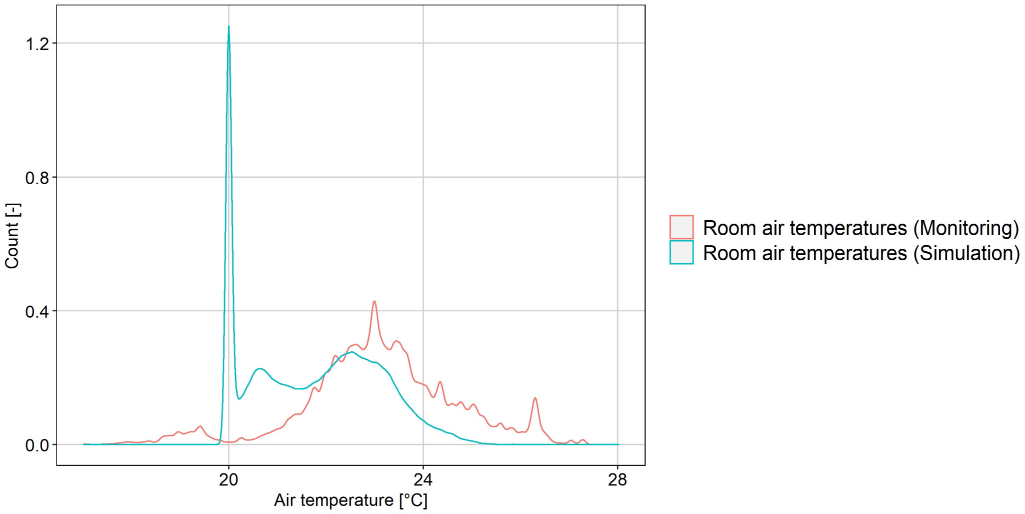


Figure 41: Cumulative distribution of the inside air temperature for monitoring and simulation

3.5 Simulation results

Within this chapter, the results for the simulations of the different concepts that were introduced in section 1.4 are shown. As one indicator for the indoor air condition, the room air temperature will be compared. Secondly, the cooling loads for the concept with air-conditioning are summarized. The simulations were carried out under the following boundaries:

- Timestep: 5 minutes
- Period: 1st of April until 30th of September
- Boundary conditions for the building according to section 2.1 and 3.2
- Setpoint for NV: 22 ± 2 °C (section 3.4)
- Cooling and heating setpoint: 24 °C / 20 °C.
- Occupancy fraction: 0.56 (section 3.3.1)
- Window opening behaviour according to section 3.3.2

The run period was extended from April to September to include the whole cooling season. This is necessary to calculate the yearly electricity demand. Three of the four concepts were modelled:

- Concept NoCooling: No ventilation or air-conditioning (situation before renovation)
- Concept NV: Night ventilation
- Concept ACS: Air-conditioning system (decentralised, ideally modelled)

Since the air speed is not considered within E+, the concept with night ventilation and ceiling fans (NVandCF) is the same for the simulation and it is therefore not simulated again. The use and the impact of ceiling fans is part of the post-processing (section 3.5.3).

3.5.1 Cooling energy consumption

The main cooling loads occur from June to August (Figure 42). Worth mentioning is the difference of cooling loads that are discharged by an ACS that is only active during occupancy (ACS_Occupancy) and cooling loads of a permanently activated ACS (ACS_Permanent. Outside the occupancy hours, more cooling loads that result from the thermal inertia of the building or high outdoor temperatures in the evening are discharged through the building envelope. Cooling loads for the whole year add up to ~ 18,800 kWh for ACS_Permanent and to **16,900 kWh** for ACS_Occupancy. For further considerations, ACS_Occupancy is used. With a floor area of approximately 872 m² per story in the office building and four floors, the conditioned area adds up to 3488 m². For ACS_Occupancy, this means a specific cooling energy consumption of **4.85 kWh/m² per year.** The peak loads for all office rooms are on average 0.603 kW per person.

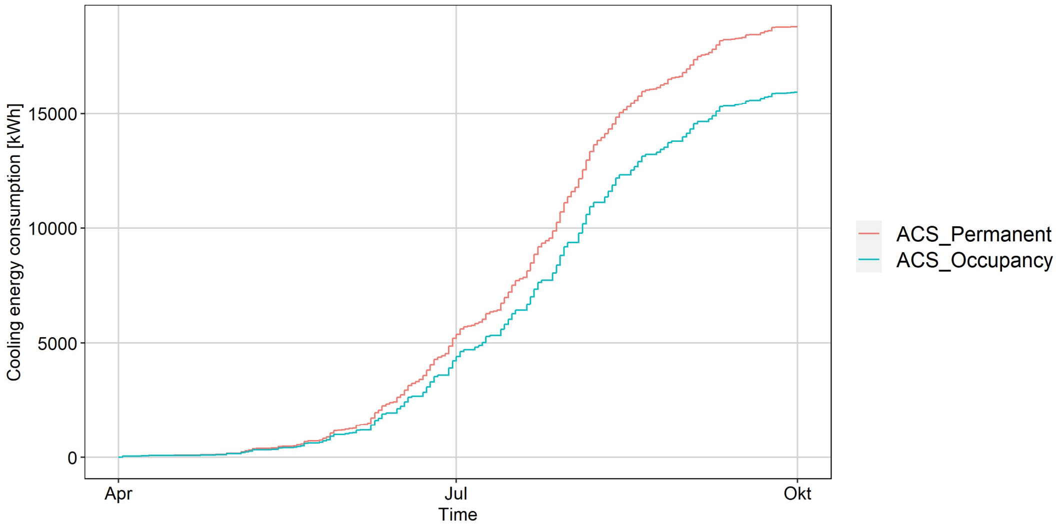


Figure 42: Cumulative cooling loads different concepts

3.5.2 Room temperature distribution

In this section, the temperature distributions of the three different cooling concepts that were simulated are compared. The temperature distribution is the focal parameter for the evaluation of comfort and productivity. Zone 24 shown in Figure 43 serves as an example.

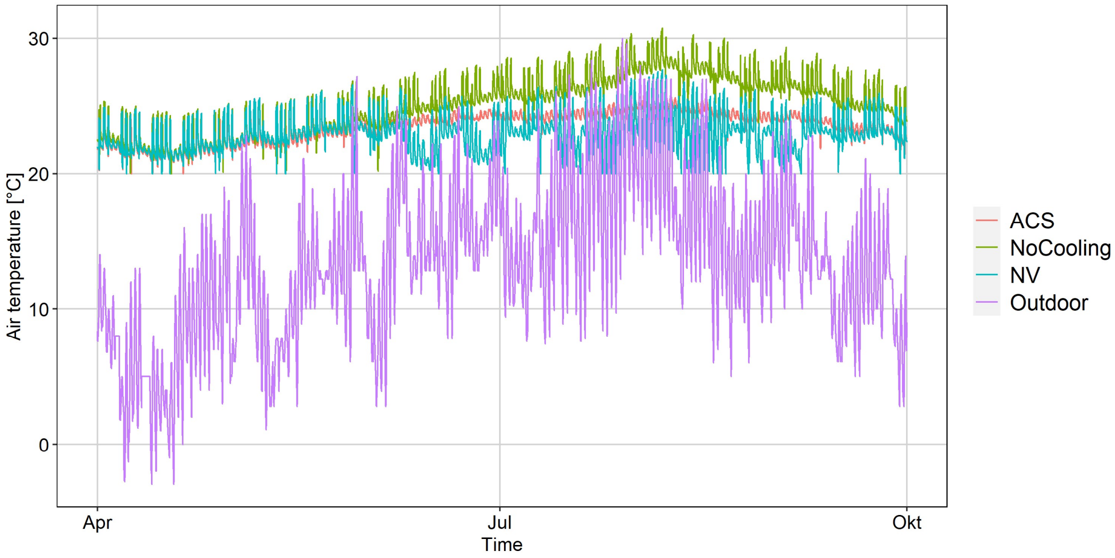


Figure 43: Air temperature over the year for different cooling strategies (Zone 24)

The concept without any cooling strategies (NoCooling) has room temperatures higher than 30 °C in summer. Additionally, indoor air temperatures are still higher than 25 °C in September even though the outdoor air temperature decreases. This is, because air exchange through open windows only occurs during occupancy times and the improved building envelope reduces the conductive heat transfer. Compared to concept NoCooling, the results for the concept with night ventilation (blue line) show less overheating during summer. The peak indoor air temperatures are around 29 °C. The temperature oscillation is larger because of the air change at night that provides room temperatures at 20 °C if the outdoor temperature falls below this setpoint. Regarding the concept with ACS, temperatures higher than 24 °C appear only outside the office hours due to the thermal inertia of the building and high outdoor temperatures in the evening.

Besides, a cumulative temperature distribution was plotted to show the difference in air temperature between the concepts for the whole building (Figure 44). All temperatures were weighted according to the maximum occupancy (1 to 20) of the associated zone. This was done to represent the different amount of floor area and air volume of these zones, which correlates with the maximum occupancy. By now, rooms with no regular occupancy were neglected. For this comparison, these air volumes are also considered as the rooms are used occasionally. Staircases and restrooms are weighted with 1, corridor, foyer, and lobby are weighted with 2 considering the respective floor area. The following vector V_T shows the quantity of repetitions of the different rooms (index) for one time step. The temperatures for zones 1, 3 and 4 occur 2 times (2 employees, lobby, foyer), T_2 once (restroom) and T_5 12 times (12 employees).

$$V_T = \left[T_1, T_1, T_2, T_3, T_3, T_4, T_4, \underbrace{T_5, \dots, T_5}_{12\ times}, T_6, \dots, T_{51} \right]^T .$$

Figure 44 excludes the timesteps outside the occupancy. The cumulative distribution shows the lowest temperatures for the concept with night ventilation. This results from the temperature setpoints: the ACS does not cool the air temperature lower than 24 °C, while night ventilation is deactivated at 20 °C. The highest temperature is present for the concept with no cooling strategy.

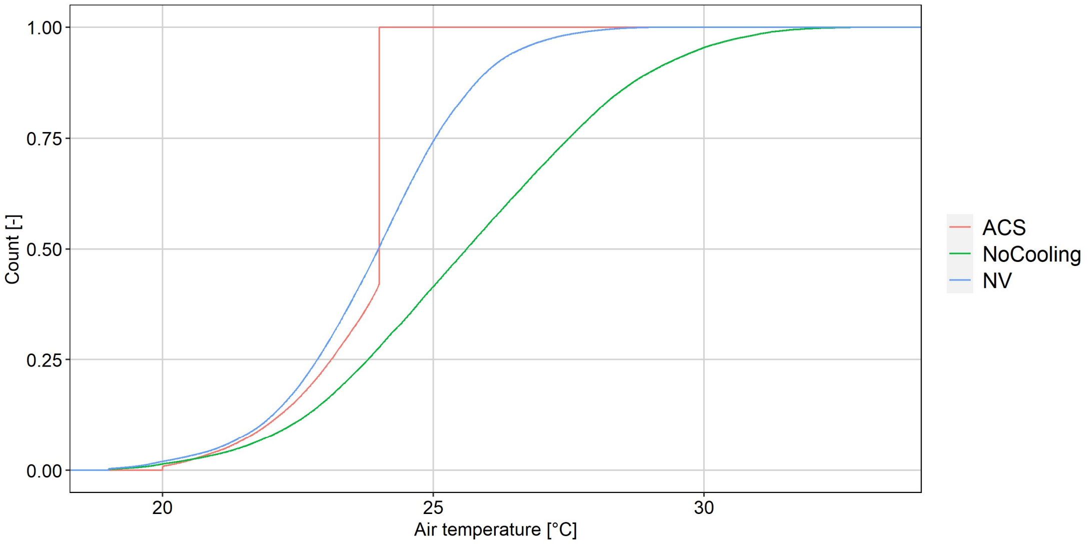


Figure 44: Cumulative temperature distribution whole building

3.5.3 Ceiling fan activation

On account of the probabilities from section 3.3.3, the ceiling fan activation was determined for concepts NoCooling and NV for the whole building and monitoring period. Albeit no cooling strategy with ceiling fans and without night ventilation is part of this research, it assists as reference and underlines the effect of night ventilation. Figure 45 shows the cumulative distribution of room temperatures with active ceiling fan. While the results for the concept NVandCF are similar for simulation and monitoring, the air temperatures with active ceiling fans are relatively higher for the concept with solely night ventilation. This is reasonable due to the warmer temperatures and the higher probability for ceiling fan usage with increasing temperatures.

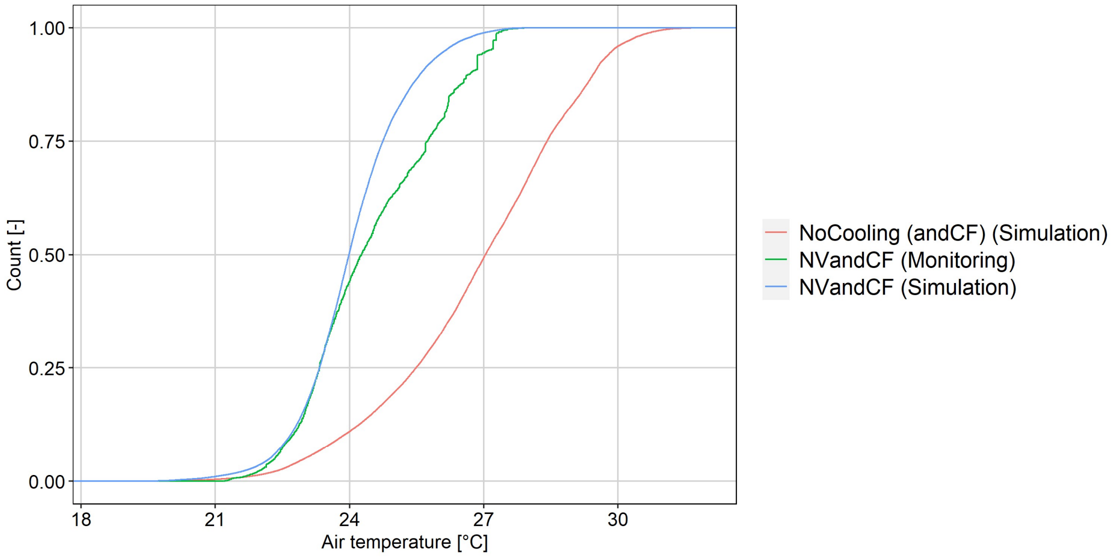


Figure 45: Temperatures with active ceiling fan, cumulative

The fan usage over time is shown in Figure 46. During the calendar weeks with lower outdoor temperatures, the difference between the time of fan usage is marginal. When the outdoor temperature increases (week 23), the difference of the ceiling fan is visible. The months when the ceiling fan is mostly used are July and August (week 27 to 36).

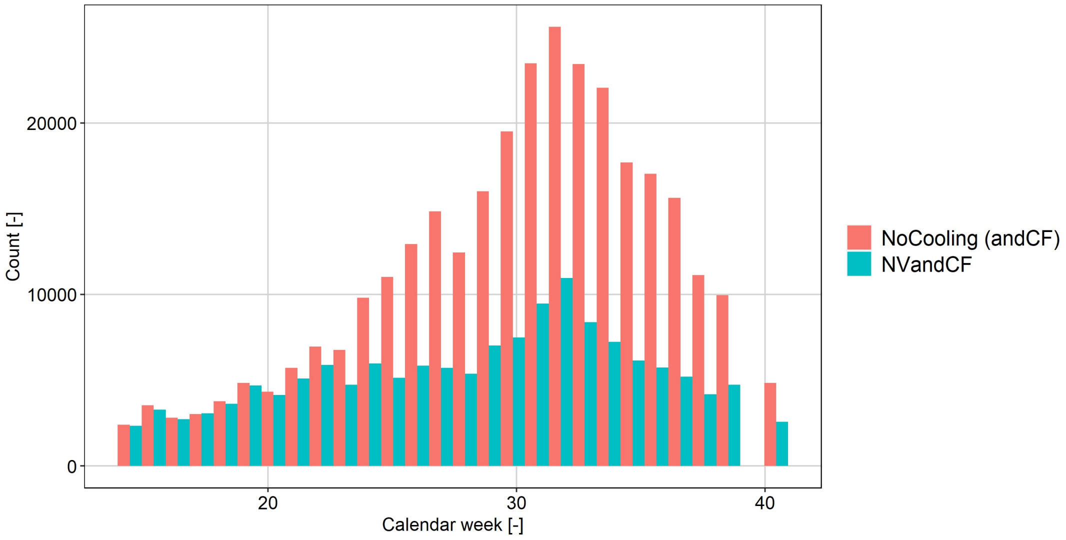


Figure 46: Histogram ceiling fan activation depending on the calendar week

Figure 47 shows the indoor air temperatures with active ceiling fan as histogram for NVandCF (simulated) and NoCooling with CF (simulated):

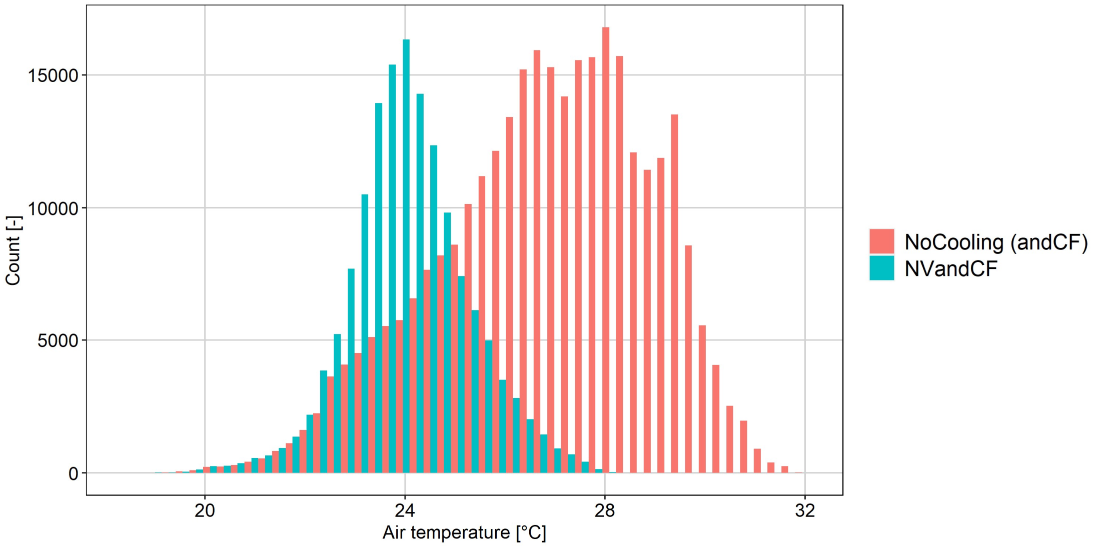


Figure 47: Histogram ceiling fan activation depending on the air temperature for the concepts with and without night ventilation, weighted, whole building

Figure 48 shows the indoor air temperatures according to the weighting from section 3.5.2 for both concepts. Especially for the concept with no cooling, the different shape of the graphs is perceptible. While the air temperature distribution (Figure 48) is symmetrical, the temperature distribution with active ceiling fans (Figure 47) has a skewness to the right. This results from the higher probability to turn the ceiling fan on when the indoor air temperature increases.

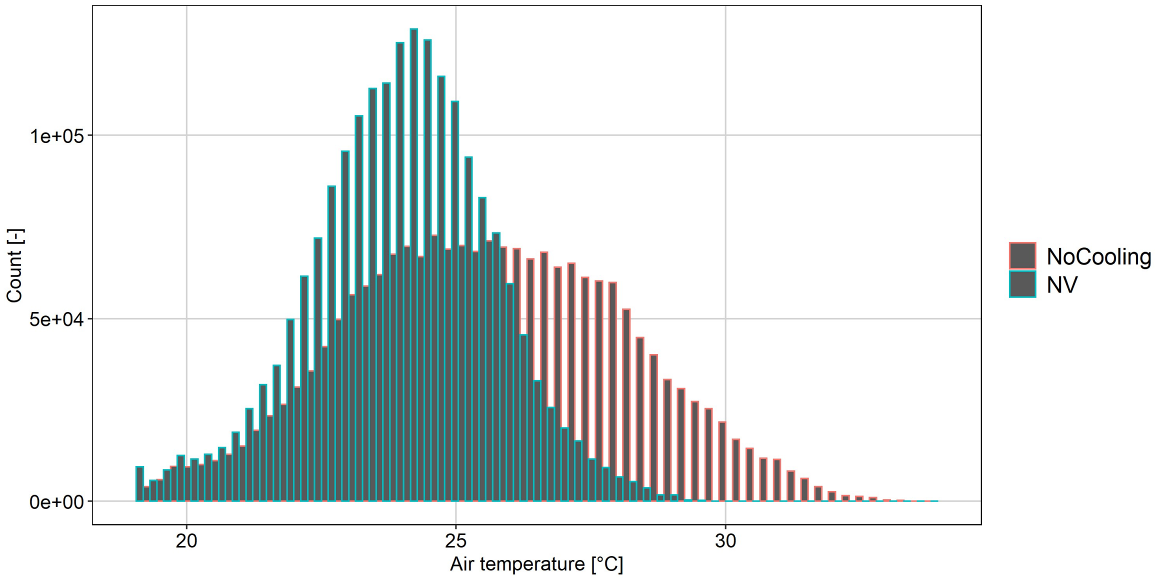


Figure 48: Histogram air temperature whole building

In sum, 146,820 timesteps with NV (7.39% of occupancy time) and 311,789 timesteps without NV (15.7% of occupancy time) were identified as timesteps, where the ceiling fan is active. Considering 157 employees implies that every employee uses the ceiling fan on average for 77.9 hours with NV and for 165.5 hours without NV. For the following calculations, only the results of the concept NVandCF are evaluated.

3.6 Modelling limitations

One model limitation is the simplification of the floor layouts and the aggregation to zones (section 3.2). Another limitation that concerns the validation process is the absence of an adequate weather data for the building's location. As explained in section 3.2.2.1, the chosen weather data file shows significant differences to the monitored air temperature. Further limitations regarding the modelling process are caused by the considerations concerning window opening. The mass flow explained in section 3.2.2.3 increases linearly with every open window with the simulation. However, the mass flow model is only valid for a room with one single window and no occurring cross-ventilation. Most of the rooms in the building contain more than one window and doors, which makes cross-ventilation possible. This makes the applicability of the model for this work uncertain. Aside from that, only completely opened windows are considered, not tilted ones. Recent findings indicate a limited applicability of the window opening behaviour model by Haldi (e.g., Schweiker et al. 2012, Haldi et al. 2017). This applies especially to buildings with air-conditioning. Furthermore, as already described in section 3.3.2, the opening probability is especially high for arrival events, which only occur once a day in this model. Accordingly, it entails fewer window openings when applying the window opening model to this building model. In short, the change of air caused by open windows might be unprecise. Adaptations to the behaviour would influence the indoor air conditions.

The occupancy was determined in sections 3.3.1 and 3.4.1. The results for the occupancy fraction during the monitoring period were not distinctive. A different fraction has an impact on the probabilities of the ceiling fan usage. The assumptions that were made for the occupancy fraction with an absence of Covid-19 measures were approximated, which has a direct effect on the internal loads.

Another limitation results from the shading setpoint 3.2.2.2 that is unknown for the building. The applied illuminance setpoint might not fit the building control in Dillingen. The same goes for the setpoint for the night ventilation setpoint which was assessed in section 3.4.1.

A further limitation for the ceiling fan usage arises from the outdoor air conditions during the monitoring period. The temperatures during the monitoring period were rather low. No ceiling fan usage at more than 28 °C was measured. Additionally, a limited amount of monitoring data for the ceiling fan usage was collected. With this small set of data for high temperatures, the prediction of ceiling fan usage might be inaccurate.

4 Cost and comfort analysis

In Chapter 4, the results of the simulations for indoor air conditions and cooling energy demand are processed to evaluate costs, comfort, and ecological impact. A productivity evaluation is a focal point for the economic outcome.

Figure 49 gives an overview of the steps to attain the ecological, economical and comfort assessment, starting from the initial literature review, the evaluation of monitoring and project data, and the analysis of the simulation results (energy consumption, ceiling fan usage). The costs and the ecological impact of the electricity usage are calculated respectively for the ACS and the ceiling fans (CF). Based on the information from the project planning (amongst others, for CF and NV) and further research (for ACS), investment, installation, and maintenance and operation costs for the single components comprise the total costs (section 1.5.4 and 4.4). Comfort is evaluated with the help of well-established comfort models, presented in section 1.5.3. The applied models vary for the different concepts, using the room air conditions from the simulations, and, if applicable, the ceiling fan usage profile (section 4.2) as input values. Lastly, the room air characteristics and the comfort outcome are used to estimate monetary costs of the employees' productivity using existing productivity models.

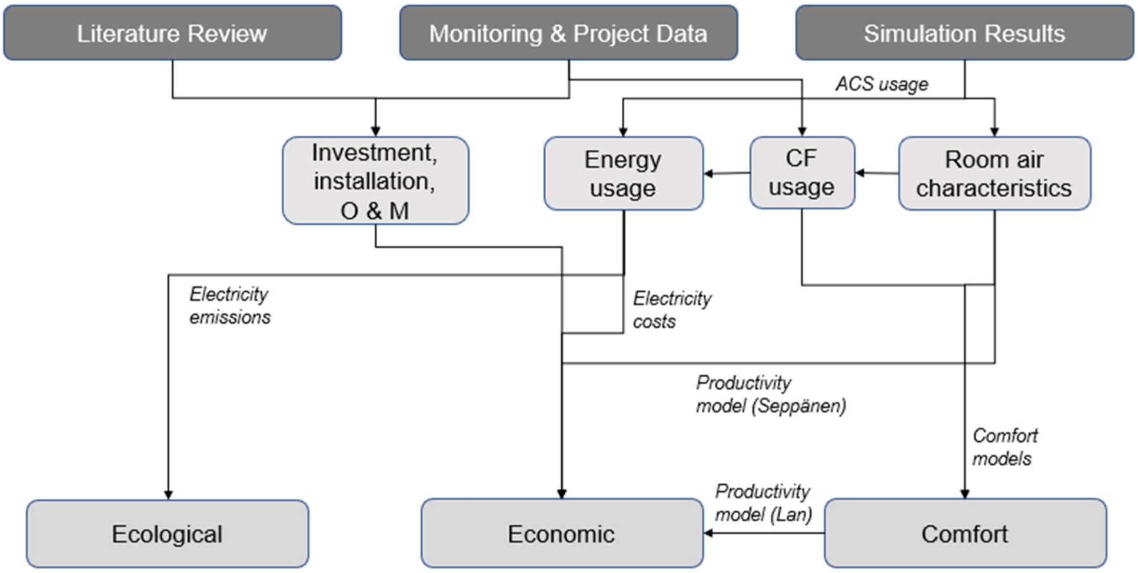


Figure 49: Flow chart for ecological, economic and comfort assessment

4.1 Ecological evaluation

The ecological evaluation was strictly assessed regarding the electricity usage. Other aspects, such as embodied energy, are out of the scope of this thesis due to the comparable low impact (Wu et al. 2012) and the lack of sufficient data. It was analysed only for two of the four concepts because NV and NoCooling have no relevant energy usage for cooling. As already determined in section 3.5.1, the cumulative cooling energy that is required during a one-year period amounts to 16,900 $kWh_{thermal}$ ($Q_{Cooling}$). Here, a split air conditioning device was presumed on a COP (Coefficient of Performance) of 3.5:

$$COP = \frac{Q_{cooling}}{E_{ACS}} \; ; \; E_{ACS} = \frac{Q_{cooling}}{3.5} \quad .$$

This leads to a yearly electricity usage (E_{ACS}) of **4,829 kWh** for active cooling.

The assessment for the ceiling fan usage is based on the results from section 3.5.3, and the presumption that the power of a ceiling fan (P_{CF}) is constant at **10 W**.

With 157 employees ($N_{Employees}$) using the ceiling fan for 77.9 hours ($t_{CFusage}$), this leads to a yearly electricity demand for the ceiling fan (E_{CF}) of:

$$E_{CF} = N_{Employees} * t_{CFusage} * P_{CF} = \; 157 * 77.9 \; h * 10 \; W = \mathbf{122 \; kWh_{electrical}}$$

The CO_2-emissions ($specCO_2$) of the German electricity mix were used for the calculation of the emissions emitted due to the usage of the ACS and ceiling fans (**401 g/kWh** (strom-report.de 2021)). The yearly emissions (CO_{2_year}) for all concepts are calculated according to the formula

$$CO_{2\_year_i} = specCO_2 * E_i$$

and are displayed in the following table:

	NoCooling	**NV**	**NVandCF**	**ACS**
Emissions [kg_{CO2}/a]	0	0	49	1,936

Table 11: Emissions from electricity usage

The yearly emission for the ACS is approximately 40 times higher than the emissions from the ceiling fan usage. To put the emissions into perspective: in 2018, the average German citizen emitted 8.4 t CO_2 per year (statista 2018). The emissions resulting from the use of the ACS are equivalent to 0.147% of the yearly emissions per capita. Another reference is the comparison to emissions caused by the individual mobility: 12.3 kg_{CO2} are emitted per employee and year, which is equal to a drive by car of approximately 50 km with a petrol use of 7 l / 100 km (myclimate.org 2021). Compared to the ceiling fan, it is less than 2 km.

4.2 Comfort evaluation

Comfort models were already introduced within section 1.5.3. The calculation and the results of the comfort evaluation are explained within this chapter. They are expressed as PMV (Fanger), the adaptive PMV (Yao), and the TSV_{sa} (Gao). These values are indicators for the thermal perception or the thermal comfort. The package "comf" (Schweiker 2016) was used for some of the following calculations. The applicability for the different concepts can be read from Table 12:

	NoCooling	**NV**	**NVandCF**	**ACS**
Fanger (Fanger 1967)				X
Yao (Yao et al. 2009)	X	X		
2-node (Nishi and Gagge 1977)			X	
Gao (Gao et al. 2015)	X	X	X	

Table 12: Applicability comfort models

The model by Fanger applies to controlled environments with an ACS and is limited to an air speed of 0.2 m/s as the discomfort through draft at higher air speeds is not included. Therefore, it is only used for the ACS concept. The model by Yao modifies the PMV model and considers adaptive measures for buildings with natural ventilation. It can be used to determine the thermal sensation for the concepts NoCooling and NV. Concept NVandCF includes ceiling fans, and resulting from this, air velocities higher than 0.2 m/s. The model does not apply for elevated air speeds (greater than 0.2 m/s), hence the thermal perception with the use of ceiling fans cannot be calculated with Yao's model. Applying the 2-Node model to concept NVandCF allows evaluating the effect of elevated air speeds but adaptive measures are not considerd. The model by Gao, however, is applicable to elevated air speeds and considers adaptive measures. Therefore, this approach offers the highest comparability between the concepts NoCooling, NV and NVandCF.

The input and output values for each of the models can be read from the following table:

	Input	**Output**
Fanger	T_{air}, T_{rad}, air velocity (AV), relative humidity (RH), clo, met	PMV
Yao	T_{air}, T_{rad}, AV, RH, clo, met, λ	aPMV
SET	T_{air}, T_{rad}, AV, RH, clo, met, exposure times, body height, body weight, turbulence intensity, driving coefficient for regulatory sweating, driving coefficient for vasolidation, driving coefficient for vasoconstriction,	SET
2-Node	SET	PMV
Gao	SET, λ_s	TSV

Table 13: Input and output overview for the comfort models and SET calculation

Fanger's model was used to evaluate the comfort for the ACS concept. Gao's model was used to determine the comfort for the concepts NoCooling, NV and NVandCF because it is the only model applicable to all of them. λ_s was declared as a range of values (section 1.5.2). For the following calculations, the average was used (-0.204).

T_{air}, T_{rad}, and the relative humidity (RH) result from the simulation. A value of 0.61 (light clothing: trouser, long-sleeve shirt) for clothing, and a value of 1.1 as average value of sitting and standing for the metabolic rate was assumed (ASHRAE 2017). The air velocity is assumed to be constant at 0.05 m/s without (active) ceiling fan and 0.6 m/s with active ceiling fan (Rissetto et al. 2021). For the remaining variables, the default value was assumed. The calculation of PMV and TSV was done for the whole simulation period. In general, PMV values higher than 0.5 are classified as uncomfortable (ASHRAE 2017). The results for PMV and TSV, expressed as percentage, which lie within the range of "slightly warm", "warm" and "hot", are displayed in Table 14:

		NoCooling	**NV**	**NVandCF**	**ACS**
PMV | TSV > 0.5	slightly warm	41.60%	5.60%	4.02%	0%
PMV | TSV > 1.5	warm	8.49%	0.08%	0.04%	0%
PMV | TSV > 2.5	hot	1.15%	0%	0%	0%

Table 14: Percentage of PMV/TSV values higher than 0.5

Almost half of the values for concept NoCooling are higher than 0.5. A considerable difference between concept NV and NVandCF can be seen for PMV values greater than 1.5. Because of the air movement provided by the ceiling fan, the number of TSV higher than 1.5 was reduced by 50%. In this thesis, the attention is directed to discomfort due to overheating, therefore, PMV/TSV lower than zero are not included into the assessment. The distribution was plotted in a histogram for PMV and TSV > 0 (Figure 50).

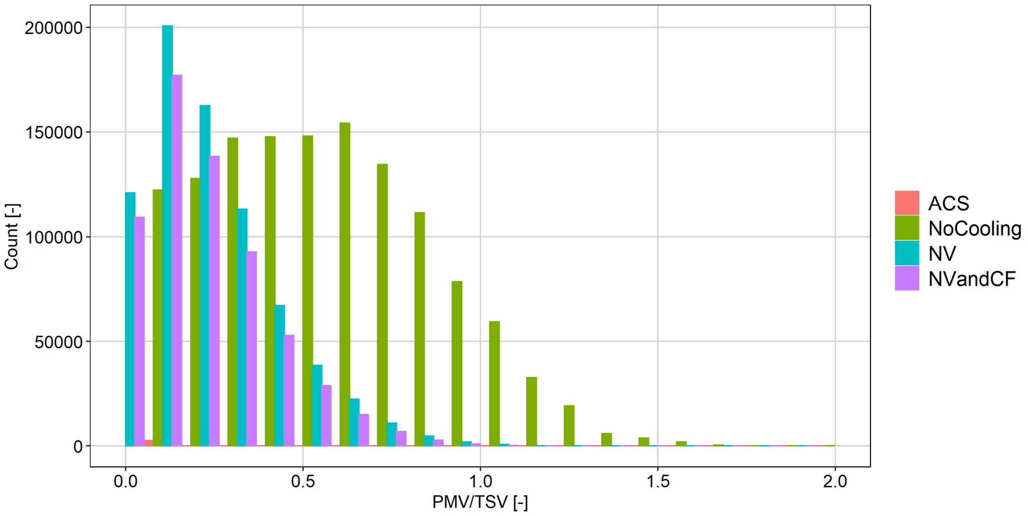


Figure 50: Histogram PMV/TSV distribution all concepts

Only a few values with PMV > 0 appear for concept ACS. Concept NVandCF provides slightly lower TSV values than concept NV without ceiling fans, whereas for concept NoCooling the thermal sensation is perceived as warm for 41.6% of the cooling period (Table 14). Figure 51 shows the cumulative distribution of the PMV/TSV for all concepts. The lowest PMV/TSV values are supplied by the ACS-concept due to the cooling setpoint of 24 °C. The difference between NV and NVandCF is low. This results from the overall small number of timesteps where the ceiling fan is in use (7.39%, section 3.5.3). Concept NoCooling shows the highest temperatures and therefore the highest TSV. The same can be seen in Figure 51.

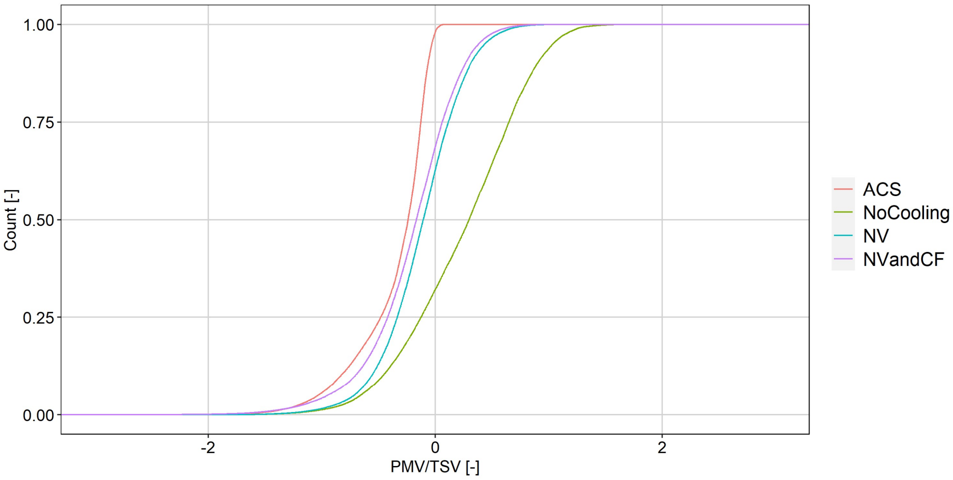


Figure 51: Cumulative distribution PMV/TSV all concepts

Figure 52 to Figure 55 display PMV and TSV depending on the indoor air temperature. For concept ACS (Figure 52), the setpoints of 20 and 24 °C are clearly visible. Almost no PMV values higher than 0 appear and no values higher than 0.5 (slightly warm) are observed. It can be deduced from the graph that a temperature range of 20 to 24 °C assures the avoidance of "warm" temperature perception but involves the risk of overcooling.

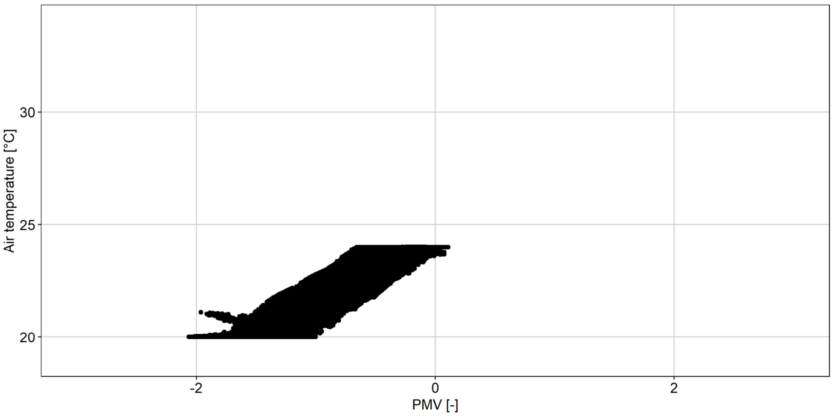


Figure 52: PMV and air temperature – Concept ACS

The diagrams for concept NoCooling (Figure 53), NV (Figure 54) and NVandCF (Figure 55) show a similar pattern as the same modelling approach was applied. With Fanger's model, the PMV increases linearly. TSV higher than 2 can be seen for temperatures above 30 °C (Figure 53).

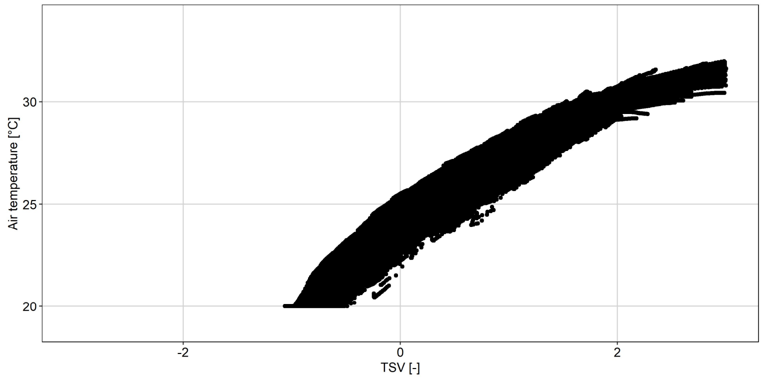


Figure 53: TSV and air temperature – Concept NoCooling

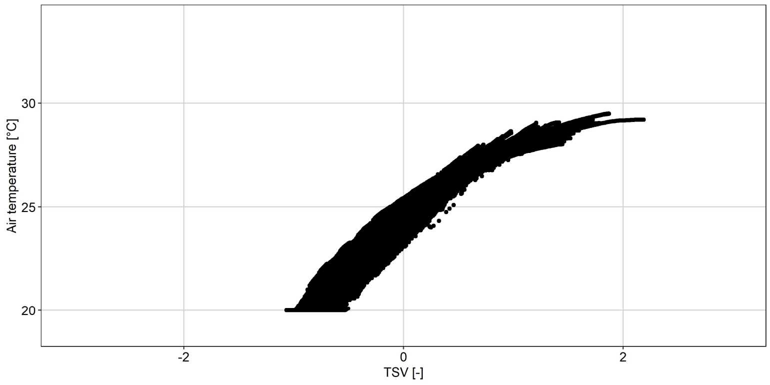


Figure 54: TSV and air temperature – Concept NV

The right area of plotted points in Figure 55 is the same as in Figure 54. The left area contains the data points where a ceiling fan is active, which results in a lower SET and TSV. Due to the probabilistic approach, the ceiling fan is also active at temperatures that are already comfortable according to Gao without elevated air speed. This produces the same cool sensation and leads to dissatisfaction according to the model, which is a limitation of the simulation. Considering personal preferences, the ceiling fan operated at temperatures lower than 24 °C may not necessarily cause dissatisfaction.

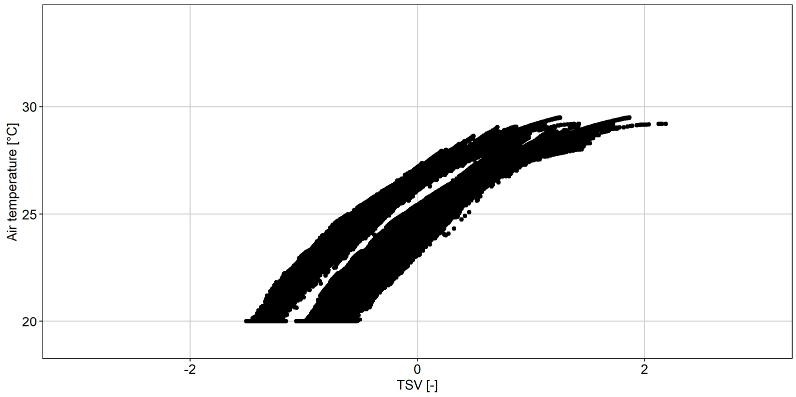


Figure 55: TSV and air temperature – Concept with NVandCF

Figure 56 shows the trend line of TSV depending on air temperature for the values with and without ceiling fan activation (concept NVandCF). As expected, the TSV is lower at a higher air velocity, which shows the effect of the air movement on thermal sensation. According to the model, at air temperatures higher than 26 °C an activation of the ceiling fan is reasonable. The reduction of high TSV (Table 14) can be explained with the probabilities for ceiling fan activation (Table 8) and Figure 55: TSV values higher than 1.5 occur at temperatures higher than 28 °C (Figure 55). At 28 °C the probability for ceiling fan activation is higher than 40% (Table 8). This results in the reduction of approximately 50% of “warm” TSV with ceiling fan activation (Table 14). The TSV values with active ceiling fans and temperatures higher than 27.5 °C correspond mostly to neutral to slightly warm sensation votes (0 to 1) (Figure 55).

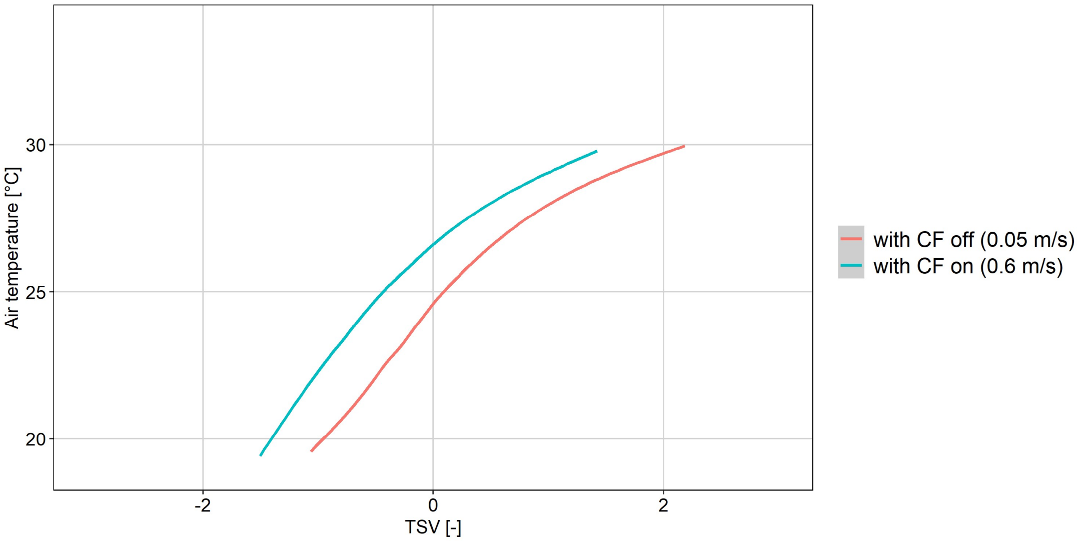


Figure 56: Trendline TSV for concept NVandCF with and without CF activation

The results show almost no comfort constraints on the account of overheating for AC systems. No installation of AC, night ventilation or ceiling fans provides an uncomfortably warm room climate for a high amount of the time. Night ventilation significantly improves the comfort sensation. The dimension of this effect would increase in warmer climates with higher outdoor air temperatures. The additional effect of ceiling fans can be observed but is limited because of the overall low outdoor temperatures at the analysed location. These results are further discussed in section 4.5.

4.3 Productivity evaluation

The productivity evaluation is considered as additional criterion for an economic assessment, measuring the monetary consequences resulting from uncomfortable indoor air climate. Available models were already introduced in section 1.5.4.

Seppänen's model depends on the indoor air temperature. The cooling effect from elevated air speed is not considered. Since this makes a comparison between concepts with and without ceiling fans difficult, the relative performance (RP) was calculated with indoor air temperature and secondly, with the SET. The results can be seen in Table 15. Besides a calculation of the mean productivity for the whole simulation results (RP_{Sepp} and RP_{Sepp_SET}, Table 15), a second calculation neglecting a decrease in RP at temperatures (respectively SET) below the temperature with the maximum productivity (T_{RPMax} = 21.75) was made. For that, the RP at temperatures or SET lower than 21.75 °C is set to the maximum productivity ($RP_{Sepp\_onlyWarm}$ and $RP_{Sepp\_SET\_onlyWarm}$, Table 15). Using the SET, elevated air speed can be included. Still, adaptive measures are not considered. This is different to Lan's model, where the TSV is used for the performance evaluation (Section 1.5.4). The average productivity was calculated in the same way as in Seppänen's model (RP_{Lan} and $RP_{Lan\_onlyWarm}$ in Table 15).

	NoCooling	**NV**	**NVandCF**	**ACS**
RP_{Sepp} [-]	0.96917	0.98601	0.98601	0.99202
$RP_{Sepp\_onlyWarm}$ [-]	0.96926	0.98613	0.98613	0.99215
RP_{Sepp_SET} [-]	0.97147	0.98942	0.99068	0.99134
$RP_{Sepp\_SET\_onlyWarm}$ [-]	0.97158	0.98956	0.99107	0.99152
RP_{Lan} [-]	0.9933987	0.9981686	0.9982245	0.9982747
$RP_{Lan\_onlyWarm}$ [-]	0.9934710	0.9982710	0.9984123	0.9986063

Table 15: Average productivity for every concept

Referring to Seppänen's approach, the differences between the concepts with ACS, with NV and with both, NV and CF, are marginal, whereas the productivity without any cooling strategy is about 2% lower. As the positive impact from natural ventilation on thermal sensation (1.5.3) is not considered in Seppänen's model, the actual RP is potentially higher for concepts NoCooling, NV, and NVandCF than calculated here.

The results with Lan’s model are approximately one order of magnitude lower. They have a higher comparability between each of the concepts because both, adaptive measures and elevated air speed, are considered. The monetary costs of the decrease in relative performance were computed according to the following formulas:

$$Costs_{PublicService} = (1 - RP) * \frac{Salary_{year}}{2} * Employees \quad ,$$

$$Costs_{ProfitCompany} = (1 - RP) * \frac{ValueCreation_{year}}{2} * Employees \quad .$$

The factor ½ in the formulas is based on the earlier assumption that the cooling period is six months long, thus the productivity loss arising from warm conditions only applies to half of the year. Two scenarios are assumed, one for public service (PS) and the second for a profit-oriented company (POC). To translate the productivity results into monetary values, the value creation of the employees, including all incidental wage costs, is required. Since the value creation for public service work is impossible to be determined, the salaries ($Salary_{year}$) are approximated under the assumption that the amount of work is constant, and therefore additional employees are necessary when productivity decreases. Salaries for public service are openly accessible, but as no information is available for the employment structure, the average salary can only be estimated. The same goes for employees in a POC. The calculation for the profit-oriented company was performed assuming the salary and a certain value creation.

- Employees: 157
- Value creation: 1.5 (assumption)
- Salary public service per year: **45,000 €** ($Salary_{year}$) (oeffentlicher-dienst.info 2021)
- Salary POC: 60,000 € (statista.com 2020)
- Value creation per year for the POC: **90,000 €** ($ValueCreation_{year}$)

$RP_{Sepp\_SET\_onlyWarm}$ and $RP_{Lan\_onlyWarm}$ were used. Productivity decrease due to overcooling is neglected. Yearly costs originating from productivity losses are displayed in Table 16:

	NoCooling	**NV**	**NVandCF**	**ACS**
Public Service (Sep.)	100,394 €	36,879 €	31,545 €	29,956 €
Profit-oriented company (Sep.)	200,787 €	73,759 €	63,090 €	59,911 €
Public Service (Lan)	23,064 €	6,108 €	5,609 €	4,923 €
Profit-oriented company (Lan)	46,127 €	12,215 €	11,217 €	9,846 €

Table 16: Yearly costs due to productivity loss

As expected, costs for the example regarding a POC are twice the costs for PS. The productivity loss costs when there is no cooling concept implemented are by far the highest ones. The results with the model by Seppänen are approximately 4 to 6 times higher than the ones with the model by Lan. The small difference between concept NV, NVandCF and ACS compared to the great difference to concept NoCooling applies to both models.

4.4 Economic evaluation

The economic evaluation was carried out under the presumption of applicability and comparability of the models that were used in section 4.2 and 4.3.
Monetary costs are composed of:

- Investment and installation costs (once)
- Maintenance costs (yearly)
- Electricity costs (yearly)
- Costs of comfort and productivity decrease (yearly)

With electricity costs of 23.03 Cent/kWh (www.stromauskunft.de 2021), the annual costs were calculated (Table 17). Analogue to the ecological evaluation in section 4.1, electricity costs are induced by the ceiling fans and the ACS. Compared to the costs emerging from productivity losses, the running costs for electricity are low, especially for the ceiling fan usage. The costs corresponding to the technical installation (section 2.3), productivity (section 4.3), and electricity usage are displayed in Table 17. Investment, operation and maintenance (O & M), and electricity costs are defined. The productivity costs were calculated for the different scenarios and productivity models.

	NoCooling	**NV**	**NVandCF**	**ACS**
Invest	57,841 €	106,284 €	202,498 €	381,412 €
O & M	1,245 €/a	2,982 €/a	6,672 €/a	15,640 €/a
Electricity	0	0	28 €/a	1,112 €/a
Productivity – PS - Sep	100,394 €/a	36,879 €/a	31,545 €/a	29,956 €/a
Productivity – POC - Sep	200,787 €/a	73,759 €/a	63,090 €/a	59,911 €/a
Productivity – PS - Lan	23,064 €/a	6,108 €/a	5,609 €/a	4,923 €/a
Productivity – POC - Lan	46,127 €/a	12,215 €/a	11,217 €/a	9,846 €/a

Table 17: Cost overview all concepts

With the findings from Olesen (2005), the costs can be checked for validity. The floor area is 3,488 m². Olesen calculated average costs for the improvement of thermal comfort from comfort class C to B and B to A. The average PPD is 12.16% for NoCooling and 5.02% for ACS, considering only PMV higher than 0 for ACS. Therefore, the installation of an

ACS can be assumed to be an improvement from comfort class C to A. This leads to the following costs:

	ACS	Olesen
PPD [%]	12.16 to 5.02	C to A
Energy [€/a]	1,112	4,708
Maintenance [€/a]	15,640	12,603
Investment [€]	384,412	610,400

Table 18: Energy, maintenance and investment costs for the ACS compared to the findings from Olesen

Table 18 shows energy, maintenance and investment costs for the district office compared to the findings from Olesen. All costs have the same order of magnitude, which indicates a validity of the cost assumptions. Olesen investigated the costs for the whole building system, including heating and not limited to cooling, which explains the higher costs of their results for investment and energy. The maintenance costs resulting from his work are assumed to be lower than 5%.

Assuming a service life of 20 years (n) and a discount rate (i) of 8% based on Zheng et al. (2019), the net present value (NPV) was calculated (Table 19). The NPV is an indicator for the investment efficiency. A positive NPV indicates that the cash flows (R_t) during the service time (t) outweigh the initial investment (Y), thus the installation is worthwhile. For this use, only negative cashflows are compared (electricity costs, O & M, productivity loss). Therefore,the NPV for NoCooling ($NPV_{NoCooling}$) is used as reference system to calculate ΔNPV:

$$NPV = Y - \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \quad , \quad \Delta NPV_i = NPV_i - NPV_{NoCooling} \quad .$$

	NV	NVandCF	ACS
ΔNPV_{Sep} – PS [€/employee]	3,555	3,044	1,375
ΔNPV_{Sep} – POC [€/employee]	7,527	7,349	5,779
ΔNPV_{Lan} – PS [€/employee]	642	-171	-1,896
ΔNPV_{Lan} – POC [€/employee]	1,704	921	-762

Table 19: Difference between net present values for concepts NV, NVandCF, and ACS and NoCooling

The results for ΔNPV calculated with Seppänen’s model are positive for ACS, NV as well as NVandCF, which reveals the investment efficiency of each concept for both scenarios. ΔNPV grows with the increase of the labour value. Lan’s model leads to a negative ΔNPV for the installation of an ACS. While ΔNPV is generally positive for the installation of NV, the economic viability of CFs in addition to NV only accrues at a higher labour value.

To assess the impact from different salaries and discount rates, the boundary values for

ΔNPV = 0 were calculated. This is shown in Figure 57 for a discount rate from 0% to 10%. The higher the discount rate is, the higher is the salary at which ΔNPV is 0. NV has the highest ratio for the difference in running costs to the difference in investment costs compared to NoCooling for the model Seppänen, which explains the highest influence of the discount rate. The maximum salary to achieve ΔNPV = 0 with a discount rate of 10% with Seppänen's model is approximately 35,000 € for concept ACS. With Lan's model it is more than 130,000 €.

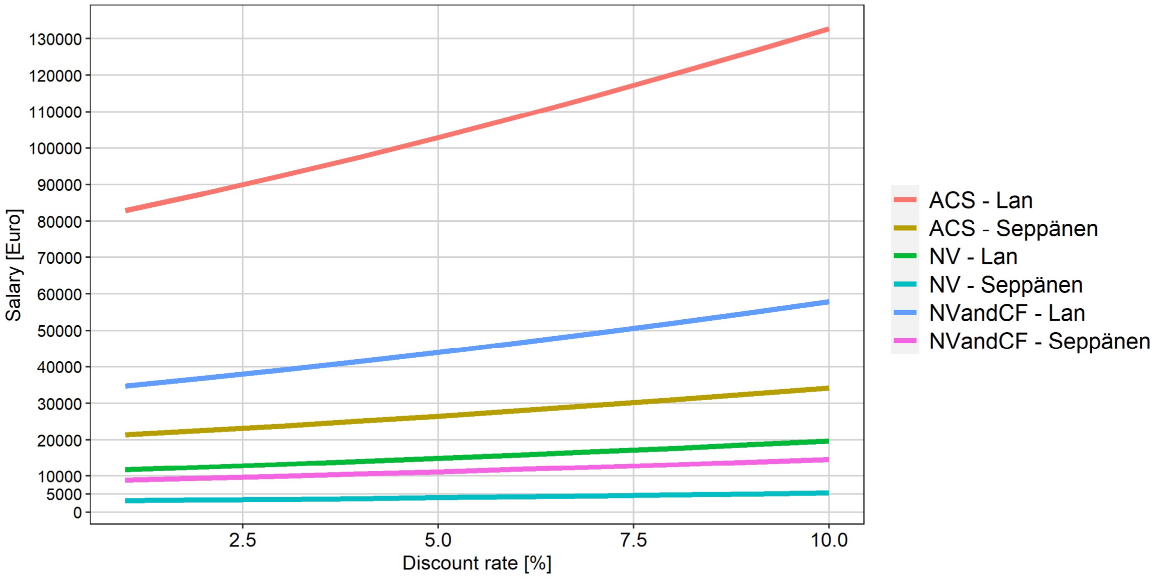


Figure 57: Boundary values (discount rate & salary) for ΔNPV = 0

4.5 Discussion

In this section, the results are summarized and compared to the findings of previous publications. Limitations of the results in this chapter are explained. The limitations corresponding to the modelling process were already explained in section 3.6.

Comfort evaluation

Research from decades ago as well as novel findings indicate an improvement of thermal comfort with elevated air speed through fans (Rissetto et al. 2021; Rohles et al. 1982). These results were used within this work. While ACS still provide the lowest results for PMV/TSV_{sa}, the improvement from night ventilation, compared to no cooling strategy system at all, is compelling. This supports the findings from Darmanis et al. (2020) , which indicate the possible coverage of cooling loads by night ventilation. The further decrease of TSV through ceiling fans is limited, which is due to the overall low outdoor temperatures at the studied location. Rissetto et al. (2021) demonstrated that personal ceiling fans supply a comfortable room climate for indoor air temperatures between 28 and 31 °C. This work endorses the finding, that ceiling fans provide comfort for an indoor air temperature of 28 °C. No statement can be made for higher temperatures because the temperatures at the building's location were too low.

The applicability of the different comfort models (ASHRAE 2017; Yao et al. 2009; Gao et al. 2015) was assessed in section 4.2. A significant inaccuracy in the TSV calculation (Gao et al. 2015) results from the assumption for λ_s. As the adaptive coefficient is based on AMV results from China, a different climate zone, the coefficient is probably inaccurate for a building in Germany. Additionally, the assumptions for clothing, metabolic rate and air speed were assumed to be constant and do not consider adaptive behaviours. Changes to the assumptions might be necessary not only due to adaptive behaviour but also due to restrictions, for example certain dress codes.

Another limitation for the comfort assessment is the constraint to evaluate warm discomfort. A decrease in comfort because of overcooling was not investigated. With an air-conditioning system or night ventilation installed, a high percentage of PMV (> 98%) or TSV_{sa} (> 62%) is negative. The same goes for the usage of the ceiling fan. However, due to the possibility of personal control by employees, it is not realistic to assume negative thermal sensation votes while the fan is turned on. This limits the applicability of the comfort models for cooling strategies with personal control, which is an important factor for the perceived comfort because ceiling fans consider personal preferences (de Dear and Brager 2001; Rawal et al. 2020; Haynes 2008).

Productivity evaluation

Haynes (2008) showed that office comfort affects productivity. Nevertheless, the extent of this impact and the detection of relevant variables are difficult to determine. Besides, the productivity is hardly assessable for most of the tasks that emerge at work and the viability of a transfer into monetary costs is uncertain. Latest research studied the effect of indoor temperature on office work performance and could not find any relationship (Porras-Salazar et al. 2021). This limits the viability of the productivity models and the appliance to this work. The uncertainty is already indicated by the results of both used productivity models (Seppänen et al. 2006; Lan et al. 2011), as the productivity loss using Seppänen's model is 4 to 6 times higher than with Lan's model. Seppänen's productivity model depends solely on air temperature and does not consider elevated air speed, adaptive measures, or personal control. With the use of the Standard Effective Temperature (Gagge et al. 1972) instead of the air temperature in Seppänen's productivity model, which is another limitation, the air movement was included in the considerations. Still, adaptive measures and personal control were not considered. Adaptive measures are contemplated in Lan's model. This strengthens the comparability of the results between the different concepts. The advantage of personal control systems, as the studied personal ceiling fan, is still disregarded. The findings from Olesen (2005) support the productivity decrease that was calculated with Seppänen’s model, similar to the results from Djukanovic et al. (2002). They suggest that with a 10% increase in dissatisfied employees, productivity will decrease by 1%. Different to this work, they investigated the impact of different extents of air pollution. The installation of night ventilation and ceiling fans reduces the number of dissatisfied employees (TSV higher than 0.5) by approximately 37% (Table 14). With 2% decrease in productivity (Table 15), the loss has the same order of magnitude as Olesen’s findings. With Lan’s model it is only 0.5%. Overall, further research is necessary to prove the validity and applicability of these productivity models.

Economic evaluation

The ACS concept comes with the highest investment and maintenance costs, which was expected beforehand. The investment costs for ceiling fans are more than half of those of the ACS, which is caused by the custom-made solution and the extensive integration on-site (section 2.3). The high investment costs associated with the concept with night ventilation and ceiling fans overestimates the costs as ceiling fans as a standard solution would reduce costs significantly. The validity of the cost assumptions was explained in section 4.4 based on the findings from Olesen (2005). The energetic costs for ACS were 20 times higher than those for the concept with ceiling fans and around 6% of the investment costs considering the assumed service life of 20 years. The total costs for the implementation of ACS, night ventilation, or night ventilation and ceiling fans, that were indicated by the net present value, show the economic viability of each concept using the model by Seppänen (Table 19). Night ventilation, and, depending on the scenarios regarding salary and value creation, additional ceiling fans, are an economically efficient investment according to the results based on Lan’s model. The best outcome arises with an installation of night ventilation without ceiling fans for both models. Calculating with a higher salary and a higher added value, the gap between concepts with and without ceiling fans shrinks. Lower installation costs for ceiling fans, or more relevance due to higher outdoor temperatures, could possibly lead to the highest net present value for the concept with ceiling fans.

The component costs were largely assumed, especially for ACS, as well as the further cost indicators, for example salaries and value creation. As the costs associated with the hardware are a focal point besides the productivity assessment, these uncertainties have a significant impact on the conclusion. The choice of the discount rate is another important factor that impacts the economic evaluation (Zheng et al. 2019). Besides, inflation rate was not considered within the calculations. These limitations were not tackled and must be considered when looking at the results of this work.

5 Conclusion

The initial question was to analyse the economic viability of personal ceiling fans in an office building. To achieve this, traditional cooling strategies in office buildings were compared to a solution with night ventilation and ceiling fans in terms of economic and comfort aspects. Energy demand and indoor climate were evaluated through a building simulation. Finally, user satisfaction was calculated and transferred into productivity loss. The ecological impact of the electricity usage of ceiling fans is approximately 20 times lower than that of ACS. On a larger scale and within a warmer environment than that used within this work, this results in a significant difference for the ecological footprint of the concepts. As embodied energy was not considered, the assessment of ecological aspects requires additional research.

The comfort assessment served the analysis of the user satisfaction and the evaluation of productivity loss due to thermal discomfort. PMV and TSV were calculated for all concepts to make a comparison of the user satisfaction for the different concepts possible. Without cooling strategy, 40% of the employees experience warm discomfort (TSV greater than 0.5) during summer. Although the ACS completely prevents discomfort by overheating, the risk of overcooling was not investigated. With the installation of night ventilation, employees' discomfort because of warm thermal sensation could be maintained lower than 6%. The further decrease in thermal sensation votes, induced by an additional installation of ceiling fans, is rather small. However, personal preferences are not considered within the used comfort models. Therefore, the positive psychological impact of personally controlled ceiling fans might be underestimated and should be further investigated.

Assuming the validity of Seppänen's model, no implementation of a cooling strategy leads to a 2% lower productivity relative to the other concepts. Considering this, the installation of night ventilation has a net present value that is 3000 € higher per employee in a public service building than that without any cooling strategy, assuming a service life of 20 years and a discount rate of 8%. Potentially 7,500 € per employee for a profit-oriented company. Similar results arise with additional installation of ceiling fans, as the increasing investment costs are compensated by the productivity improvement. Because of the high investment costs, the concept with an ACS has a lower gap in net present values that is approximately 5,800 €. The economic viability of a ceiling fan in moderate climate zones is limited, while the viability of the use of night ventilation in refurbished buildings is evident. Further research on warmer environments and a reduction of the investment costs for ceiling fans may justify the economic viability of ceiling fans. Especially under the effect of global warming, cooling loads will further increase in the future (Jenkins et al. 2008), which will also enhance the necessity of personal ventilation.

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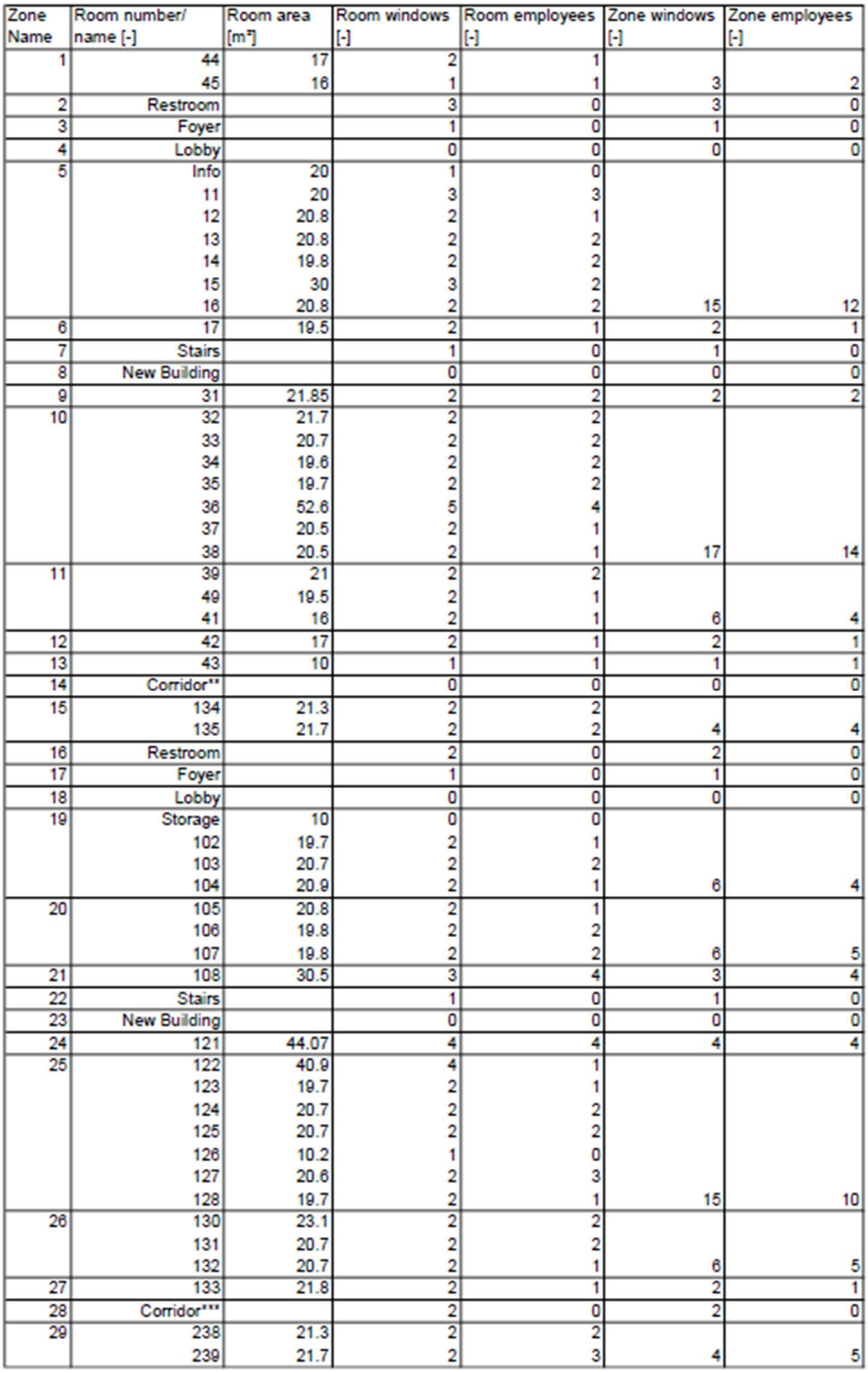
7 Annex

Annex 1: Description of thermal zones: number of rooms, employees and windows in each room and thermal zone

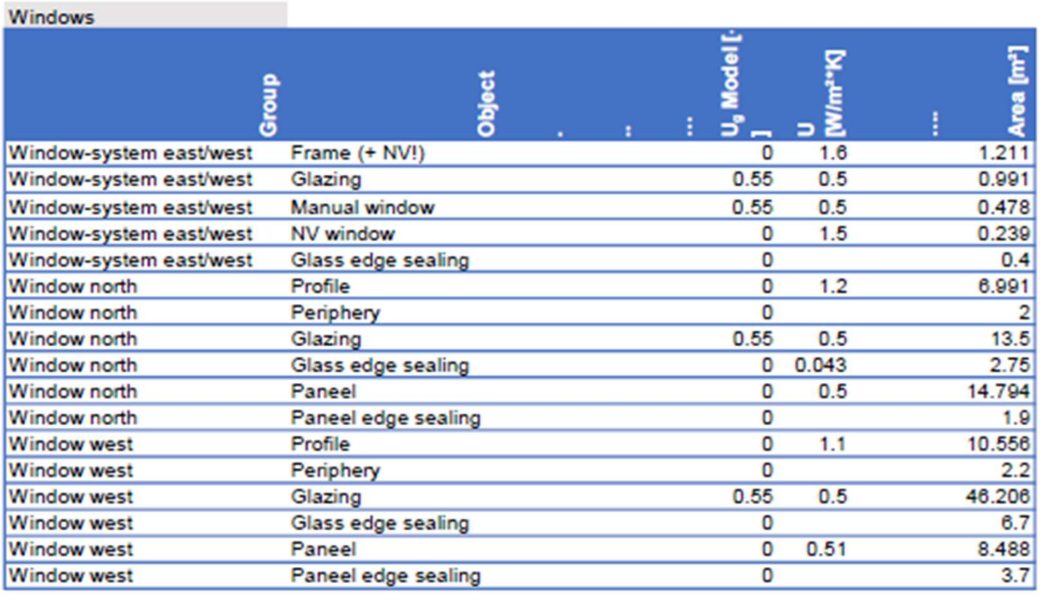


Zone Name	Room number/ name [-]	Room area [m^2]	Room windows [-]	Room employees [-]	Zone windows [-]	Zone employees [-]
1	44	17	2	1		
	45	16	1	1	3	2
2	Restroom		3	0	3	0
3	Foyer		1	0	1	0
4	Lobby		0	0	0	0
5	Info	20	1	0		
	11	20	3	3		
	12	20.8	2	1		
	13	20.8	2	2		
	14	19.8	2	2		
	15	30	3	2		
	16	20.8	2	2	15	12
6	17	19.5	2	1	2	1
7	Stairs		1	0	1	0
8	New Building		0	0	0	0
9	31	21.85	2	2	2	2
10	32	21.7	2	2		
	33	20.7	2	2		
	34	19.6	2	2		
	35	19.7	2	2		
	36	52.6	5	4		
	37	20.5	2	1		
	38	20.5	2	1	17	14
11	39	21	2	2		
	49	19.5	2	1		
	41	16	2	1	6	4
12	42	17	2	1	2	1
13	43	10	1	1	1	1
14	Corridor**		0	0	0	0
15	134	21.3	2	2		
	135	21.7	2	2	4	4
16	Restroom		2	0	2	0
17	Foyer		1	0	1	0
18	Lobby		0	0	0	0
19	Storage	10	0	0		
	102	19.7	2	1		
	103	20.7	2	2		
	104	20.9	2	1	6	4
20	105	20.8	2	1		
	106	19.8	2	2		
	107	19.8	2	2	6	5
21	108	30.5	3	4	3	4
22	Stairs		1	0	1	0
23	New Building		0	0	0	0
24	121	44.07	4	4	4	4
25	122	40.9	4	1		
	123	19.7	2	1		
	124	20.7	2	2		
	125	20.7	2	2		
	126	10.2	1	0		
	127	20.6	2	3		
	128	19.7	2	1	15	10
26	130	23.1	2	2		
	131	20.7	2	2		
	132	20.7	2	1	6	5
27	133	21.8	2	1	2	1
28	Corridor***		2	0	2	0
29	238	21.3	2	2		
	239	21.7	2	3	4	5

30	Restroom		2	0	2	0
31	Foyer		5	0	5	0
32	201	9.15	1	0		
	202	20.6	2	1		
	203	20.7	2	1		
	204	20.9	2	1		
	205	20.4	2	2		
	206	19.8	2	2		
	207	19.8	2	1		
	208	20.8	2	2	15	10
33	209	30.5	3	2	3	2
34	Stairs		1	0	1	0
35	New Building		0	0	0	0
36	224	22.46	2	2	2	2
37	225	20.5	2	2		
	226	20.7	2	2		
	227	20	2	2		
	228	18.5	2	2		
	229	23	2	2		
	230	18.4	2	1		
	231	32.5	3	3		
	232	19.8	2	1		
	233**	26.15	0	1		
	234	23.2	2	1		
	235	20.7	2	2		
	236	20.7	2	1	23	20
38	237	21.8	2	1	2	1
39	Corridor*		0	0	0	0
40	339	21.7	2	1		
	340	20.7	2	1	4	2
41	Restroom		2	0	2	0
42	Foyer		5	0	5	0
43	301	20.5	2	2		
	302	19.9	2	2		
	303	15.5	2	2		
	304	16	1	1		
	305	20.4	2	2		
	306	19.8	2	2		
	307	19.6	2	2		
	308	21.5	2	2	15	15
44	309	29.9	3	3	3	3
45	Stairs		1	0	1	0
46	New Building		0	0	0	0
47	325	21.85	2	1	2	1
48	326	21.5	2	2		
	327	20.6	2	2		
	328	19.5	2	1		
	329	19.7	2	2		
	330	31.3	3	2		
	331	20.7	2	2		
	332	20.7	2	2		
	333	19.8	2	2	17	15
49	335	22.2	2	2		
	336	20.7	2	2		
	337	20.7	2	2	6	6
50	338	22.8	2	1	2	1
51	Corridor***		0	0	0	0
					219	157

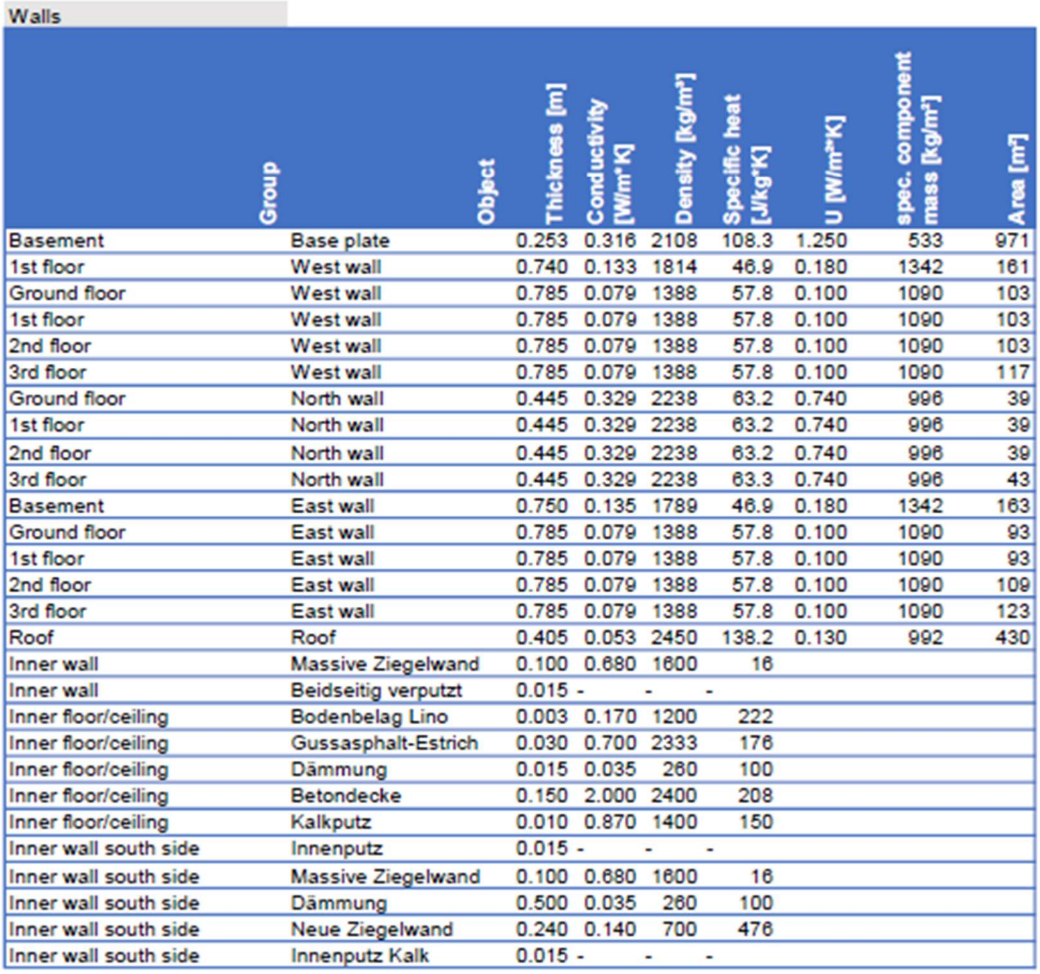
* + North window
** + West window
*** + North & west window

<u>Annex 2:</u> Building elements' properties*



Windows

Group	Object	.	:	...	U_g Model [-]	U [W/m²*K]	...	Area [m²]
Window-system east/west	Frame (+ NV!)				0	1.6		1.211
Window-system east/west	Glazing				0.55	0.5		0.991
Window-system east/west	Manual window				0.55	0.5		0.478
Window-system east/west	NV window				0	1.5		0.239
Window-system east/west	Glass edge sealing				0			0.4
Window north	Profile				0	1.2		6.991
Window north	Periphery				0			2
Window north	Glazing				0.55	0.5		13.5
Window north	Glass edge sealing				0	0.043		2.75
Window north	Paneel				0	0.5		14.794
Window north	Paneel edge sealing				0			1.9
Window west	Profile				0	1.1		10.556
Window west	Periphery				0			2.2
Window west	Glazing				0.55	0.5		46.206
Window west	Glass edge sealing				0			6.7
Window west	Paneel				0	0.51		8.488
Window west	Paneel edge sealing				0			3.7

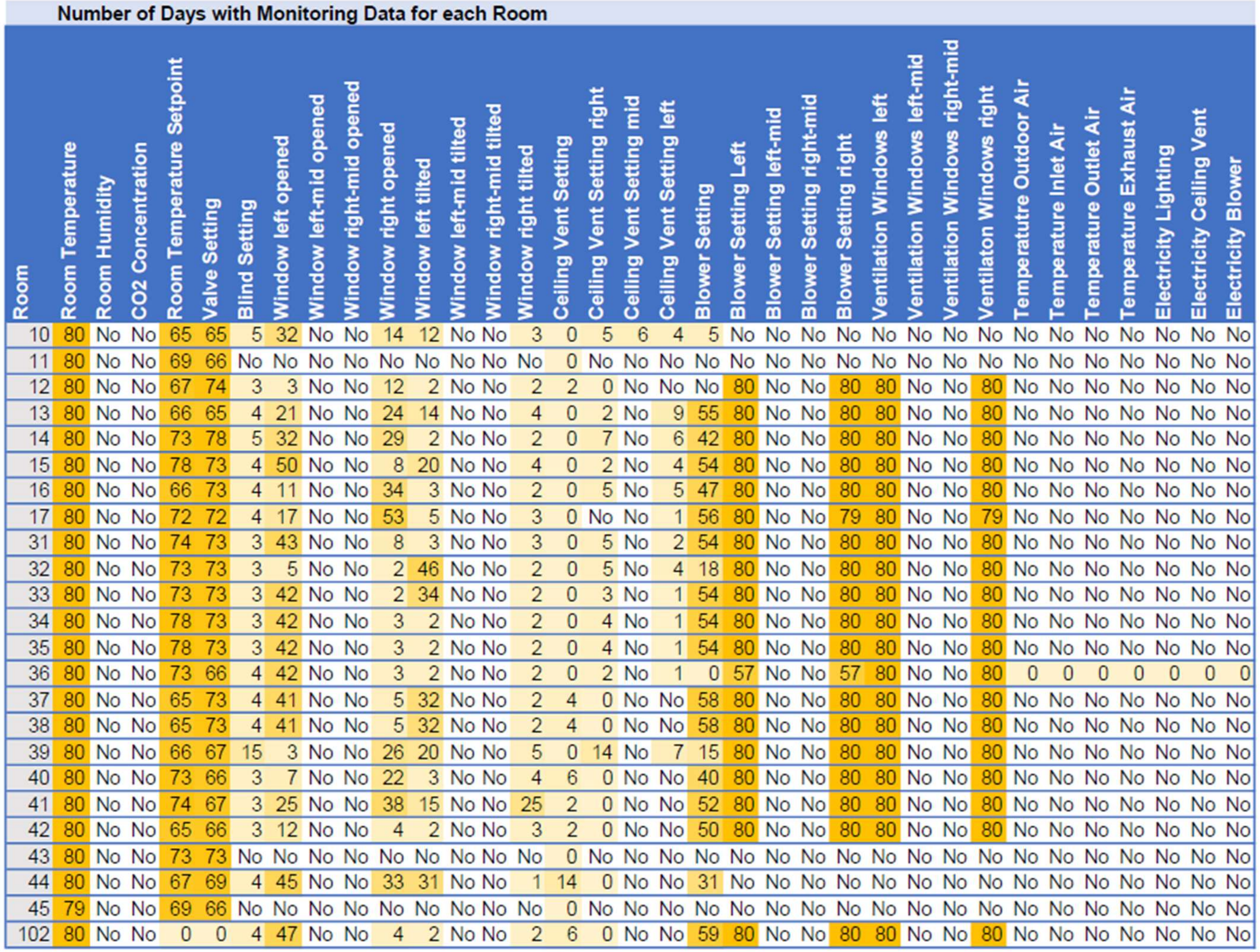


Walls

Group	Object	Thickness [m]	Conductivity [W/m*K]	Density [kg/m³]	Specific heat [J/kg*K]	U [W/m²*K]	spec. component mass [kg/m²]	Area [m²]
Basement	Base plate	0.253	0.316	2108	108.3	1.250	533	971
1st floor	West wall	0.740	0.133	1814	46.9	0.180	1342	161
Ground floor	West wall	0.785	0.079	1388	57.8	0.100	1090	103
1st floor	West wall	0.785	0.079	1388	57.8	0.100	1090	103
2nd floor	West wall	0.785	0.079	1388	57.8	0.100	1090	103
3rd floor	West wall	0.785	0.079	1388	57.8	0.100	1090	117
Ground floor	North wall	0.445	0.329	2238	63.2	0.740	996	39
1st floor	North wall	0.445	0.329	2238	63.2	0.740	996	39
2nd floor	North wall	0.445	0.329	2238	63.2	0.740	996	39
3rd floor	North wall	0.445	0.329	2238	63.3	0.740	996	43
Basement	East wall	0.750	0.135	1789	46.9	0.180	1342	163
Ground floor	East wall	0.785	0.079	1388	57.8	0.100	1090	93
1st floor	East wall	0.785	0.079	1388	57.8	0.100	1090	93
2nd floor	East wall	0.785	0.079	1388	57.8	0.100	1090	109
3rd floor	East wall	0.785	0.079	1388	57.8	0.100	1090	123
Roof	Roof	0.405	0.053	2450	138.2	0.130	992	430
Inner wall	Massive Ziegelwand	0.100	0.680	1600	16			
Inner wall	Beidseitig verputzt	0.015	-	-	-			
Inner floor/ceiling	Bodenbelag Lino	0.003	0.170	1200	222			
Inner floor/ceiling	Gussasphalt-Estrich	0.030	0.700	2333	176			
Inner floor/ceiling	Dämmung	0.015	0.035	260	100			
Inner floor/ceiling	Betondecke	0.150	2.000	2400	208			
Inner floor/ceiling	Kalkputz	0.010	0.870	1400	150			
Inner wall south side	Innenputz	0.015	-	-	-			
Inner wall south side	Massive Ziegelwand	0.100	0.680	1600	16			
Inner wall south side	Dämmung	0.500	0.035	260	100			
Inner wall south side	Neue Ziegelwand	0.240	0.140	700	476			
Inner wall south side	Innenputz Kalk	0.015	-	-	-			

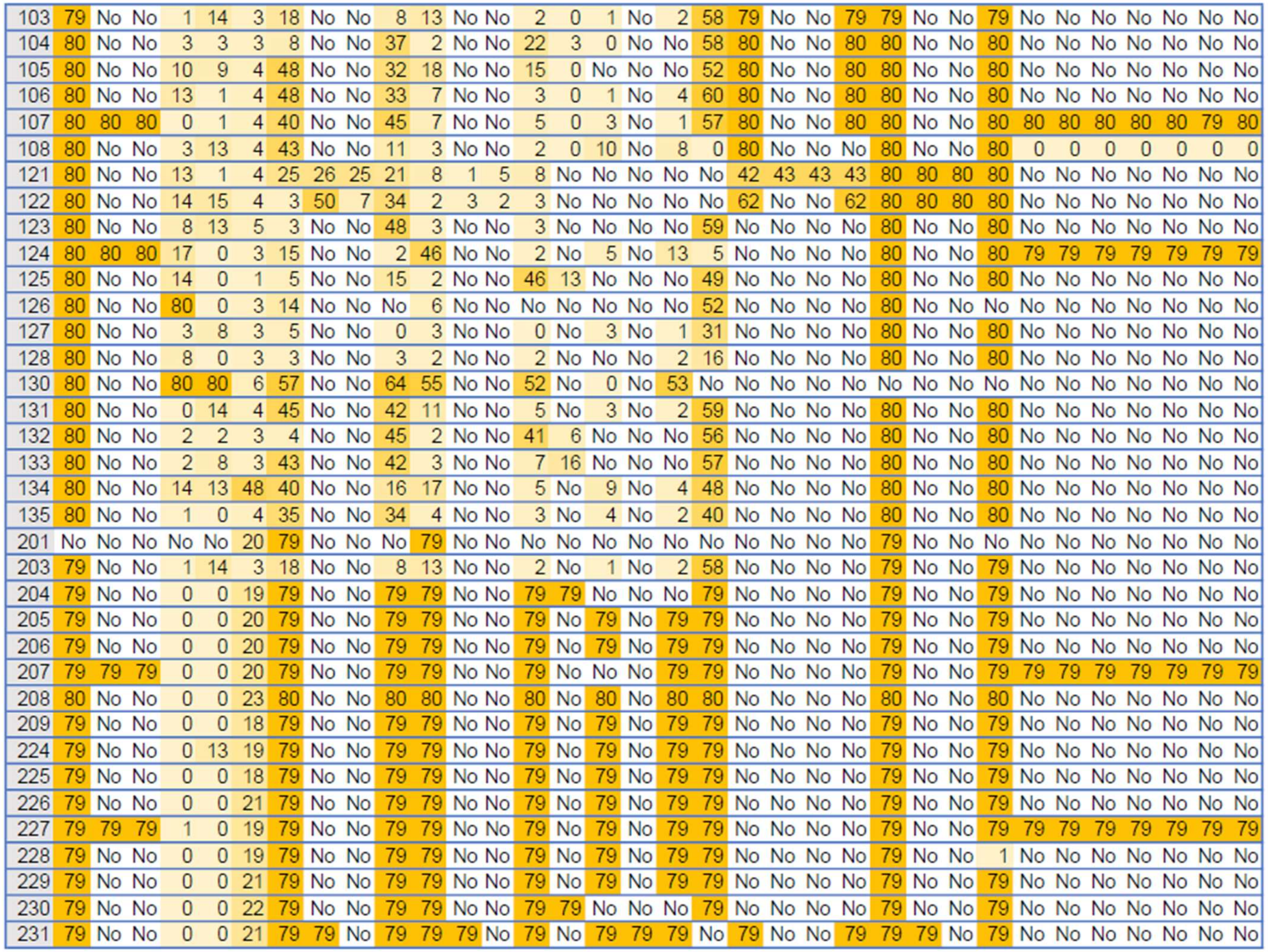
*The values for west and north window apply to ground floor to 3rd floor combined.

Annex 3: Overview monitoring data*



Number of Days with Monitoring Data for each Room

Room	Room Temperature	Room Humidity	CO2 Concentration	Room Temperature Setpoint	Valve Setting	Blind Setting	Window left opened	Window left-mid opened	Window right-mid opened	Window right opened	Window left tilted	Window left-mid tilted	Window right-mid tilted	Window right tilted	Ceiling Vent Setting	Ceiling Vent Setting right	Ceiling Vent Setting mid	Ceiling Vent Setting left	Blower Setting	Blower Setting Left	Blower Setting left-mid	Blower Setting right-mid	Blower Setting right	Ventilation Windows left	Ventilation Windows left-mid	Ventilation Windows right-mid	Ventilaton Windows right	Temperature Outdoor Air	Temperature Inlet Air	Temperature Outlet Air	Temperature Exhaust Air	Electricity Lighting	Electricity Ceiling Vent	Electricity Blower
10	80	No	No	65	65	5	32	No	No	14	12	No	No	3	0	5	6	4	5	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
11	80	No	No	69	66	No	No	No	No	No	No	No	No	No	0	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
12	80	No	No	67	74	3	3	No	No	12	2	No	No	2	2	0	No	No	No	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
13	80	No	No	66	65	4	21	No	No	24	14	No	No	4	0	2	No	9	55	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
14	80	No	No	73	78	5	32	No	No	29	2	No	No	2	0	7	No	6	42	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
15	80	No	No	78	73	4	50	No	No	8	20	No	No	4	0	2	No	4	54	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
16	80	No	No	66	73	4	11	No	No	34	3	No	No	2	0	5	No	5	47	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
17	80	No	No	72	72	4	17	No	No	53	5	No	No	3	0	No	No	1	56	80	No	No	79	80	No	No	79	No	No	No	No	No	No	No
31	80	No	No	74	73	3	43	No	No	8	3	No	No	3	0	5	No	2	54	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
32	80	No	No	73	73	3	5	No	No	2	46	No	No	2	0	5	No	4	18	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
33	80	No	No	73	73	3	42	No	No	2	34	No	No	2	0	3	No	1	54	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
34	80	No	No	78	73	3	42	No	No	3	2	No	No	2	0	4	No	1	54	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
35	80	No	No	78	73	3	42	No	No	3	2	No	No	2	0	4	No	1	54	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
36	80	No	No	73	66	4	42	No	No	3	2	No	No	2	0	2	No	1	0	57	No	No	57	80	No	No	80	0	0	0	0	0	0	0
37	80	No	No	65	73	4	41	No	No	5	32	No	No	2	4	0	No	No	58	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
38	80	No	No	65	73	4	41	No	No	5	32	No	No	2	4	0	No	No	58	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
39	80	No	No	66	67	15	3	No	No	26	20	No	No	5	0	14	No	7	15	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
40	80	No	No	73	66	3	7	No	No	22	3	No	No	4	6	0	No	No	40	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
41	80	No	No	74	67	3	25	No	No	38	15	No	No	25	2	0	No	No	52	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
42	80	No	No	65	66	3	12	No	No	4	2	No	No	3	2	0	No	No	50	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
43	80	No	No	73	73	No	No	No	No	No	No	No	No	No	0	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
44	80	No	No	67	69	4	45	No	No	33	31	No	No	1	14	0	No	No	31	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
45	79	No	No	69	66	No	No	No	No	No	No	No	No	No	0	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
102	80	No	No	0	0	4	47	No	No	4	2	No	No	2	6	0	No	No	59	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No



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104	80	No	No	3	3	3	8	No	No	37	2	No	No	22	3	0	No	No	58	80	No	No	80	80	No	No	80	No	No	No	No	No	No	No
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107	80	80	80	0	1	4	40	No	No	45	7	No	No	5	0	3	No	1	57	80	No	No	80	80	No	No	80	80	80	80	80	80	79	80
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121	80	No	No	13	1	4	25	26	25	21	8	1	5	8	No	No	No	No	No	42	43	43	43	80	80	80	80	No	No	No	No	No	No	No
122	80	No	No	14	15	4	3	50	7	34	2	3	2	3	No	No	No	No	No	62	No	No	62	80	80	80	80	No	No	No	No	No	No	No
123	80	No	No	8	13	5	3	No	No	48	3	No	No	3	No	No	No	No	59	No	No	No	No	80	No	No	80	No	No	No	No	No	No	No
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125	80	No	No	14	0	1	5	No	No	15	2	No	No	46	13	No	No	No	49	No	No	No	No	80	No	No	80	No	No	No	No	No	No	No
126	80	No	No	80	0	3	14	No	No	No	6	No	No	No	No	No	No	No	52	No	No	No	No	80	No	No	No	No	No	No	No	No	No	No
127	80	No	No	3	8	3	5	No	No	0	3	No	No	0	No	3	No	1	31	No	No	No	No	80	No	No	80	No	No	No	No	No	No	No
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130	80	No	No	80	80	6	57	No	No	64	55	No	No	52	No	0	No	53	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
131	80	No	No	0	14	4	45	No	No	42	11	No	No	5	No	3	No	2	59	No	No	No	No	80	No	No	80	No	No	No	No	No	No	No
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225	79	No	No	0	0	18	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
226	79	No	No	0	0	21	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
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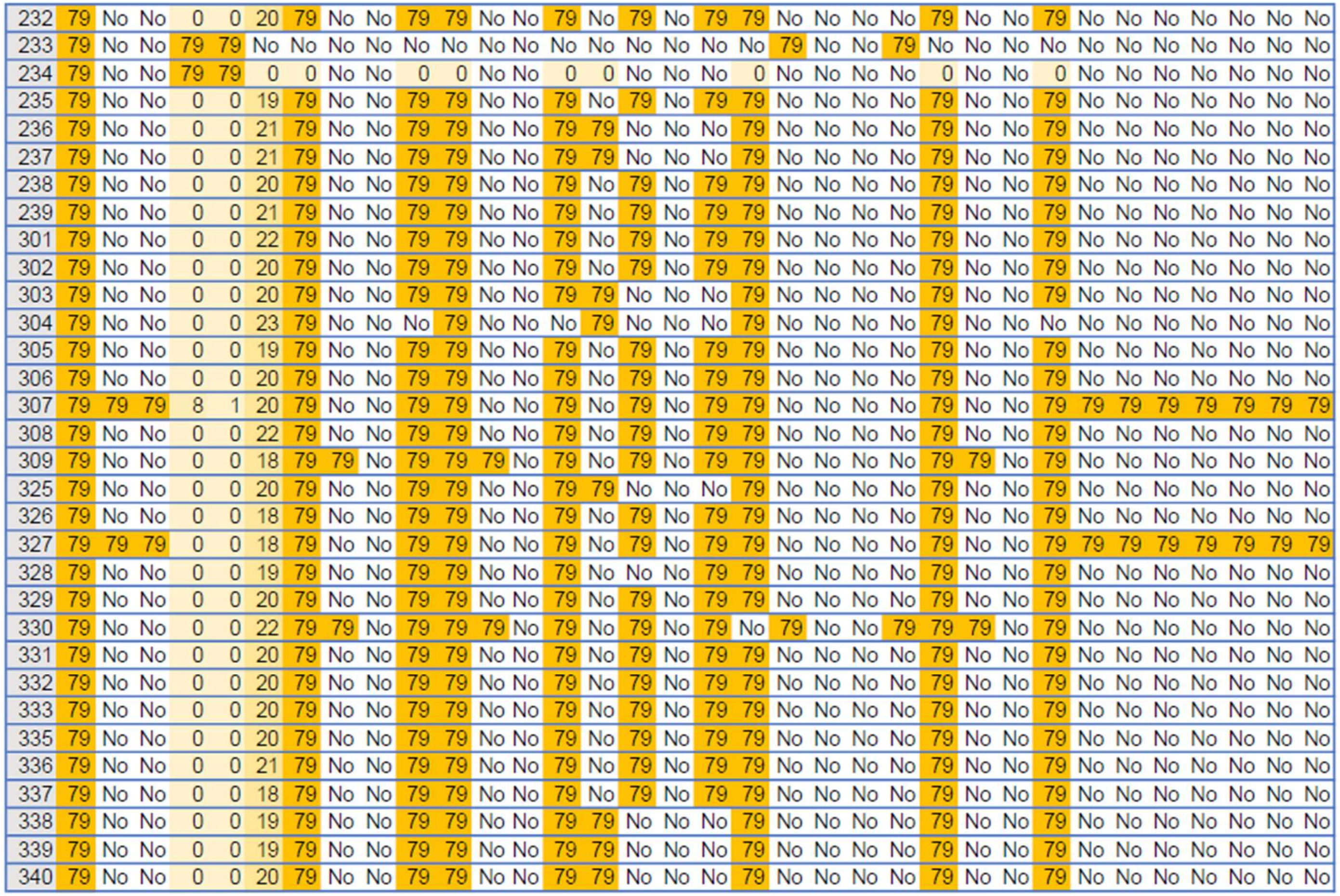
228	79	No	No	0	0	19	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	1	No	No	No	No	No	No	No
229	79	No	No	0	0	21	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
230	79	No	No	0	0	22	79	No	No	79	79	No	No	79	79	No	No	No	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
231	79	No	No	0	0	21	79	79	No	79	79	79	No	79	No	79	79	79	No	79	No	No	79	79	79	No	79	No	No	No	No	No	No	No



232	79	No	No	0	0	20	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
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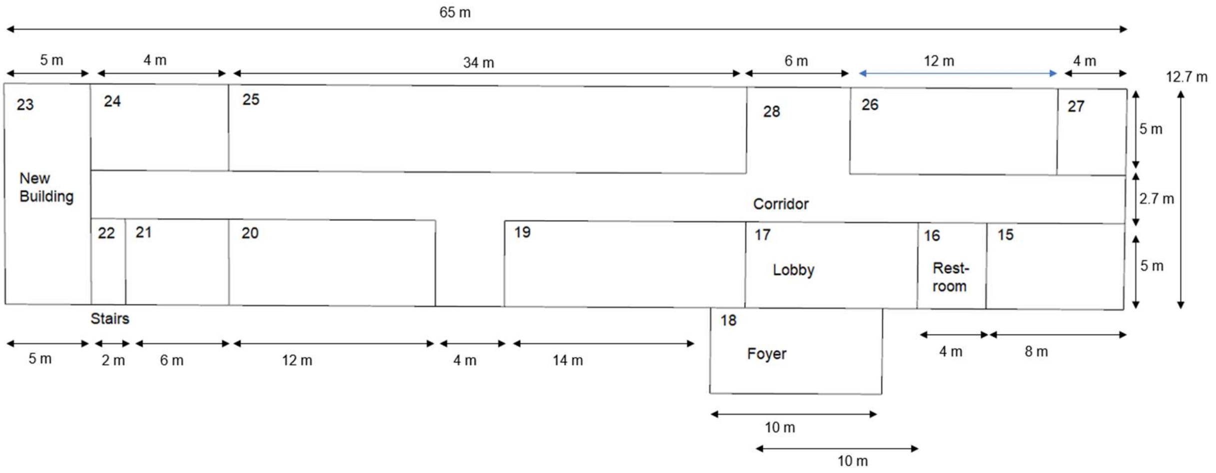
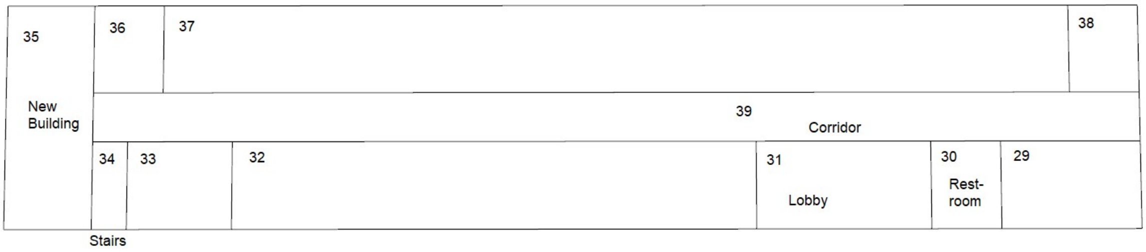
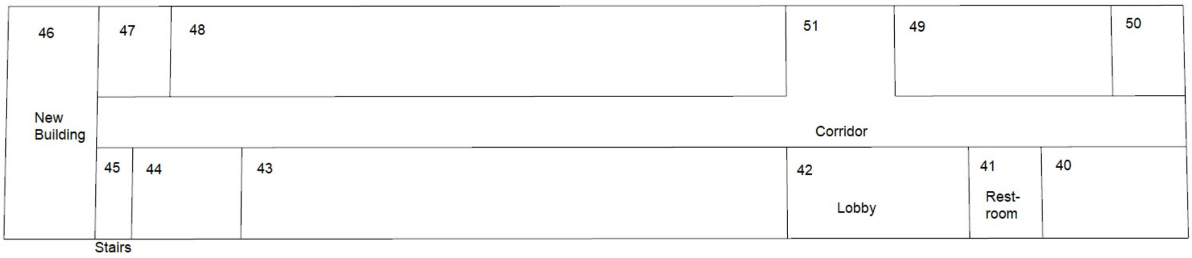
234	79	No	No	79	79	0	0	No	No	0	0	No	No	0	0	No	No	No	0	No	No	No	No	0	No	No	0	No	No	No	No	No	No	No
235	79	No	No	0	0	19	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
236	79	No	No	0	0	21	79	No	No	79	79	No	No	79	79	No	No	No	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
237	79	No	No	0	0	21	79	No	No	79	79	No	No	79	79	No	No	No	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
238	79	No	No	0	0	20	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
239	79	No	No	0	0	21	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
301	79	No	No	0	0	22	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
302	79	No	No	0	0	20	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
303	79	No	No	0	0	20	79	No	No	79	79	No	No	79	79	No	No	No	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
304	79	No	No	0	0	23	79	No	No	No	79	No	No	No	79	No	No	No	79	No	No	No	No	79	No	No	No	No	No	No	No	No	No	No
305	79	No	No	0	0	19	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
306	79	No	No	0	0	20	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
307	79	79	79	8	1	20	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	79	79	79	79	79	79	79
308	79	No	No	0	0	22	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
309	79	No	No	0	0	18	79	79	No	79	79	79	No	79	No	79	No	79	79	No	No	No	No	79	79	No	79	No	No	No	No	No	No	No
325	79	No	No	0	0	20	79	No	No	79	79	No	No	79	79	No	No	No	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
326	79	No	No	0	0	18	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
327	79	79	79	0	0	18	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	79	79	79	79	79	79	79
328	79	No	No	0	0	19	79	No	No	79	79	No	No	79	No	No	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
329	79	No	No	0	0	20	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
330	79	No	No	0	0	22	79	79	No	79	79	79	No	79	No	79	No	79	No	79	No	No	79	79	79	No	79	No	No	No	No	No	No	No
331	79	No	No	0	0	20	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
332	79	No	No	0	0	20	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
333	79	No	No	0	0	20	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
335	79	No	No	0	0	20	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
336	79	No	No	0	0	21	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
337	79	No	No	0	0	18	79	No	No	79	79	No	No	79	No	79	No	79	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
338	79	No	No	0	0	19	79	No	No	79	79	No	No	79	79	No	No	No	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
339	79	No	No	0	0	19	79	No	No	79	79	No	No	79	79	No	No	No	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No
340	79	No	No	0	0	20	79	No	No	79	79	No	No	79	79	No	No	No	79	No	No	No	No	79	No	No	79	No	No	No	No	No	No	No

* The number shows the count of days with existing monitoring data. If the table states „No“, no measuring device was installed.

Annex 4: Thermal zones in 1st, 2nd, and 3rd floor







Annex 5: Floor plan ground floor, 1st, 2nd, and 3rd floor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FLUR 2a
FLUR 2b
FLUR 2c
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BÜRO


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LICHTFLUR
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FLUR 3a
FLUR 3b
FLUR 3c
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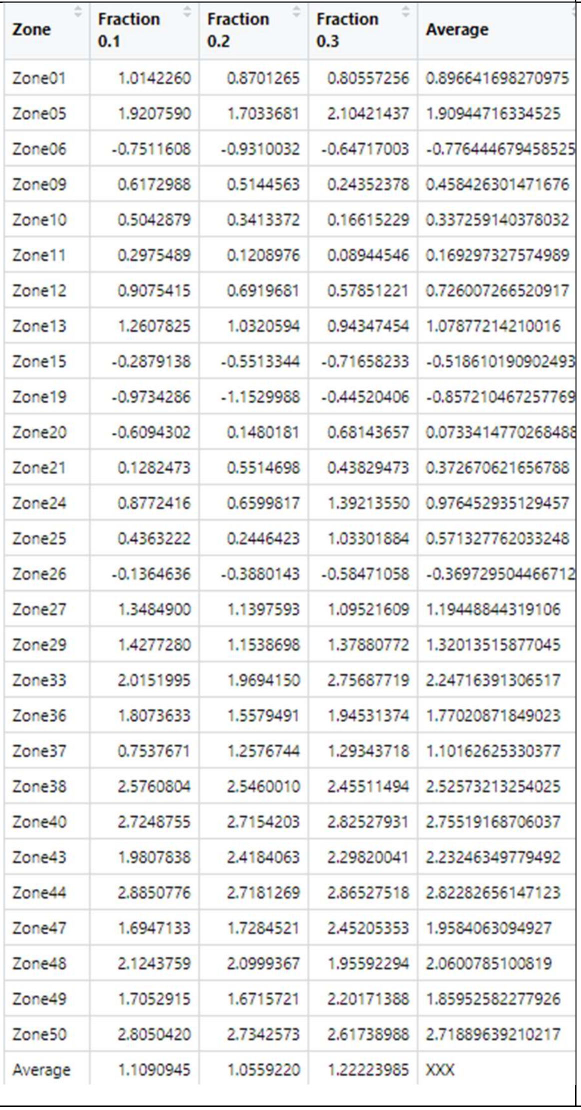
<u>Annex 6:</u> Parameter variation results

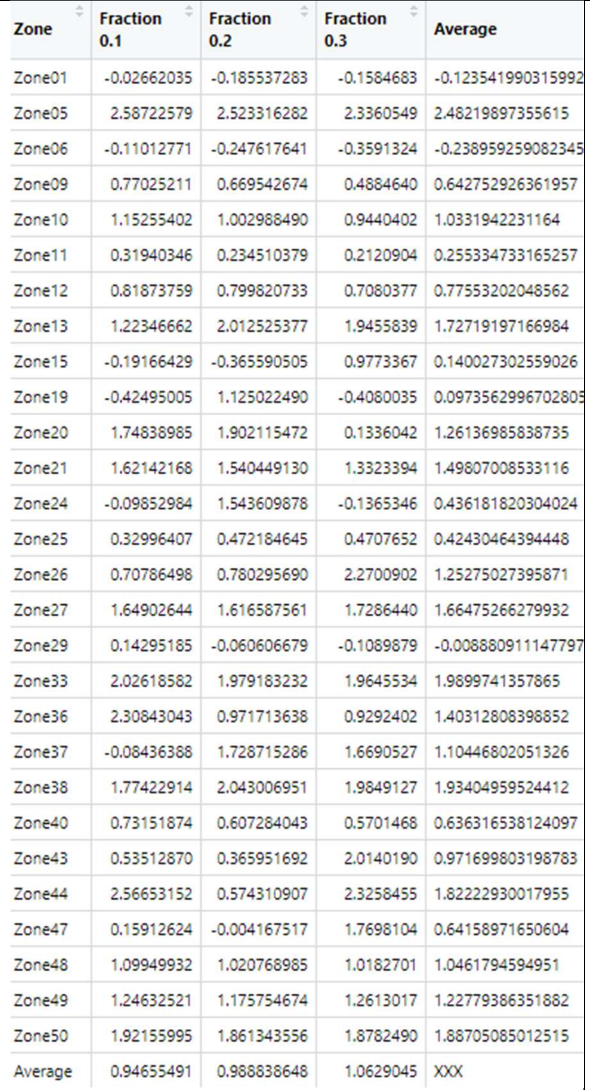
T_{Set} = 21°C

Week 35



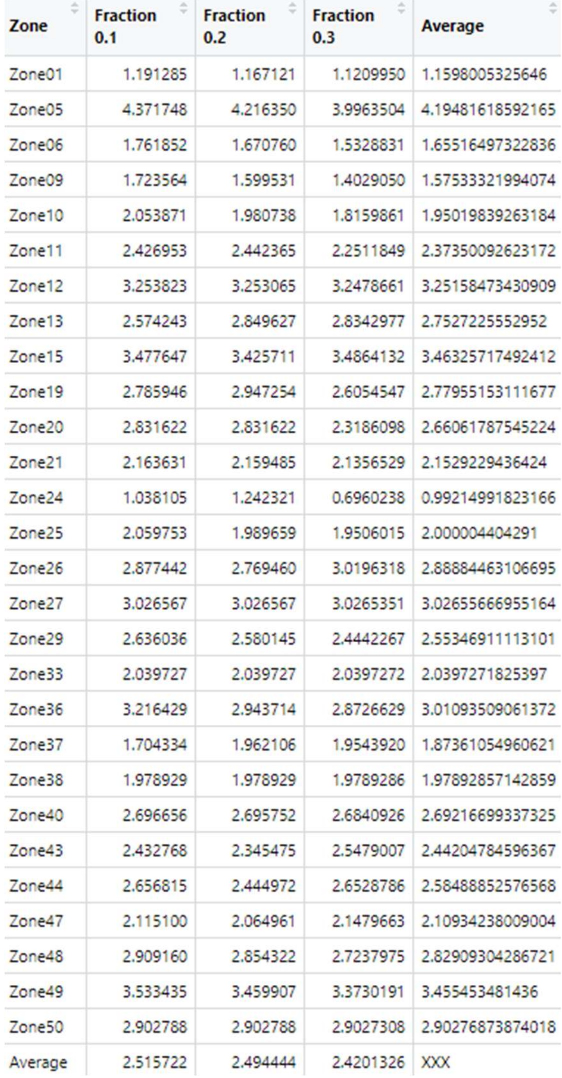
Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	1.0142260	0.8701265	0.80557256	0.896641698270975
Zone05	1.9207590	1.7033681	2.10421437	1.90944716334525
Zone06	-0.7511608	-0.9310032	-0.64717003	-0.776444679458525
Zone09	0.6172988	0.5144563	0.24352378	0.458426301471676
Zone10	0.5042879	0.3413372	0.16615229	0.337259140378032
Zone11	0.2975489	0.1208976	0.08944546	0.169297327574989
Zone12	0.9075415	0.6919681	0.57851221	0.726007266520917
Zone13	1.2607825	1.0320594	0.94347454	1.07877214210016
Zone15	-0.2879138	-0.5513344	-0.71658233	-0.518610190902493
Zone19	-0.9734286	-1.1529988	-0.44520406	-0.857210467257769
Zone20	-0.6094302	0.1480181	0.68143657	0.0733414770268488
Zone21	0.1282473	0.5514698	0.43829473	0.372670621656788
Zone24	0.8772416	0.6599817	1.39213550	0.976452935129457
Zone25	0.4363222	0.2446423	1.03301884	0.571327762033248
Zone26	-0.1364636	-0.3880143	-0.58471058	-0.369729504466712
Zone27	1.3484900	1.1397593	1.09521609	1.19448844319106
Zone29	1.4277280	1.1538698	1.37880772	1.32013515877045
Zone33	2.0151995	1.9694150	2.75687719	2.24716391306517
Zone36	1.8073633	1.5579491	1.94531374	1.77020871849023
Zone37	0.7537671	1.2576744	1.29343718	1.10162625330377
Zone38	2.5760804	2.5460010	2.45511494	2.52573213254025
Zone40	2.7248755	2.7154203	2.82527931	2.75519168706037
Zone43	1.9807838	2.4184063	2.29820041	2.23246349779492
Zone44	2.8850776	2.7181269	2.86527518	2.82282656147123
Zone47	1.6947133	1.7284521	2.45205353	1.9584063094927
Zone48	2.1243759	2.0999367	1.95592294	2.0600785100819
Zone49	1.7052915	1.6715721	2.20171388	1.85952582277926
Zone50	2.8050420	2.7342573	2.61738988	2.71889639210217
Average	1.1090945	1.0559220	1.22223985	XXX

Week 36 & 37



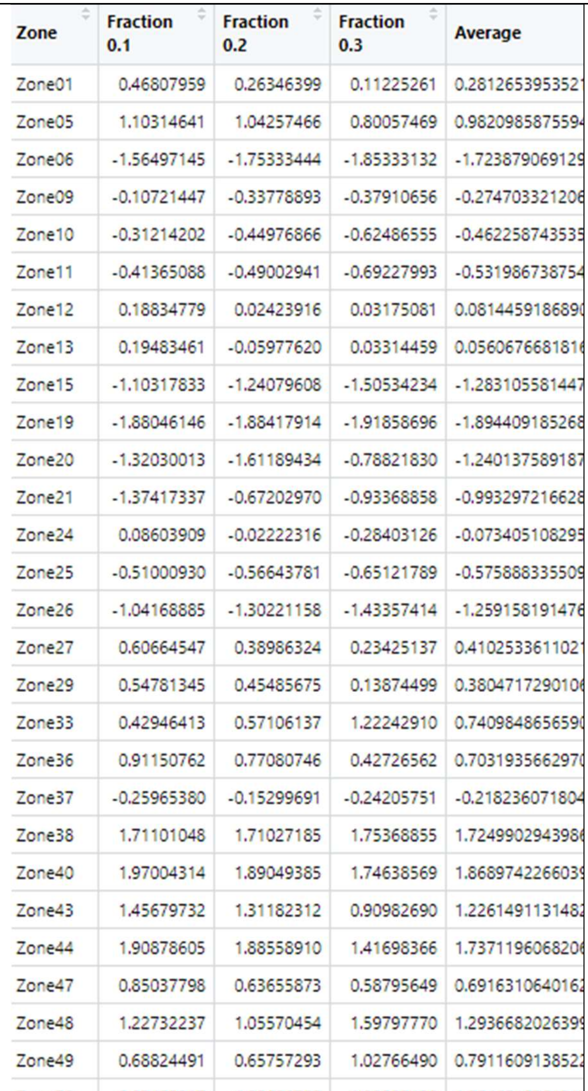
Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	-0.02662035	-0.185537283	-0.1584683	-0.123541990315992
Zone05	2.58722579	2.523316282	2.3360549	2.48219897355615
Zone06	-0.11012771	-0.247617641	-0.3591324	-0.238959259082345
Zone09	0.77025211	0.669542674	0.4884640	0.642752926361957
Zone10	1.15255402	1.002988490	0.9440402	1.0331942231164
Zone11	0.31940346	0.234510379	0.2120904	0.255334733165257
Zone12	0.81873759	0.799820733	0.7080377	0.77553202048562
Zone13	1.22346662	2.012525377	1.9455839	1.72719197166984
Zone15	-0.19166429	-0.365590505	0.9773367	0.140027302559026
Zone19	-0.42495005	1.125022490	-0.4080035	0.0973562996702805
Zone20	1.74838985	1.902115472	0.1336042	1.26136985838735
Zone21	1.62142168	1.540449130	1.3323394	1.49807008533116
Zone24	-0.09852984	1.543609878	-0.1365346	0.436181820304024
Zone25	0.32996407	0.472184645	0.4707652	0.42430464394448
Zone26	0.70786498	0.780295690	2.2700902	1.25275027395871
Zone27	1.64902644	1.616587561	1.7286440	1.66475266279932
Zone29	0.14295185	-0.060606679	-0.1089879	-0.008880911147797
Zone33	2.02618582	1.979183232	1.9645534	1.9899741357865
Zone36	2.30843043	0.971713638	0.9292402	1.40312808398852
Zone37	-0.08436388	1.728715286	1.6690527	1.10446802051326
Zone38	1.77422914	2.043006951	1.9849127	1.93404959524412
Zone40	0.73151874	0.607284043	0.5701468	0.636316538124097
Zone43	0.53512870	0.365951692	2.0140190	0.971699803198783
Zone44	2.56653152	0.574310907	2.3258455	1.82222930017955
Zone47	0.15912624	-0.004167517	1.7698104	0.64158971650604
Zone48	1.09949932	1.020768985	1.0182701	1.0461794594951
Zone49	1.24632521	1.175754674	1.2613017	1.22779386351882
Zone50	1.92155995	1.861343556	1.8782490	1.88705085012515
Average	0.94655491	0.988838648	1.0629045	XXX

Week 42

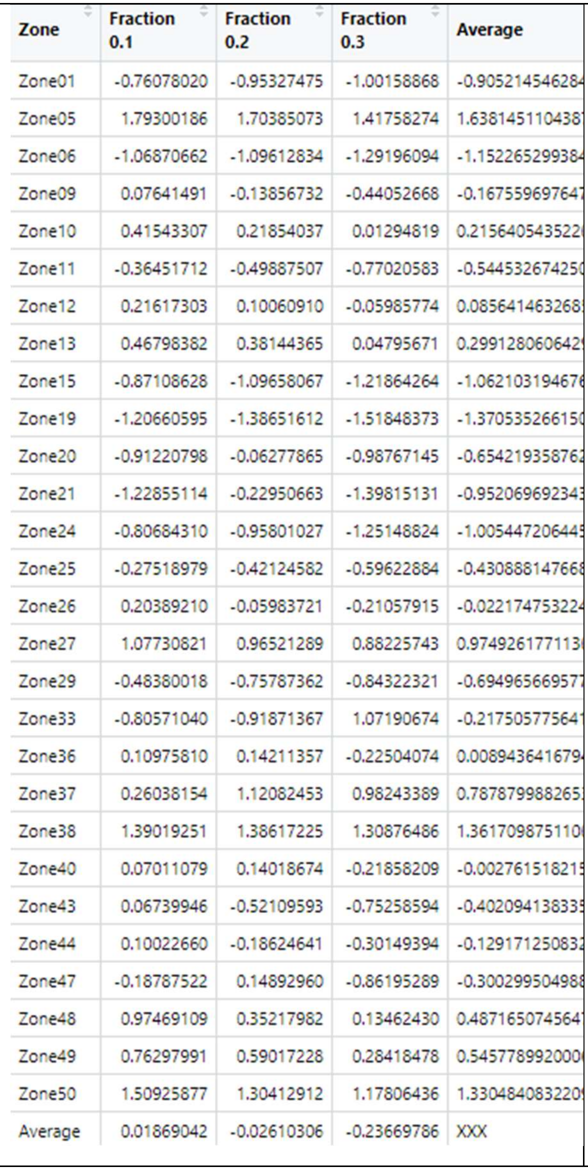


Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	1.191285	1.167121	1.1209950	1.1598005325646
Zone05	4.371748	4.216350	3.9963504	4.19481618592165
Zone06	1.761852	1.670760	1.5328831	1.65516497322836
Zone09	1.723564	1.599531	1.4029050	1.57533321994074
Zone10	2.053871	1.980738	1.8159861	1.95019839263184
Zone11	2.426953	2.442365	2.2511849	2.37350092623172
Zone12	3.253823	3.253065	3.2478661	3.25158473430909
Zone13	2.574243	2.849627	2.8342977	2.7527225552952
Zone15	3.477647	3.425711	3.4864132	3.46325717492412
Zone19	2.785946	2.947254	2.6054547	2.77955153111677
Zone20	2.831622	2.831622	2.3186098	2.66061787545224
Zone21	2.163631	2.159485	2.1356529	2.1529229436424
Zone24	1.038105	1.242321	0.6960238	0.99214991823166
Zone25	2.059753	1.989659	1.9506015	2.000004404291
Zone26	2.877442	2.769460	3.0196318	2.88884463106695
Zone27	3.026567	3.026567	3.0265351	3.02655666955164
Zone29	2.636036	2.580145	2.4442267	2.55346911113101
Zone33	2.039727	2.039727	2.0397272	2.0397271825397
Zone36	3.216429	2.943714	2.8726629	3.01093509061372
Zone37	1.704334	1.962106	1.9543920	1.87361054960621
Zone38	1.978929	1.978929	1.9789286	1.97892857142859
Zone40	2.696656	2.695752	2.6840926	2.69216699337325
Zone43	2.432768	2.345475	2.5479007	2.44204784596367
Zone44	2.656815	2.444972	2.6528786	2.58488852576568
Zone47	2.115100	2.064961	2.1479663	2.10934238009004
Zone48	2.909160	2.854322	2.7237975	2.82909304286721
Zone49	3.533435	3.459907	3.3730191	3.455453481436
Zone50	2.902788	2.902788	2.9027308	2.90276873874018
Average	2.515722	2.494444	2.4201326	XXX

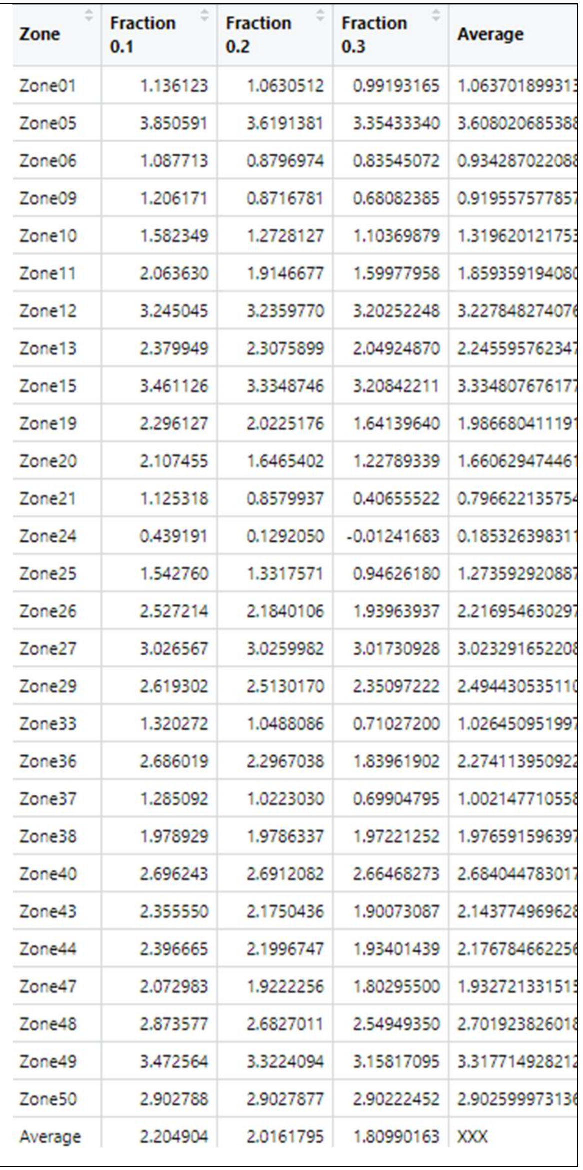
T_{Set} = 22°C



Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	0.46807959	0.26346399	0.11225261	0.2812653953521
Zone05	1.10314641	1.04257466	0.80057469	0.9820985875594
Zone06	-1.56497145	-1.75333444	-1.85333132	-1.723879069129
Zone09	-0.10721447	-0.33778893	-0.37910656	-0.274703321206
Zone10	-0.31214202	-0.44976866	-0.62486555	-0.462258743535
Zone11	-0.41365088	-0.49002941	-0.69227993	-0.531986738754
Zone12	0.18834779	0.02423916	0.03175081	0.0814459186890
Zone13	0.19483461	-0.05977620	0.03314459	0.0560676681816
Zone15	-1.10317833	-1.24079608	-1.50534234	-1.283105581447
Zone19	-1.88046146	-1.88417914	-1.91858696	-1.894409185268
Zone20	-1.32030013	-1.61189434	-0.78821830	-1.240137589187
Zone21	-1.37417337	-0.67202970	-0.93368858	-0.993297216628
Zone24	0.08603909	-0.02222316	-0.28403126	-0.073405108295
Zone25	-0.51000930	-0.56643781	-0.65121789	-0.575888335509
Zone26	-1.04168885	-1.30221158	-1.43357414	-1.259158191476
Zone27	0.60664547	0.38986324	0.23425137	0.4102533611021
Zone29	0.54781345	0.45485675	0.13874499	0.3804717290106
Zone33	0.42946413	0.57106137	1.22242910	0.7409848656590
Zone36	0.91150762	0.77080746	0.42726562	0.7031935662970
Zone37	-0.25965380	-0.15299691	-0.24205751	-0.218236071804
Zone38	1.71101048	1.71027185	1.75368855	1.7249902943986
Zone40	1.97004314	1.89049385	1.74638569	1.8689742266039
Zone43	1.45679732	1.31182312	0.90982690	1.2261491131482
Zone44	1.90878605	1.88558910	1.41698366	1.7371196068206
Zone47	0.85037798	0.63655873	0.58795649	0.6916310640162
Zone48	1.22732237	1.05570454	1.59797770	1.2936682026399
Zone49	0.68824491	0.65757293	1.02766490	0.7911609138522
Zone50	2.03489317	1.99606765	1.92299486	1.9846518964348
Average	0.23199677	0.14705293	0.09491401	XXX

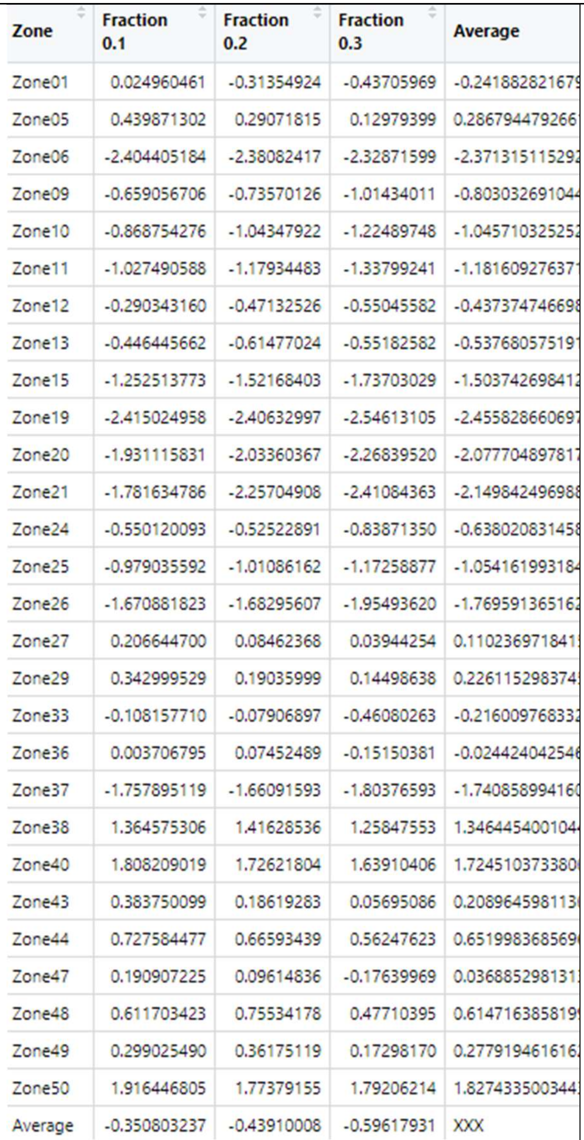


Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	-0.76078020	-0.95327475	-1.00158868	-0.905214546284
Zone05	1.79300186	1.70385073	1.41758274	1.6381451104387
Zone06	-1.06870662	-1.09612834	-1.29196094	-1.152265299384
Zone09	0.07641491	-0.13856732	-0.44052668	-0.167559697647
Zone10	0.41543307	0.21854037	0.01294819	0.2156405435220
Zone11	-0.36451712	-0.49887507	-0.77020583	-0.544532674250
Zone12	0.21617303	0.10060910	-0.05985774	0.0856414632685
Zone13	0.46798382	0.38144365	0.04795671	0.2991280606429
Zone15	-0.87108628	-1.09658067	-1.21864264	-1.062103194676
Zone19	-1.20660595	-1.38651612	-1.51848373	-1.370535266150
Zone20	-0.91220798	-0.06277865	-0.98767145	-0.654219358762
Zone21	-1.22855114	-0.22950663	-1.39815131	-0.952069692343
Zone24	-0.80684310	-0.95801027	-1.25148824	-1.005447206445
Zone25	-0.27518979	-0.42124582	-0.59622884	-0.430888147668
Zone26	0.20389210	-0.05983721	-0.21057915	-0.022174753224
Zone27	1.07730821	0.96521289	0.88225743	0.9749261771130
Zone29	-0.48380018	-0.75787362	-0.84322321	-0.694965669577
Zone33	-0.80571040	-0.91871367	1.07190674	-0.217505775641
Zone36	0.10975810	0.14211357	-0.22504074	0.0089436416794
Zone37	0.26038154	1.12082453	0.98243389	0.7878799882653
Zone38	1.39019251	1.38617225	1.30876486	1.3617098751100
Zone40	0.07011079	0.14018674	-0.21858209	-0.002761518215
Zone43	0.06739946	-0.52109593	-0.75258594	-0.402094138335
Zone44	0.10022660	-0.18624641	-0.30149394	-0.129171250832
Zone47	-0.18787522	0.14892960	-0.86195289	-0.300299504988
Zone48	0.97469109	0.35217982	0.13462430	0.4871650745647
Zone49	0.76297991	0.59017228	0.28418478	0.5457789920000
Zone50	1.50925877	1.30412912	1.17806436	1.3304840832209
Average	0.01869042	-0.02610306	-0.23669786	XXX

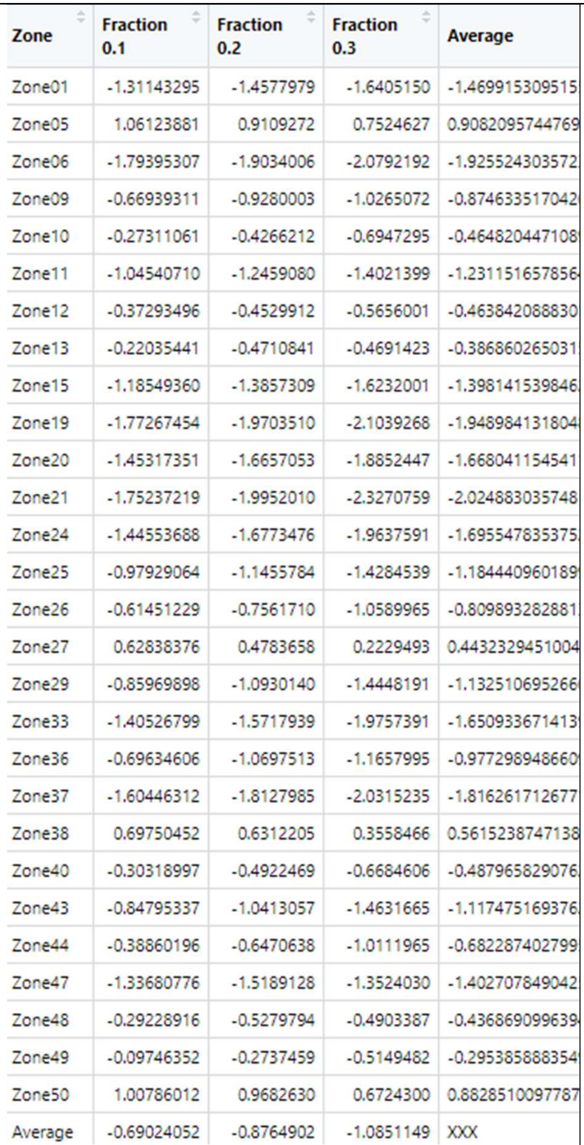


Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	1.136123	1.0630512	0.99193165	1.063701899313
Zone05	3.850591	3.6191381	3.35433340	3.608020685388
Zone06	1.087713	0.8796974	0.83545072	0.934287022088
Zone09	1.206171	0.8716781	0.68082385	0.919557577857
Zone10	1.582349	1.2728127	1.10369879	1.319620121753
Zone11	2.063630	1.9146677	1.59977958	1.859359194080
Zone12	3.245045	3.2359770	3.20252248	3.227848274076
Zone13	2.379949	2.3075899	2.04924870	2.245595762347
Zone15	3.461126	3.3348746	3.20842211	3.334807676177
Zone19	2.296127	2.0225176	1.64139640	1.986680411191
Zone20	2.107455	1.6465402	1.22789339	1.660629474461
Zone21	1.125318	0.8579937	0.40655522	0.796622135754
Zone24	0.439191	0.1292050	-0.01241683	0.185326398311
Zone25	1.542760	1.3317571	0.94626180	1.273592920887
Zone26	2.527214	2.1840106	1.93963937	2.216954630297
Zone27	3.026567	3.0259982	3.01730928	3.023291652208
Zone29	2.619302	2.5130170	2.35097222	2.494430535110
Zone33	1.320272	1.0488086	0.71027200	1.026450951997
Zone36	2.686019	2.2967038	1.83961902	2.274113950922
Zone37	1.285092	1.0223030	0.69904795	1.002147710558
Zone38	1.978929	1.9786337	1.97221252	1.976591596397
Zone40	2.696243	2.6912082	2.66468273	2.684044783017
Zone43	2.355550	2.1750436	1.90073087	2.143774969628
Zone44	2.396665	2.1996747	1.93401439	2.176784662256
Zone47	2.072983	1.9222256	1.80295500	1.932721331515
Zone48	2.873577	2.6827011	2.54949350	2.701923826018
Zone49	3.472564	3.3224094	3.15817095	3.317714928212
Zone50	2.902788	2.9027877	2.90222452	2.902599973136
Average	2.204904	2.0161795	1.80990163	XXX

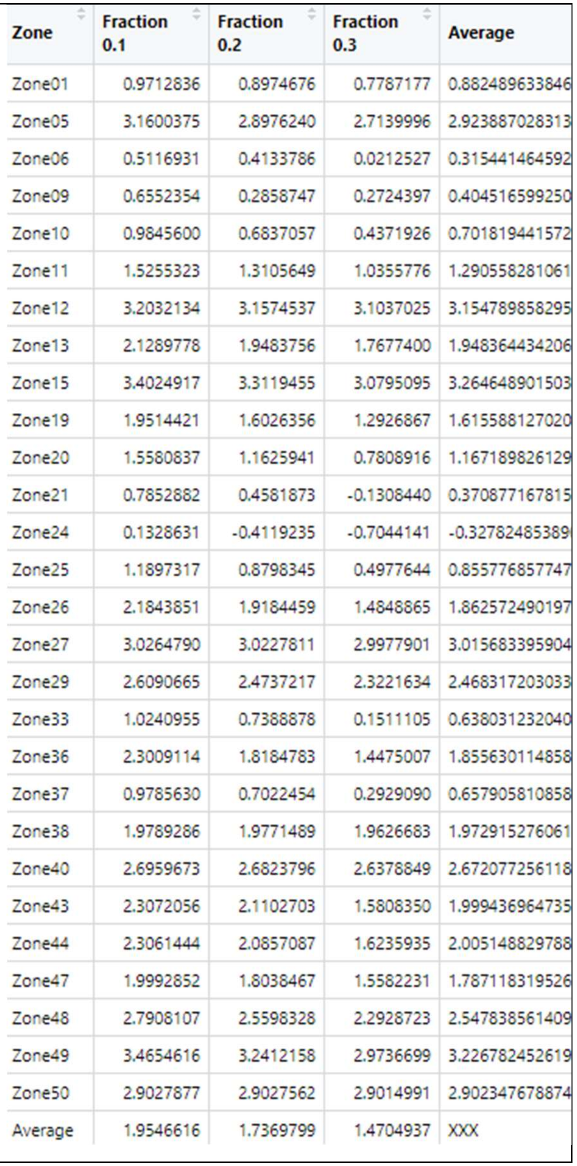
T_{Set} = 23°C



Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	0.024960461	-0.31354924	-0.43705969	-0.24188282167
Zone05	0.439871302	0.29071815	0.12979399	0.28679447926
Zone06	-2.404405184	-2.38082417	-2.32871599	-2.37131511529
Zone09	-0.659056706	-0.73570126	-1.01434011	-0.80303269104
Zone10	-0.868754276	-1.04347922	-1.22489748	-1.04571032525
Zone11	-1.027490588	-1.17934483	-1.33799241	-1.18160927637
Zone12	-0.290343160	-0.47132526	-0.55045582	-0.43737474669
Zone13	-0.446445662	-0.61477024	-0.55182582	-0.53768057519
Zone15	-1.252513773	-1.52168403	-1.73703029	-1.50374269841
Zone19	-2.415024958	-2.40632997	-2.54613105	-2.45582866069
Zone20	-1.931115831	-2.03360367	-2.26839520	-2.07770489781
Zone21	-1.781634786	-2.25704908	-2.41084363	-2.14984249698
Zone24	-0.550120093	-0.52522891	-0.83871350	-0.63802083145
Zone25	-0.979035592	-1.01086162	-1.17258877	-1.05416199318
Zone26	-1.670881823	-1.68295607	-1.95493620	-1.76959136516
Zone27	0.206644700	0.08462368	0.03944254	0.11023697184
Zone29	0.342999529	0.19035999	0.14498638	0.22611529837
Zone33	-0.108157710	-0.07906897	-0.46080263	-0.21600976833
Zone36	0.003706795	0.07452489	-0.15150381	-0.02442404254
Zone37	-1.757895119	-1.66091593	-1.80376593	-1.74085899416
Zone38	1.364575306	1.41628536	1.25847553	1.34644540010
Zone40	1.808209019	1.72621804	1.63910406	1.72451037338
Zone43	0.383750099	0.18619283	0.05695086	0.20896459811
Zone44	0.727584477	0.66593439	0.56247623	0.65199836856
Zone47	0.190907225	0.09614836	-0.17639969	0.03688529813
Zone48	0.611703423	0.75534178	0.47710395	0.61471638581
Zone49	0.299025490	0.36175119	0.17298170	0.27791946161
Zone50	1.916446805	1.77379155	1.79206214	1.82743350034
Average	-0.350803237	-0.43910008	-0.59617931	XXX

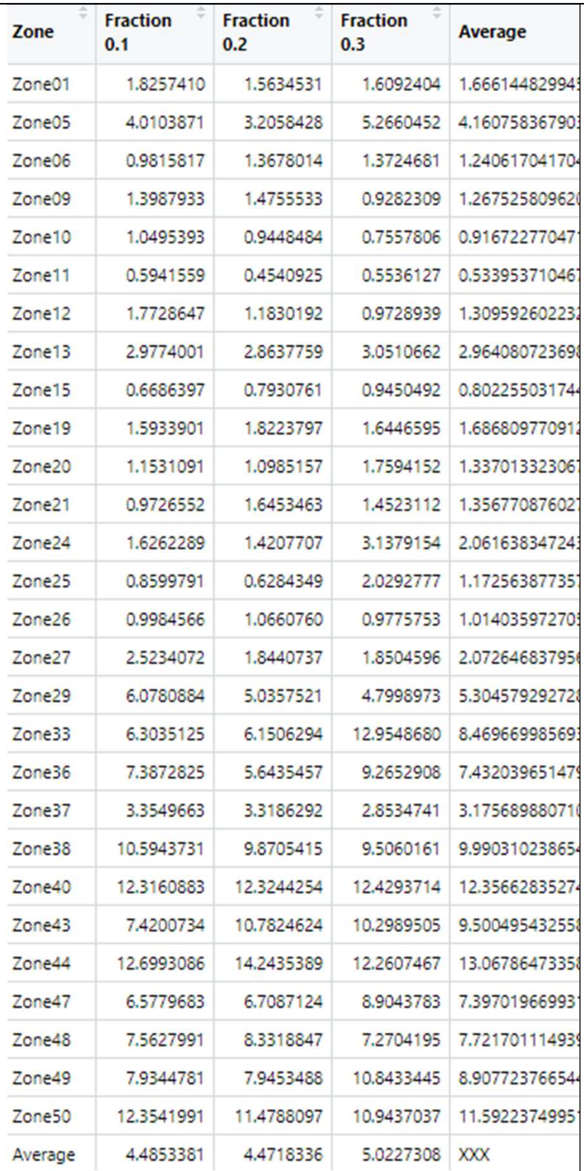


Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	-1.31143295	-1.4577979	-1.6405150	-1.469915309515
Zone05	1.06123881	0.9109272	0.7524627	0.9082095744769
Zone06	-1.79395307	-1.9034006	-2.0792192	-1.925524303572
Zone09	-0.66939311	-0.9280003	-1.0265072	-0.874633517042
Zone10	-0.27311061	-0.4266212	-0.6947295	-0.464820447108
Zone11	-1.04540710	-1.2459080	-1.4021399	-1.231151657856
Zone12	-0.37293496	-0.4529912	-0.5656001	-0.463842088830
Zone13	-0.22035441	-0.4710841	-0.4691423	-0.386860265031
Zone15	-1.18549360	-1.3857309	-1.6232001	-1.398141539846
Zone19	-1.77267454	-1.9703510	-2.1039268	-1.948984131804
Zone20	-1.45317351	-1.6657053	-1.8852447	-1.668041154541
Zone21	-1.75237219	-1.9952010	-2.3270759	-2.024883035748
Zone24	-1.44553688	-1.6773476	-1.9637591	-1.695547835375
Zone25	-0.97929064	-1.1455784	-1.4284539	-1.184440960189
Zone26	-0.61451229	-0.7561710	-1.0589965	-0.809893282881
Zone27	0.62838376	0.4783658	0.2229493	0.4432329451004
Zone29	-0.85969898	-1.0930140	-1.4448191	-1.132510695266
Zone33	-1.40526799	-1.5717939	-1.9757391	-1.650933671413
Zone36	-0.69634606	-1.0697513	-1.1657995	-0.977298948660
Zone37	-1.60446312	-1.8127985	-2.0315235	-1.816261712677
Zone38	0.69750452	0.6312205	0.3558466	0.5615238747138
Zone40	-0.30318997	-0.4922469	-0.6684606	-0.487965829076
Zone43	-0.84795337	-1.0413057	-1.4631665	-1.117475169376
Zone44	-0.38860196	-0.6470638	-1.0111965	-0.682287402799
Zone47	-1.33680776	-1.5189128	-1.3524030	-1.402707849042
Zone48	-0.29228916	-0.5279794	-0.4903387	-0.436869099639
Zone49	-0.09746352	-0.2737459	-0.5149482	-0.295385888354
Zone50	1.00786012	0.9682630	0.6724300	0.8828510097787
Average	-0.69024052	-0.8764902	-1.0851149	XXX

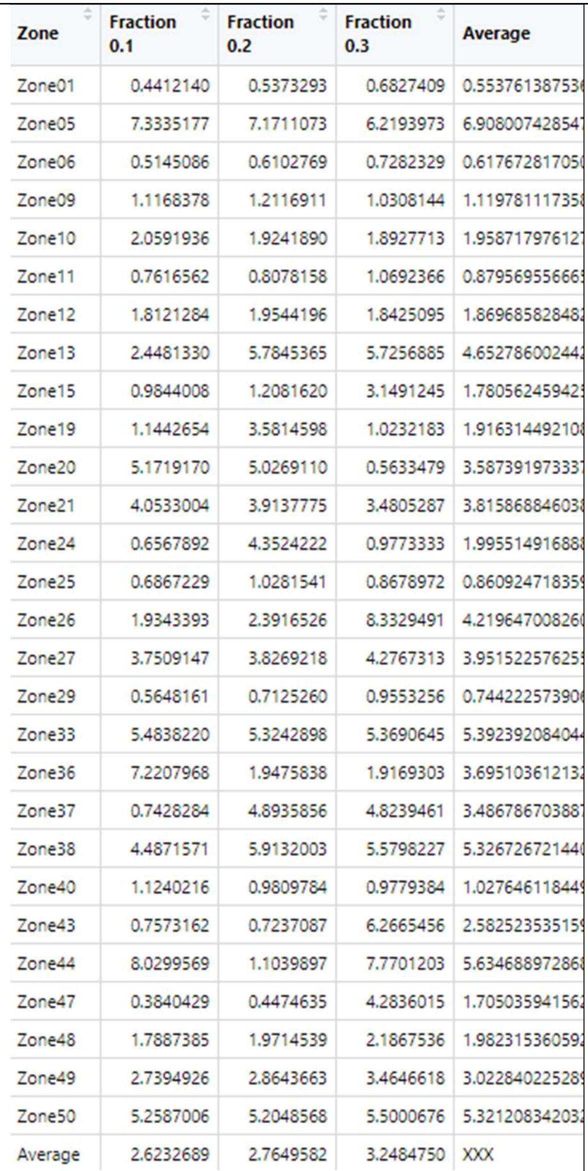


Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	0.9712836	0.8974676	0.7787177	0.882489633846
Zone05	3.1600375	2.8976240	2.7139996	2.923887028313
Zone06	0.5116931	0.4133786	0.0212527	0.315441464592
Zone09	0.6552354	0.2858747	0.2724397	0.404516599250
Zone10	0.9845600	0.6837057	0.4371926	0.701819441572
Zone11	1.5255323	1.3105649	1.0355776	1.290558281061
Zone12	3.2032134	3.1574537	3.1037025	3.154789858295
Zone13	2.1289778	1.9483756	1.7677400	1.948364434206
Zone15	3.4024917	3.3119455	3.0795095	3.264648901503
Zone19	1.9514421	1.6026356	1.2926867	1.615588127020
Zone20	1.5580837	1.1625941	0.7808916	1.167189826129
Zone21	0.7852882	0.4581873	-0.1308440	0.370877167815
Zone24	0.1328631	-0.4119235	-0.7044141	-0.32782485389
Zone25	1.1897317	0.8798345	0.4977644	0.855776857747
Zone26	2.1843851	1.9184459	1.4848865	1.862572490197
Zone27	3.0264790	3.0227811	2.9977901	3.015683395904
Zone29	2.6090665	2.4737217	2.3221634	2.468317203033
Zone33	1.0240955	0.7388878	0.1511105	0.638031232040
Zone36	2.3009114	1.8184783	1.4475007	1.855630114858
Zone37	0.9785630	0.7022454	0.2929090	0.657905810858
Zone38	1.9789286	1.9771489	1.9626683	1.972915276061
Zone40	2.6959673	2.6823796	2.6378849	2.672077256118
Zone43	2.3072056	2.1102703	1.5808350	1.999436964735
Zone44	2.3061444	2.0857087	1.6235935	2.005148829788
Zone47	1.9992852	1.8038467	1.5582231	1.787118319526
Zone48	2.7908107	2.5598328	2.2928723	2.547838561409
Zone49	3.4654616	3.2412158	2.9736699	3.226782452619
Zone50	2.9027877	2.9027562	2.9014991	2.902347678874
Average	1.9546616	1.7369799	1.4704937	XXX

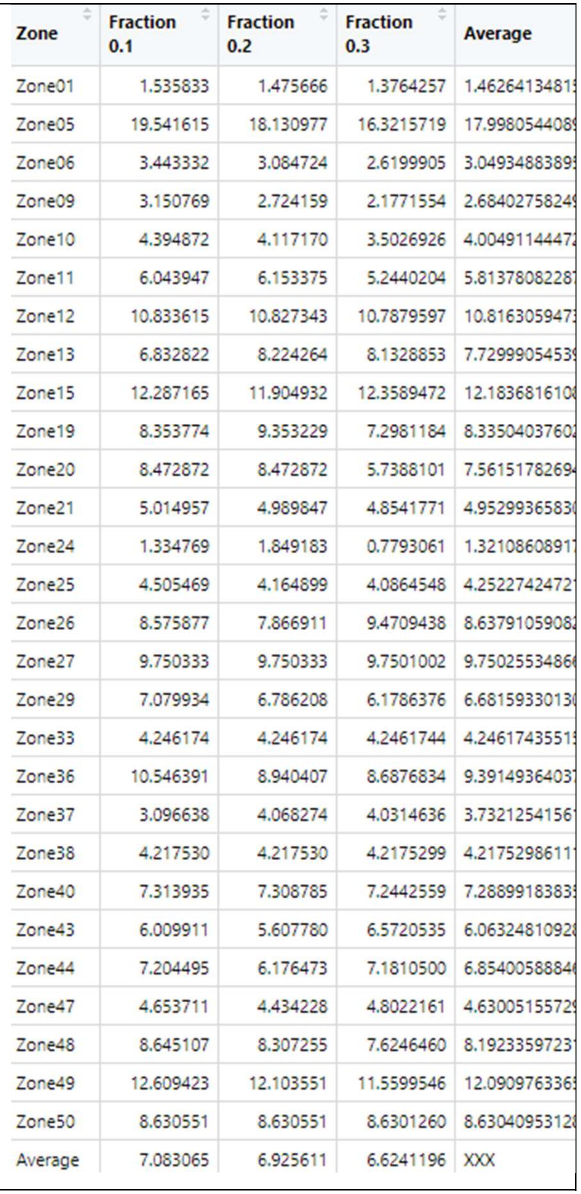
T_{Set} = 21°C (Square)



Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	1.8257410	1.5634531	1.6092404	1.66614482994
Zone05	4.0103871	3.2058428	5.2660452	4.16075836790
Zone06	0.9815817	1.3678014	1.3724681	1.24061704170
Zone09	1.3987933	1.4755533	0.9282309	1.26752580962
Zone10	1.0495393	0.9448484	0.7557806	0.91672277047
Zone11	0.5941559	0.4540925	0.5536127	0.53395371046
Zone12	1.7728647	1.1830192	0.9728939	1.30959260223
Zone13	2.9774001	2.8637759	3.0510662	2.96408072369
Zone15	0.6686397	0.7930761	0.9450492	0.80225503174
Zone19	1.5933901	1.8223797	1.6446595	1.68680977091
Zone20	1.1531091	1.0985157	1.7594152	1.33701332306
Zone21	0.9726552	1.6453463	1.4523112	1.35677087602
Zone24	1.6262289	1.4207707	3.1379154	2.06163834724
Zone25	0.8599791	0.6284349	2.0292777	1.17256387735
Zone26	0.9984566	1.0660760	0.9775753	1.01403597270
Zone27	2.5234072	1.8440737	1.8504596	2.07264683795
Zone29	6.0780884	5.0357521	4.7998973	5.30457929272
Zone33	6.3035125	6.1506294	12.9548680	8.46966998569
Zone36	7.3872825	5.6435457	9.2652908	7.43203965147
Zone37	3.3549663	3.3186292	2.8534741	3.17568988071
Zone38	10.5943731	9.8705415	9.5060161	9.99031023865
Zone40	12.3160883	12.3244254	12.4293714	12.3566283527
Zone43	7.4200734	10.7824624	10.2989505	9.50049543255
Zone44	12.6993086	14.2435389	12.2607467	13.0678647335
Zone47	6.5779683	6.7087124	8.9043783	7.39701966993
Zone48	7.5627991	8.3318847	7.2704195	7.72170111493
Zone49	7.9344781	7.9453488	10.8433445	8.90772376654
Zone50	12.3541991	11.4788097	10.9437037	11.5922374995
Average	4.4853381	4.4718336	5.0227308	XXX

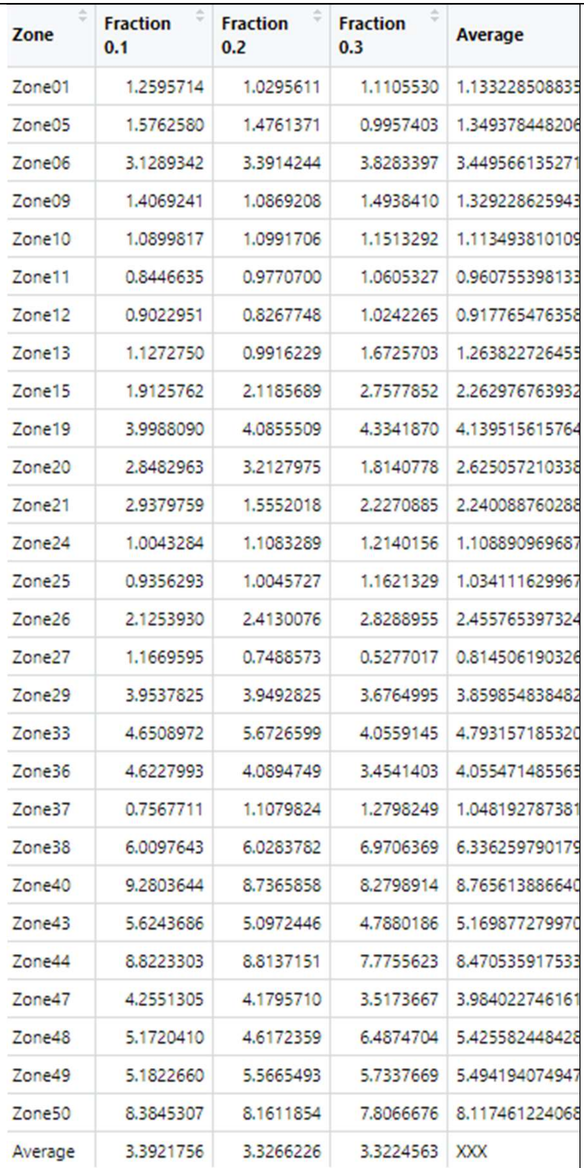


Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	0.4412140	0.5373293	0.6827409	0.55376138753
Zone05	7.3335177	7.1711073	6.2193973	6.90800742854
Zone06	0.5145086	0.6102769	0.7282329	0.61767281705
Zone09	1.1168378	1.2116911	1.0308144	1.11978111735
Zone10	2.0591936	1.9241890	1.8927713	1.95871797612
Zone11	0.7616562	0.8078158	1.0692366	0.87956955666
Zone12	1.8121284	1.9544196	1.8425095	1.86968582848
Zone13	2.4481330	5.7845365	5.7256885	4.65278600244
Zone15	0.9844008	1.2081620	3.1491245	1.78056245942
Zone19	1.1442654	3.5814598	1.0232183	1.91631449210
Zone20	5.1719170	5.0269110	0.5633479	3.58739197333
Zone21	4.0533004	3.9137775	3.4805287	3.81586884603
Zone24	0.6567892	4.3524222	0.9773333	1.99551491688
Zone25	0.6867229	1.0281541	0.8678972	0.86092471835
Zone26	1.9343393	2.3916526	8.3329491	4.21964700826
Zone27	3.7509147	3.8269218	4.2767313	3.95152257625
Zone29	0.5648161	0.7125260	0.9553256	0.74422257390
Zone33	5.4838220	5.3242898	5.3690645	5.39239208404
Zone36	7.2207968	1.9475838	1.9169303	3.69510361213
Zone37	0.7428284	4.8935856	4.8239461	3.48678670388
Zone38	4.4871571	5.9132003	5.5798227	5.32672672144
Zone40	1.1240216	0.9809784	0.9779384	1.02764611844
Zone43	0.7573162	0.7237087	6.2665456	2.58252353515
Zone44	8.0299569	1.1039897	7.7701203	5.63468897286
Zone47	0.3840429	0.4474635	4.2836015	1.70503594156
Zone48	1.7887385	1.9714539	2.1867536	1.98231536059
Zone49	2.7394926	2.8643663	3.4646618	3.02284022528
Zone50	5.2587006	5.2048568	5.5000676	5.32120834203
Average	2.6232689	2.7649582	3.2484750	XXX

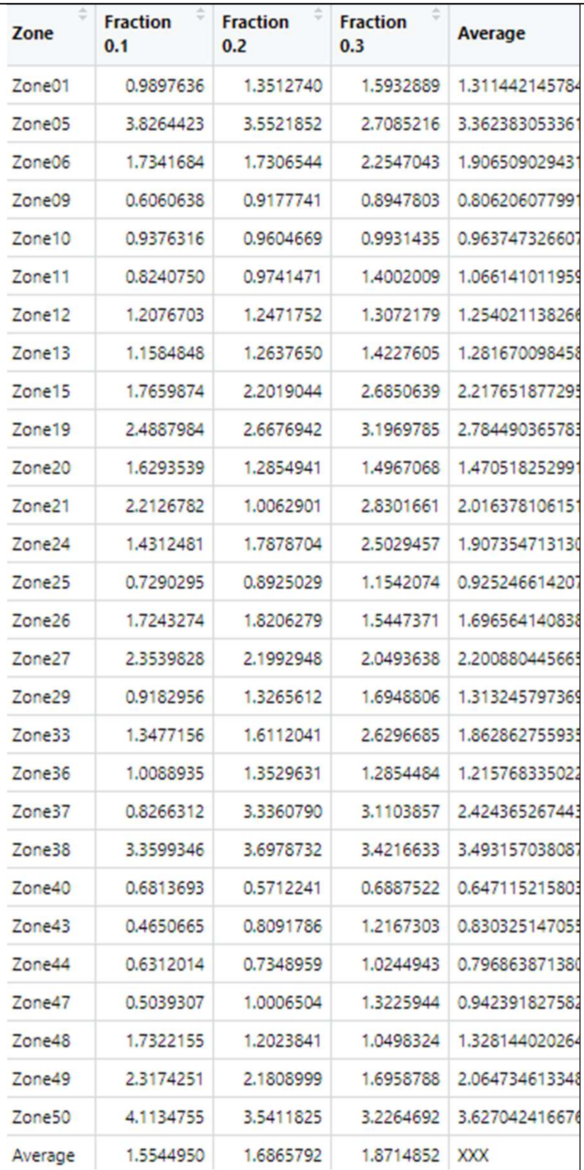


Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	1.535833	1.475666	1.3764257	1.4626413481
Zone05	19.541615	18.130977	16.3215719	17.998054408
Zone06	3.443332	3.084724	2.6199905	3.0493488389
Zone09	3.150769	2.724159	2.1771554	2.6840275824
Zone10	4.394872	4.117170	3.5026926	4.0049114447
Zone11	6.043947	6.153375	5.2440204	5.8137808228
Zone12	10.833615	10.827343	10.7879597	10.816305947
Zone13	6.832822	8.224264	8.1328853	7.7299905453
Zone15	12.287165	11.904932	12.3589472	12.183681610
Zone19	8.353774	9.353229	7.2981184	8.3350403760
Zone20	8.472872	8.472872	5.7388101	7.5615178269
Zone21	5.014957	4.989847	4.8541771	4.9529936583
Zone24	1.334769	1.849183	0.7793061	1.3210860891
Zone25	4.505469	4.164899	4.0864548	4.2522742472
Zone26	8.575877	7.866911	9.4709438	8.6379105908
Zone27	9.750333	9.750333	9.7501002	9.7502553486
Zone29	7.079934	6.786208	6.1786376	6.6815933013
Zone33	4.246174	4.246174	4.2461744	4.2461743551
Zone36	10.546391	8.940407	8.6876834	9.3914936403
Zone37	3.096638	4.068274	4.0314636	3.7321254156
Zone38	4.217530	4.217530	4.2175299	4.2175298611
Zone40	7.313935	7.308785	7.2442559	7.2889918383
Zone43	6.009911	5.607780	6.5720535	6.0632481092
Zone44	7.204495	6.176473	7.1810500	6.8540058884
Zone47	4.653711	4.434228	4.8022161	4.6300515572
Zone48	8.645107	8.307255	7.6246460	8.1923359723
Zone49	12.609423	12.103551	11.5599546	12.090976336
Zone50	8.630551	8.630551	8.6301260	8.6304095312
Average	7.083065	6.925611	6.6241196	XXX

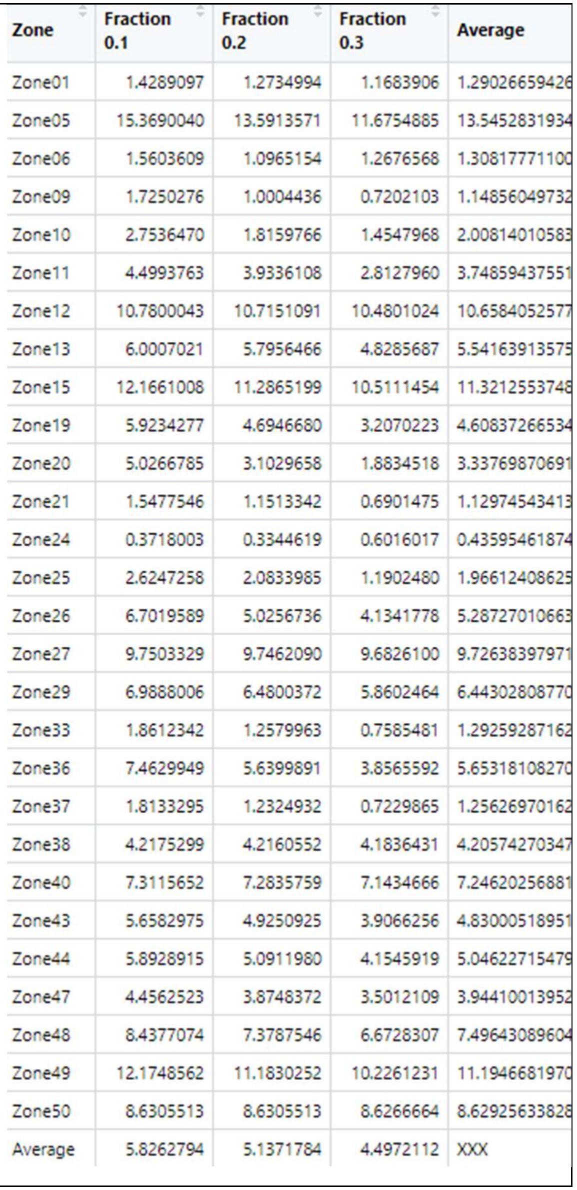
T_{Set} = 22°C (Square)



Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	1.2595714	1.0295611	1.1105530	1.133228508835
Zone05	1.5762580	1.4761371	0.9957403	1.349378448206
Zone06	3.1289342	3.3914244	3.8283397	3.449566135271
Zone09	1.4069241	1.0869208	1.4938410	1.329228625943
Zone10	1.0899817	1.0991706	1.1513292	1.113493810109
Zone11	0.8446635	0.9770700	1.0605327	0.960755398133
Zone12	0.9022951	0.8267748	1.0242265	0.917765476358
Zone13	1.1272750	0.9916229	1.6725703	1.263822726455
Zone15	1.9125762	2.1185689	2.7577852	2.262976763932
Zone19	3.9988090	4.0855509	4.3341870	4.139515615764
Zone20	2.8482963	3.2127975	1.8140778	2.625057210338
Zone21	2.9379759	1.5552018	2.2270885	2.240088760288
Zone24	1.0043284	1.1083289	1.2140156	1.108890969687
Zone25	0.9356293	1.0045727	1.1621329	1.034111629967
Zone26	2.1253930	2.4130076	2.8288955	2.455765397324
Zone27	1.1669595	0.7488573	0.5277017	0.814506190326
Zone29	3.9537825	3.9492825	3.6764995	3.859854838482
Zone33	4.6508972	5.6726599	4.0559145	4.793157185320
Zone36	4.6227993	4.0894749	3.4541403	4.055471485565
Zone37	0.7567711	1.1079824	1.2798249	1.048192787381
Zone38	6.0097643	6.0283782	6.9706369	6.336259790179
Zone40	9.2803644	8.7365858	8.2798914	8.765613886640
Zone43	5.6243686	5.0972446	4.7880186	5.169877279970
Zone44	8.8223303	8.8137151	7.7755623	8.470535917533
Zone47	4.2551305	4.1795710	3.5173667	3.984022746161
Zone48	5.1720410	4.6172359	6.4874704	5.425582448428
Zone49	5.1822660	5.5665493	5.7337669	5.494194074947
Zone50	8.3845307	8.1611854	7.8066676	8.117461224068
Average	3.3921756	3.3266226	3.3224563	XXX

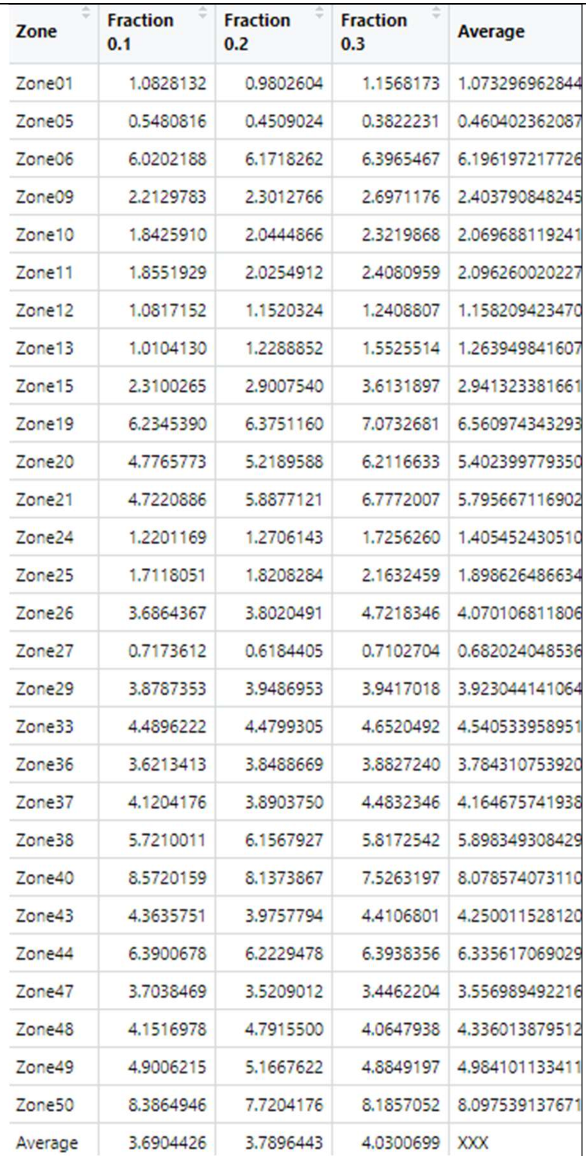


Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	0.9897636	1.3512740	1.5932889	1.311442145784
Zone05	3.8264423	3.5521852	2.7085216	3.362383053361
Zone06	1.7341684	1.7306544	2.2547043	1.906509029431
Zone09	0.6060638	0.9177741	0.8947803	0.806206077991
Zone10	0.9376316	0.9604669	0.9931435	0.963747326607
Zone11	0.8240750	0.9741471	1.4002009	1.066141011959
Zone12	1.2076703	1.2471752	1.3072179	1.254021138266
Zone13	1.1584848	1.2637650	1.4227605	1.281670098458
Zone15	1.7659874	2.2019044	2.6850639	2.217651877295
Zone19	2.4887984	2.6676942	3.1969785	2.784490365783
Zone20	1.6293539	1.2854941	1.4967068	1.470518252991
Zone21	2.2126782	1.0062901	2.8301661	2.016378106151
Zone24	1.4312481	1.7878704	2.5029457	1.907354713130
Zone25	0.7290295	0.8925029	1.1542074	0.925246614207
Zone26	1.7243274	1.8206279	1.5447371	1.696564140838
Zone27	2.3539828	2.1992948	2.0493638	2.200880445665
Zone29	0.9182956	1.3265612	1.6948806	1.313245797369
Zone33	1.3477156	1.6112041	2.6296685	1.862862755935
Zone36	1.0088935	1.3529631	1.2854484	1.215768335022
Zone37	0.8266312	3.3360790	3.1103857	2.424365267443
Zone38	3.3599346	3.6978732	3.4216633	3.493157038087
Zone40	0.6813693	0.5712241	0.6887522	0.647115215803
Zone43	0.4650665	0.8091786	1.2167303	0.830325147055
Zone44	0.6312014	0.7348959	1.0244943	0.796863871380
Zone47	0.5039307	1.0006504	1.3225944	0.942391827582
Zone48	1.7322155	1.2023841	1.0498324	1.328144020264
Zone49	2.3174251	2.1808999	1.6958788	2.064734613348
Zone50	4.1134755	3.5411825	3.2264692	3.627042416676
Average	1.5544950	1.6865792	1.8714852	XXX

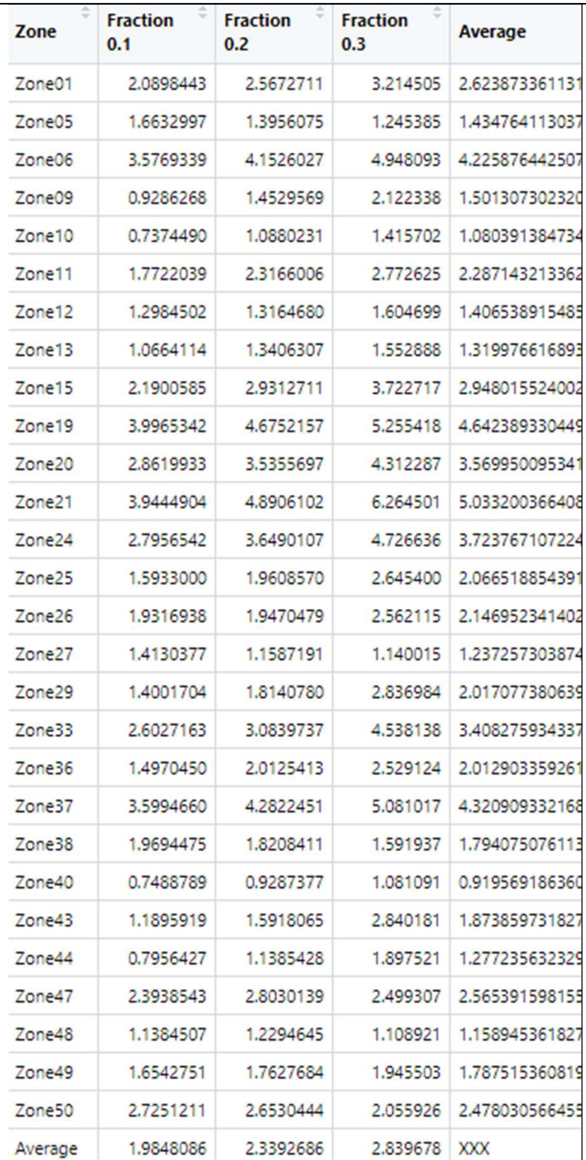


Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	1.4289097	1.2734994	1.1683906	1.29026659426
Zone05	15.3690040	13.5913571	11.6754885	13.5452831934
Zone06	1.5603609	1.0965154	1.2676568	1.30817771100
Zone09	1.7250276	1.0004436	0.7202103	1.14856049732
Zone10	2.7536470	1.8159766	1.4547968	2.00814010583
Zone11	4.4993763	3.9336108	2.8127960	3.74859437551
Zone12	10.7800043	10.7151091	10.4801024	10.6584052577
Zone13	6.0007021	5.7956466	4.8285687	5.54163913575
Zone15	12.1661008	11.2865199	10.5111454	11.3212553748
Zone19	5.9234277	4.6946680	3.2070223	4.60837266534
Zone20	5.0266785	3.1029658	1.8834518	3.33769870691
Zone21	1.5477546	1.1513342	0.6901475	1.12974543413
Zone24	0.3718003	0.3344619	0.6016017	0.43595461874
Zone25	2.6247258	2.0833985	1.1902480	1.96612408625
Zone26	6.7019589	5.0256736	4.1341778	5.28727010663
Zone27	9.7503329	9.7462090	9.6826100	9.72638397971
Zone29	6.9888006	6.4800372	5.8602464	6.44302808770
Zone33	1.8612342	1.2579963	0.7585481	1.29259287162
Zone36	7.4629949	5.6399891	3.8565592	5.65318108270
Zone37	1.8133295	1.2324932	0.7229865	1.25626970162
Zone38	4.2175299	4.2160552	4.1836431	4.20574270347
Zone40	7.3115652	7.2835759	7.1434666	7.24620256881
Zone43	5.6582975	4.9250925	3.9066256	4.83000518951
Zone44	5.8928915	5.0911980	4.1545919	5.04622715479
Zone47	4.4562523	3.8748372	3.5012109	3.94410013952
Zone48	8.4377074	7.3787546	6.6728307	7.49643089604
Zone49	12.1748562	11.1830252	10.2261231	11.1946681970
Zone50	8.6305513	8.6305513	8.6266664	8.62925633828
Average	5.8262794	5.1371784	4.4972112	XXX

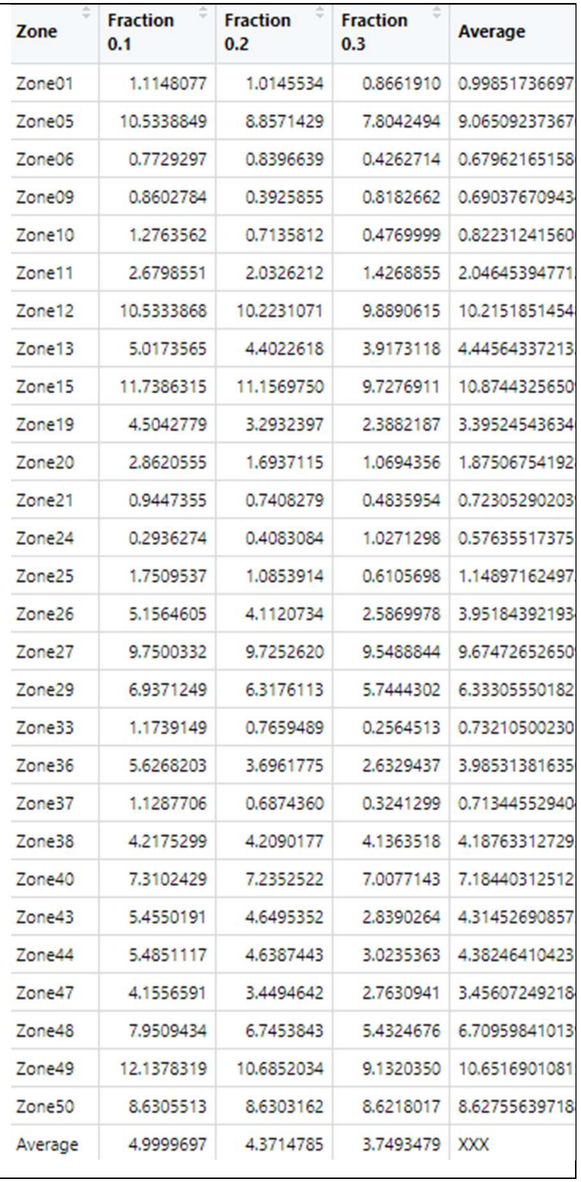
T_{Set} = 23°C (Square)



Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	1.0828132	0.9802604	1.1568173	1.073296962844
Zone05	0.5480816	0.4509024	0.3822231	0.460402362087
Zone06	6.0202188	6.1718262	6.3965467	6.196197217726
Zone09	2.2129783	2.3012766	2.6971176	2.403790848245
Zone10	1.8425910	2.0444866	2.3219868	2.069688119241
Zone11	1.8551929	2.0254912	2.4080959	2.096260020227
Zone12	1.0817152	1.1520324	1.2408807	1.158209423470
Zone13	1.0104130	1.2288852	1.5525514	1.263949841607
Zone15	2.3100265	2.9007540	3.6131897	2.941323381661
Zone19	6.2345390	6.3751160	7.0732681	6.560974343293
Zone20	4.7765773	5.2189588	6.2116633	5.402399779350
Zone21	4.7220886	5.8877121	6.7772007	5.795667116902
Zone24	1.2201169	1.2706143	1.7256260	1.405452430510
Zone25	1.7118051	1.8208284	2.1632459	1.898626486634
Zone26	3.6864367	3.8020491	4.7218346	4.070106811806
Zone27	0.7173612	0.6184405	0.7102704	0.682024048536
Zone29	3.8787353	3.9486953	3.9417018	3.923044141064
Zone33	4.4896222	4.4799305	4.6520492	4.540533958951
Zone36	3.6213413	3.8488669	3.8827240	3.784310753920
Zone37	4.1204176	3.8903750	4.4832346	4.164675741938
Zone38	5.7210011	6.1567927	5.8172542	5.898349308429
Zone40	8.5720159	8.1373867	7.5263197	8.078574073110
Zone43	4.3635751	3.9757794	4.4106801	4.250011528120
Zone44	6.3900678	6.2229478	6.3938356	6.335617069029
Zone47	3.7038469	3.5209012	3.4462204	3.556989492216
Zone48	4.1516978	4.7915500	4.0647938	4.336013879512
Zone49	4.9006215	5.1667622	4.8849197	4.984101133411
Zone50	8.3864946	7.7204176	8.1857052	8.097539137671
Average	3.6904426	3.7896443	4.0300699	XXX



Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	2.0898443	2.5672711	3.214505	2.62387336113
Zone05	1.6632997	1.3956075	1.245385	1.434764113037
Zone06	3.5769339	4.1526027	4.948093	4.225876442507
Zone09	0.9286268	1.4529569	2.122338	1.50130730232
Zone10	0.7374490	1.0880231	1.415702	1.080391384734
Zone11	1.7722039	2.3166006	2.772625	2.287143213362
Zone12	1.2984502	1.3164680	1.604699	1.40653891548
Zone13	1.0664114	1.3406307	1.552888	1.31997661689
Zone15	2.1900585	2.9312711	3.722717	2.948015524002
Zone19	3.9965342	4.6752157	5.255418	4.64238933044
Zone20	2.8619933	3.5355697	4.312287	3.56995009534
Zone21	3.9444904	4.8906102	6.264501	5.03320036640
Zone24	2.7956542	3.6490107	4.726636	3.723767107224
Zone25	1.5933000	1.9608570	2.645400	2.06651885439
Zone26	1.9316938	1.9470479	2.562115	2.146952341402
Zone27	1.4130377	1.1587191	1.140015	1.237257303874
Zone29	1.4001704	1.8140780	2.836984	2.01707738063
Zone33	2.6027163	3.0839737	4.538138	3.408275934337
Zone36	1.4970450	2.0125413	2.529124	2.01290335926
Zone37	3.5994660	4.2822451	5.081017	4.32090933216
Zone38	1.9694475	1.8208411	1.591937	1.79407507611
Zone40	0.7488789	0.9287377	1.081091	0.91956918636
Zone43	1.1895919	1.5918065	2.840181	1.873859731827
Zone44	0.7956427	1.1385428	1.897521	1.27723563232
Zone47	2.3938543	2.8030139	2.499307	2.56539159815
Zone48	1.1384507	1.2294645	1.108921	1.158945361827
Zone49	1.6542751	1.7627684	1.945503	1.78751536081
Zone50	2.7251211	2.6530444	2.055926	2.47803056645
Average	1.9848086	2.3392686	2.839678	XXX



Zone	Fraction 0.1	Fraction 0.2	Fraction 0.3	Average
Zone01	1.1148077	1.0145534	0.8661910	0.99851736697
Zone05	10.5338849	8.8571429	7.8042494	9.06509237367
Zone06	0.7729297	0.8396639	0.4262714	0.67962165158
Zone09	0.8602784	0.3925855	0.8182662	0.69037670943
Zone10	1.2763562	0.7135812	0.4769999	0.82231241560
Zone11	2.6798551	2.0326212	1.4268855	2.04645394771
Zone12	10.5333868	10.2231071	9.8890615	10.2151851454
Zone13	5.0173565	4.4022618	3.9173118	4.44564337213
Zone15	11.7386315	11.1569750	9.7276911	10.8744325650
Zone19	4.5042779	3.2932397	2.3882187	3.39524543634
Zone20	2.8620555	1.6937115	1.0694356	1.87506754192
Zone21	0.9447355	0.7408279	0.4835954	0.72305290203
Zone24	0.2936274	0.4083084	1.0271298	0.57635517375
Zone25	1.7509537	1.0853914	0.6105698	1.14897162497
Zone26	5.1564605	4.1120734	2.5869978	3.95184392193
Zone27	9.7500332	9.7252620	9.5488844	9.67472652650
Zone29	6.9371249	6.3176113	5.7444302	6.33305550182
Zone33	1.1739149	0.7659489	0.2564513	0.73210500230
Zone36	5.6268203	3.6961775	2.6329437	3.98531381635
Zone37	1.1287706	0.6874360	0.3241299	0.71344552940
Zone38	4.2175299	4.2090177	4.1363518	4.18763312729
Zone40	7.3102429	7.2352522	7.0077143	7.18440312512
Zone43	5.4550191	4.6495352	2.8390264	4.31452690857
Zone44	5.4851117	4.6387443	3.0235363	4.38246410423
Zone47	4.1556591	3.4494642	2.7630941	3.45607249218
Zone48	7.9509434	6.7453843	5.4324676	6.70959841013
Zone49	12.1378319	10.6852034	9.1320350	10.6516901081
Zone50	8.6305513	8.6303162	8.6218017	8.62755639718
Average	4.9999697	4.3714785	3.7493479	XXX

Statuory declaration

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Karlsruhe, 29.07.2021

Date, Location

Mattis Knudsen

Author