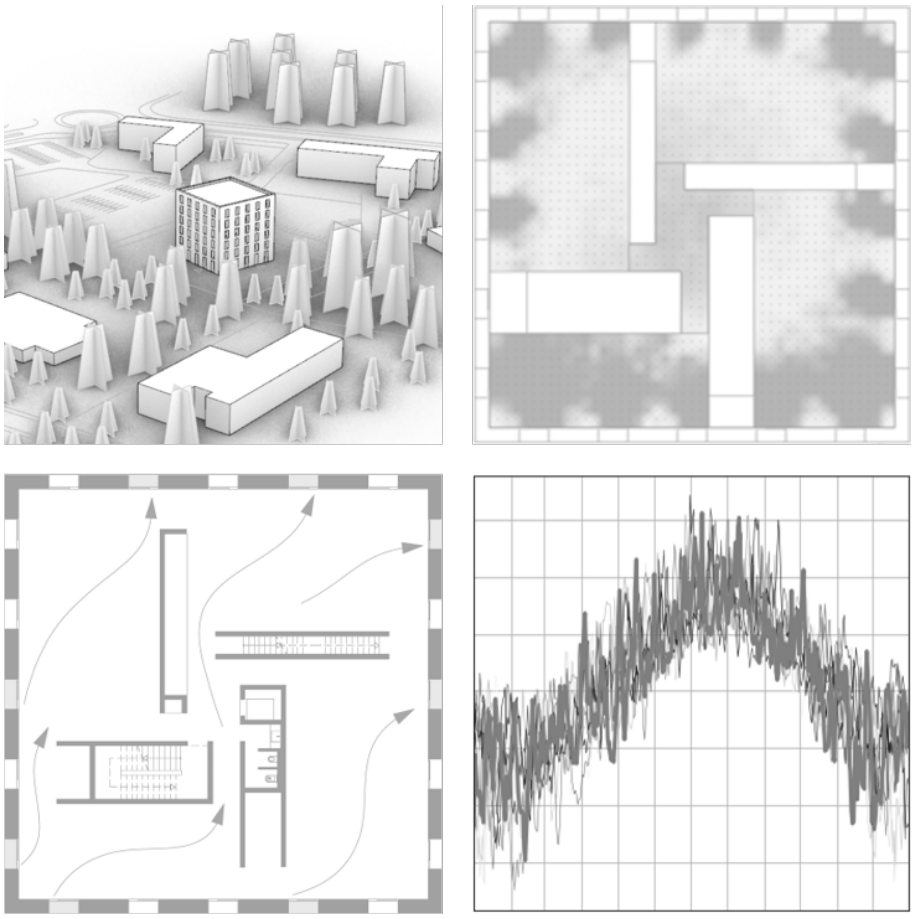
Building 2226 on the Test Bench

Simulation study on the relocated 2226 building by Baumschlager Eberle



Building Simulation 2021 - Bruges - Students competition

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June 20, 2021

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Executive Summary

The present simulation study investigates the concept of the *2226* building which is originally situated in Lustenau, Austria. The building is designed without an active system for heating and cooling. To maintain indoor temperatures the building envelope is highly thermally insulated by a 0.81 m thick brick wall resulting in a thermal transmittance of U = 0.12 W/m²K. Together with concrete ceilings the building mass also puffers seasonal temperature swings. In the context of the *Students Competition* of the *Building Simulation 2021* conference the building is transposed to a new location in Kortrijk, Belgium, to investigate indoor thermal and visual comfort and energy performance in Building performance simulation (BPS) tools. For thermal simulations and the assessment of the energy performance the software IDA Indoor Climate and Energy (IDA ICE) and for the simulation of daylight and artificial light ClimateStudio (CS) as plugin for Rhino are used.

First, all modeling assumptions are collected based on the original concept. A natural ventilation concept by opening panels is designed and tested in building simulation. Second, thermal and visual comfort at the new location have been assessed in a baseline simulation. For the main thermal comfort metrics indoor temperature and indoor air quality (CO_2 concentration) summer and winter have to be differentiated: Solar gains are moderate due to reduced window size and large recess depth of the window reveal. Together with low internal loads, summer comfort is not critical and the maximum temperature of 26 °C is mainly respected. On the contrary, in winter the aimed minimum temperature of 22 °C is not reached. With missing solar or internal gains and low ambient temperatures it is either too cold inside when the CO_2 driven ventilation is activated or the the CO_2 overruns the recommended threshold when openings are kept close. According to the daylight simulation the working spaces generally show good results within the recommended ranges. However, without internal blinds disturbing glare might occur.

Third, various parameter studies have been executed in both thermal and daylight simulation. They focus on the influence of window geometry and glazing properties, variations in the local climate and in the use intensity. To conclude, different Heating ventilation air-conditioning (HVAC) systems like a Concrete core heating and cooling (CCHC) or an air handling unit (AHU) have been investigated to assess the energy indicators of different options.

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Acronyms

AHU air handling unit. II, IV, V, 8, 16, 18, 19

ASE annual sunlight exposure. VIII, 8, 10, 11

BPS Building performance simulation. II

CCHC Concrete core heating and cooling. II, IV, 1, 17, 18, 20

CFD Computational Fluid Dynamics. 7

COP coefficient of performance. 17, 18

CS ClimateStudio. II, 8, 10

DF daylight factor. VIII, 8, 10, 11

DGP daylight glare probability. IV, VIII, IX, 8, 10, 12, 14, 15

DST daylight saving time. 10

EBC Energy in Buildings and Communities. 18

EER energy efficiency ratio. 18

EPBD Energy Performance of Buildings Directive. 5

EPEX European Power Exchange. 17

EPW EnergyPlus weather. VI, 2, 12

ETICS External Thermal Insulation Composite System. III, 3, 4, 14

HVAC Heating ventilation air-conditioning. II, 1

IAQ indoor air quality. IV, 17

IDA ICE IDA Indoor Climate and Energy. II, IV, V, 7, 8, 16, 17

IEA International Energy Agency. 18

IES Illuminating Engineering Society. VIII

LT light transmittance. 10

NMF Neutral Model Format. 16

OF openness factor. 10

PEF primary energy factor. 18

PVGIS Photovoltaic Geographical Information System. IV, 2, 12

RES renewable energy sources. 17, 18

sDA spatial daylight autonomy. VIII, 8, 10, 11, 14, 15

sDG spatial disturbing glare. VIII, 10, 11, 14

UDI useful daylight illuminance. VIII, 8, 10, 11, 14, 15, 20

VAV variable air volume. 16

1. Introduction

Reducing the energy consumption of buildings towards net zero energy buildings is the main challenge for both building research and practice. To meet the emission targets, a commonly applied strategy is the integration of renewable energies in the heating and cooling supply. Today, renewable energies are often combined with generators based on fossil fuels in multivalent systems which often results in high complexity for the operation management and automation of such systems.

At the same time, building owners and users are getting more aware of the need for healthy and comfortable living and working spaces. This includes aspects of thermal comfort, air quality as well as visual and acoustic comfort. To meet these requirements many buildings are increasingly equipped with complex HVAC components and low-temperature which lead to high effort in operation and automation. In many buildings a “performance gap” between predicted and measured comfort and energy has been observed [4]. As a consequence buildings do not meet predicted emission targets, often due to malfunctions of technical systems.

In contrast to that, low-tech strategies and “lean buildings” aim at reducing the error-proneness of such systems. The *2226* building is an example for such an approach. Key features of the energy concept are the absence of an active heating or cooling system, high insulation and high thermal mass of the building envelope particularly by monolithic brick walls and concrete ceilings. Nevertheless, user requirements for thermal and visual comfort have to be met.

Main competition question

The main competition question of the *Building Simulation 2021 Students Competition* is as follows:

“*How would you adapt the concept of the low-tech building* 2226 *if you were to build it in Kortrijk (President Kennedypark 10, 8500 Kortrijk, Belgium)? Can you improve the indoor air quality, thermal, visual and acoustical comfort with minimal impact on energy use?*”

When “exporting” such a low-tech approach to a different location, two main questions are important: First, how does a low-tech concept perform in different climatic conditions? This includes the resilience against the climate at the particular region as well as against variations of the local climate over different years. Second, how does the building behave with different users and with users in a rented building in particular?

Comments on the challenge the report

We chose to work on the subquestions of *building envelope*, *visual comfort*, *thermal comfort* and *indoor air quality*.

This report is divided in two main sections 2 *Modeling specifications* and 3 *Building Performance*. In section 2 we present the modeling assumptions and develop a baseline model for both thermal and energy simulation and daylight. In section 3 we investigate the impact of different internal loads and climate variations on temperature, air quality, humidity and daylight.

We, Isil, Tugcin, Ghadeer and Karl are a group of Phd students at the University of Wuppertal. We have different backgrounds from architecture, civil engineering and mechanical engineering. In buildings these disciplines come together. Therefore, the different aspects are connected whenever reasonable. Our aim was to provide a coherent study considering aspects which go beyond the competition questions. This includes e.g. variations of the local climate, flexible operation of Concrete core heating and cooling (CCHC) systems or aspects of user behavior. For an easier evaluation, a direct mapping of questions and answers is provided in appendix A.

2. Modeling specifications

2.1. Climate

The EnergyPlus weather (EPW) data for for location Brussels [5, 6] is used as a baseline in all simulation. This weather file is composed of monthly periods from different years between 1983 to 1998. To evaluate the resilience against climatic variations, 10 weather files for historical data between 2007 and 2016 have been generated based on data from the EU project PVGIS [7]. Figure 1 depicts the time series for the daily mean of temperatures and daily sums of global radiation (left side) for the EPW weather file and the 10 PVGIS files. To give a general metric mean annual temperatures and the yearly sum of global radiation are presented in the middle bar charts. Compared to the weather files based on PVGIS the the yearly sum of irradiation drops by up to 20 %. The reason might be different measuring methods: wile the EPW weather is based on weather stations on the ground, the PVGIS data is based on satellite data. For a building without a heating system, low temperatures in winter and periods with low solar irradiation are crucial. To quantify these critical periods hours per day below 0 °C, the maximum of consecutive hours below 0 °C, total days with irradiation below 500 Wh/m²d and consecutive days with irradiation below 500 Wh/m²d are analyzed. First, significant differences can be found between the individual data sets, e.g. between a maximum of 19 consecutive hours below 0 °C in 2015 and 300 in 2012. Second, the EPW weather seems to be a rather average year for these extreme cold and low radiative periods.

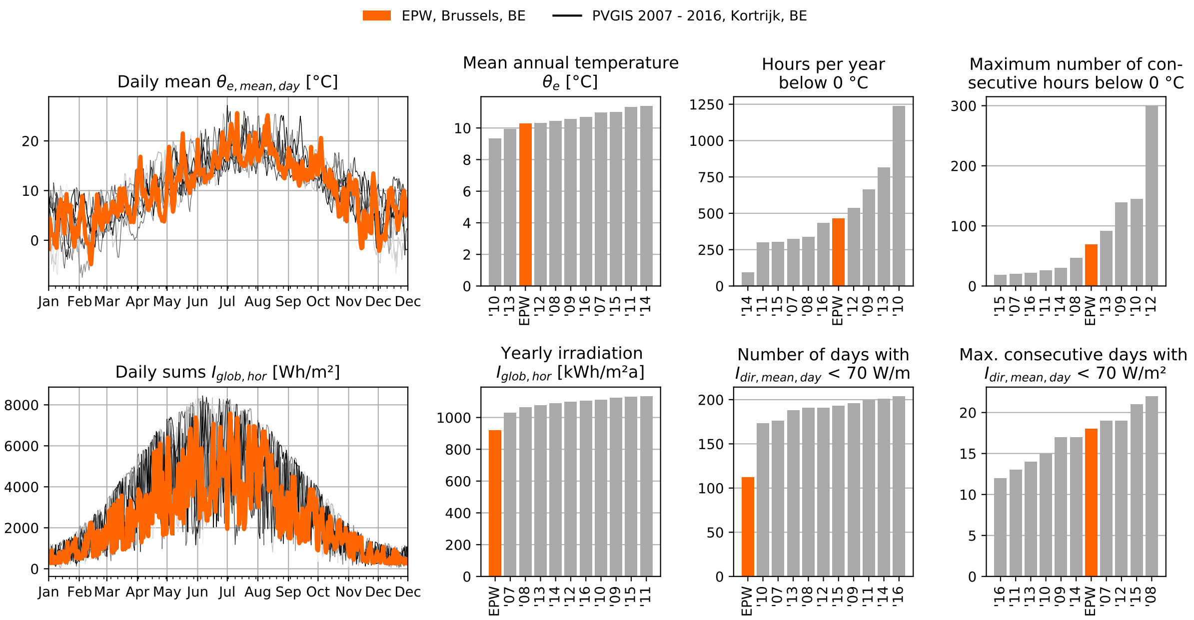


Figure 1: Comparison of EPW weather file and 10 weather files based on PVGIS for temperature and irradiation

The evaluation of climate files illustrates the different characteristics from year to year. For a concepts like *2226* this is particularly important since there is no system to compensate yearly climatic variation. The impact is evaluated in subsubsection 3.1.1.

2.2. Site context

The site context as one of the key inputs in the performance evaluation, including neighbor buildings, vegetation, topography, has been carefully considered (see Figure 2). Geometry and surfaces of surroundings have been simplified to increase simulation speed. To focus on the influence of the climate at the "new" location and different user patterns, the building is assumed to be transferred in the same orientation from Lusteau (AT) to Kortrijk (BE) without rotation (see Figure 3).

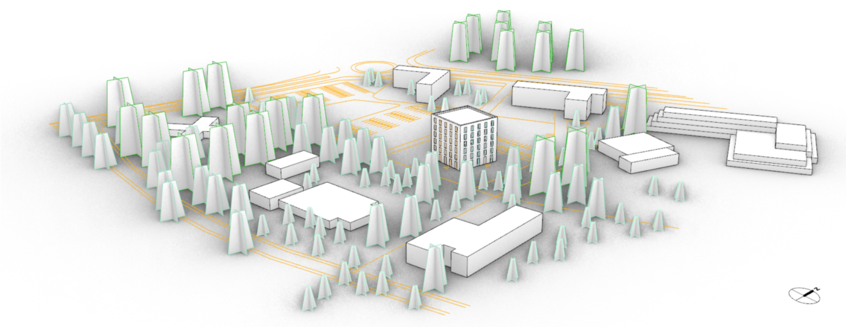


Figure 2: Site Model south-east perspective in Kortrijk, Belgium.

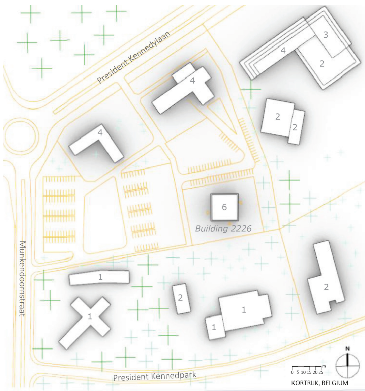


Figure 3: Site Plan.

2.3. Geometry and building envelope

2.3.1. Opaque constructions

Based on drawings and sections [1] as well as reports [2, 3] the assumed opaque constructions are presented in Table B.1[1]. Alternative constructions with an ETICS and a timber construction have been designed (answer to question 1, see Table B.1). The thermal transmittance of the outside wall including $R_{s,i} = 0.13$ m²K/W and $R_{s,e} = 0.04$ m²K/W is $U_{wall} = 0.12$ W/m²K (answer to question 1, calculation see Appendix A). The overall thermal transmittance of the building envelope including walls floor slab and ceiling is 0.25 W/m²K (answer to question 3, calculation see Appendix A).

The properties of the building envelope, namely the outside wall, are, besides internal masses, a key element of the *2226* concept. To preliminarily assess the thermal properties of the default construction and different alternatives (cf. Table B.1), a brief study for the dynamical thermal characteristics according to DIN EN ISO 13786:2018 [8] has been carried out (answer to question 2). Besides the U-Value, the thermal admittance (ability to absorb and release energy in W/m²K), the areal heat capacity (ability to buffer energy in kJ/m²K) and the time shift (lag between stimulation and reaction) are evaluated according to the detailed method chapter 8 of DIN EN ISO 13786:2018 [8][2]. The characteristics are calculated for sinusodial temperature swings with a defined period length. Different period lengths of 24 h, 1 week and 4 weeks have been evaluated separately to reflect the short and long term damping potential. A full description is provided in [9].

Figure 4 compares the default construction based on bricks, an ETICS with concrete as massive layer and a massive timber construction. The U-value, the thermal admittance and the areal heat capacity are presented for different brick, concrete or timber thicknesses (x-axis). For the brick construction, on the one hand, the width of the wall is necessary to reach the desired low U-Value of 0.12 W/m²K. Due to the high transmission of concrete the U-Value is, more or less independent of the concrete thickness of the ETICS. On the other hand, the maximum of the areal heat capacity depends on the thickness of the brick layer and the period length. While for short term variations of 24 h a maximum areal heat capacity is reached at 0.1 m brick, for long term variations it is reached at the planned brick layer thickness of 0.76 cm. Due to the monolithic constructions internal and external values are in the same range. For the ETICS with heavy concrete on the inside and lighter insulation on the outside the areal heat capacity reaches the same scale for short term temperature swings. However, for long term variations of a month the internal areal heat capacity is about 10 times higher than

[1]Depending on the source parameters may slightly vary such as the U-Value of the external wall between 0.12 and 0.13 W/m²K.
[2]The calculation of complex matrices according to the procedure in [8] has been done in Python 3.8. A free tool by Daniel Rüdisser is available under
`https://www.htflux.com/en/free-calculation-tool-for-thermal-mass-of-building-components-iso-13786/`

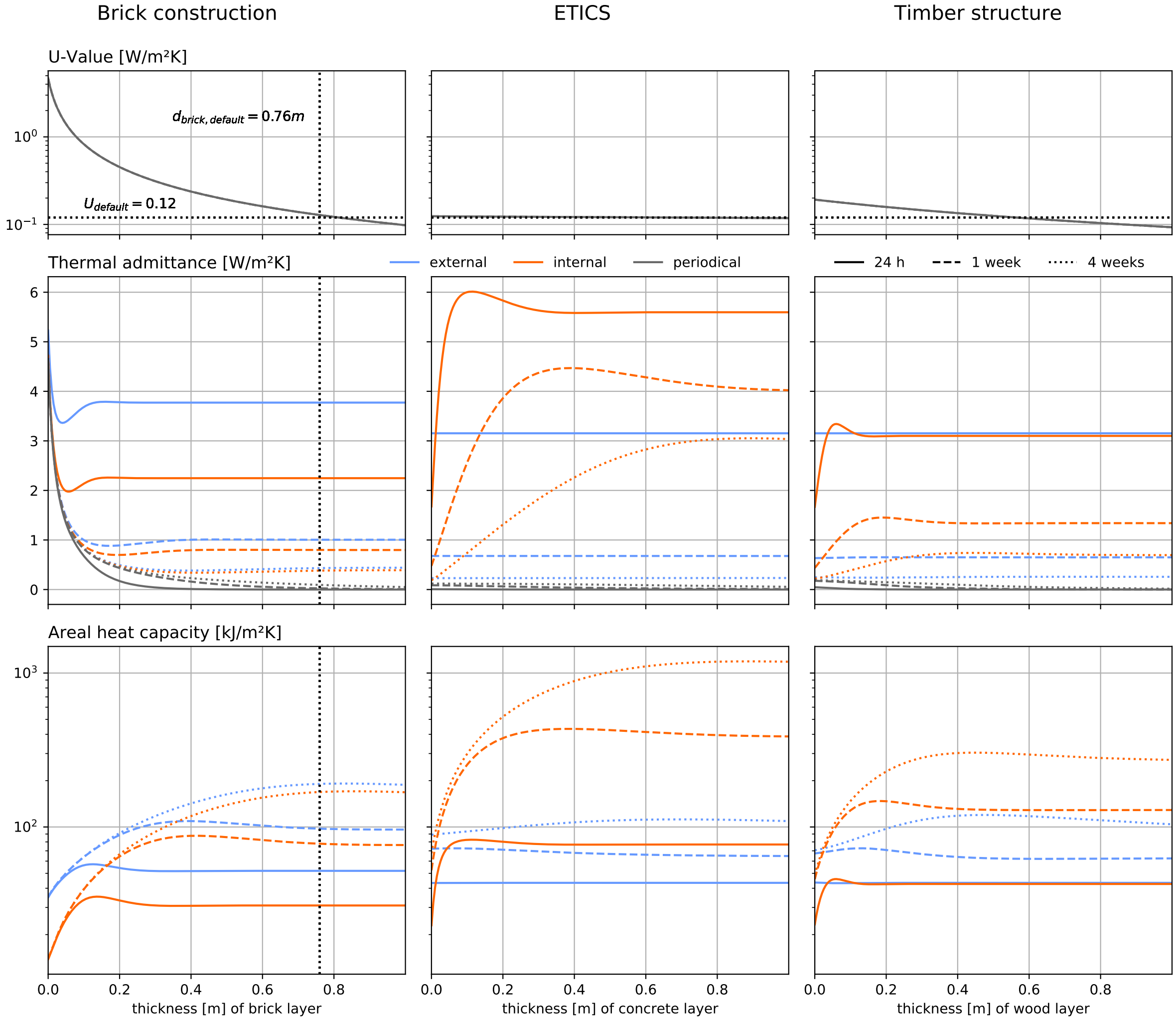


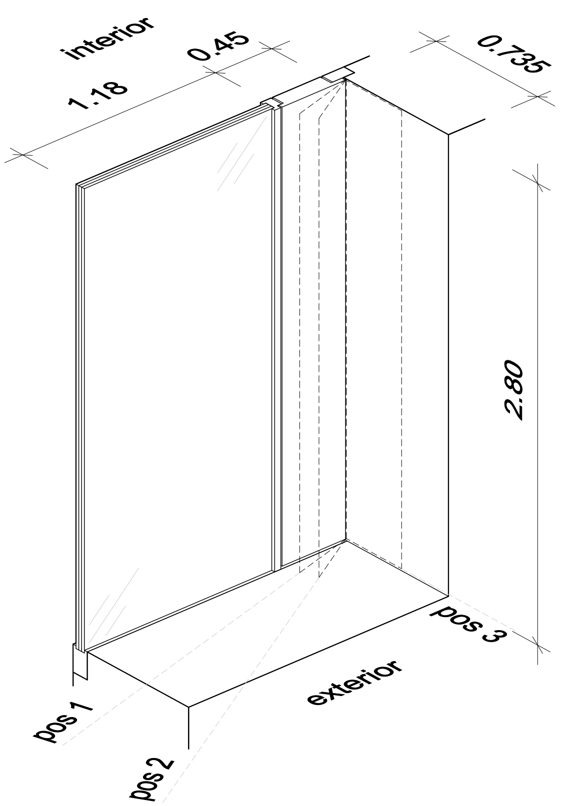
Figure 4: Dynamical thermal characteristics according to ISO 13786 of different constructions (cf. Table B.1).

for the brick wall. The timber structure shows comparable characteristics to the default brick construction. After about 20 cm the internal thermal admittance stays nearly unchanged for the brick construction, while it continues increasing for the concrete construction, particularly for 4 week swings. This analysis shows that the default brick construction is optimized for the U-Value and areal heat capacity at monthly temperature swings. However, the ETICS shows better performance at the same wall thickness or a thinner wall would be possible, respectively.

Besides the calculation of life cycle costs, a life cycle assessment would be important. Society is getting more aware of the huge consumption of resources and amount of waste from construction sites. Purely mineral constructions like the brick construction in building *2226* are a way to avoid dumping of special waste of glued constructions like a conventional ETICS. Aspects of reuse and recycling have to become self-evident in future construction processes [10].

2.3.2. Transparent constructions

The properties of the glazing and the geometry of windows including the opening panel for natural ventilation (cf. concept in subsection 2.5) are depicted in Figure 5 according to [1, 2, 3]. More detailed boundary conditions particularly for daylight analysis are provided in Appendix C.



Net opening width x height of the wall 1.63 x 2.80 m

Window to glazing ratio WGR = 0.16

Wall depth d_{wall} = 0.813 m
Recess depth d_{recess} = 0.735 m

Glazing properties
Triple glazing heat protection glass
4:14:4:14:4 (Argon 90 %)
Coatings on position 2 and 5
Solar factor g = 0.5
Visible light transmission $T_{vis,tot}$ = 74.0 %
Visible light reflectance $R_{vis,front}$ = 18.8 %
Visible light reflectance $R_{vis,back}$ = 16.4 %

U_g = 0.7 W/m²K
U_w = 0.63 W/m²K

Width of the glazing $w_{glazing}$ = 1.18 m
Width of the opaque panel + framing w_{opaque} = 0.45 m
Opaque ratio seen from outside r_{opaque} = 27.6 %

Assumed net opening width x height of the ventilation panel 0.32 x 2.65 m (free flow cross-section)

Figure 5: Detail of window reveal, glazing properties and opening positions 1, 2 and 3 for ventilation

2.4. Internal loads

In the absence of an active heating system internal loads are the only internal heat gain. According to the utilization planning a maximum occupancy of 16 persons per floor is assumed. This is equivalent to a very low occupancy rate of 29 m²/person. Table 1 compares different levels of occupancy and internal loads for the European standards standards DIN EN 15232-1:2017-12 [11] and DIN EN 16798-1:2021-04 Annex B [12] as well as the German standard DIN V 18599-10 [13] (calculation of the energy demand according to the Energy Performance of Buildings Directive (EPBD)) where the electrical load for equipment varies between 50 and 204 W/m². In the real case (right column), due to the very low occupancy rate, the specific heat input from equipment is rather low and using default user profiles from standards would largely overestimate internal loads. For the occupancy a slightly adopted profile according to [11] is used Figure B.2.

According floor plans and pictures [14] each of the four office areas is equipped with two floor lamps. With 150 W per lamp [15] a specific load of ca. 2.6 W/m² is reached. Including further general lighting and the middle zone a total specific load of 5 W/m² is assumed. The desk related floor lamps are assumed to be equipped with a daylight sensor dimming to the target illuminance and a presence sensor. The general lighting is assumed to be on during occupation. The resulting energy consumption is presented in subsection 3.3.

For the simulation of indoor thermal comfort (cf. subsubsection 3.1.1) an occupancy rate of 100 % has been defined (all users present at occupied hours). Contrary, for the simulation of the energy performance (cf. subsection 3.3) an average occupancy rate of 60 % is assumed to take into account holidays, external meetings etc.

Table 1: Internal loads

		DIN EN 15232-1	DIN EN 16798	DIN V 18599-10			baseline simulation
				low	medium	high	
maximum occupancy density	m^2/p.	13.3	17	12	10	8	29
El. load per person	W/p.	133	204	50	100	150	100 (assumption)
Specific heat input equipment	W/m^2	10	12	4.2	10	18.8	3.45
Full load hours	h/d	8.325	11	6	6	6	8 (assumption)
Daily heat input equipment	Wh/m^2d	83.25	132	25	60	112.5	27.59

2.5. Ventilation

In a concept such as *2226* without heating system, window opening is the only way to actively influence the indoor temperatures, CO_2 and humidity. Furthermore, it has to be used very carefully to respect the comfort boundaries. Ventilation has to be activated when air quality is insufficient or when it is to warm inside and colder outside while keeping indoor air velocities are as low as possible to avoid draft. While in winter ventilation mainly has to assure good air quality at minimum ventilation losses, in summer, air quality is typically not a problem. In warmer periods, windows can be opened more often during the day and night ventilation has to activated to prevent and reduce overheating.

As in the original floor plan we assume 1. the different floor areas to be connected by open corridors 2. fixed glazing and motor-driven openable opaque panels and 3. two opening panels per wall orientation as a compromise between high opening area and costs for motors. However, for efficient ventilation in winter and high flow rates in summer opening all panels per wall would be beneficial. The net opening area per panel is assumed with a width of 0.32 m and a height of 2.65 m (cf. Figure 5). The pressure coefficients are calculated according to the ASHRAE Handbook Fundamentals [16] and shown in Figure B.1 (Answer to question 17).

To complement the climatic condition in subsection 2.1 the windrose shows a typical distribution for moderate climate region in the north atlantic (cf. Figure 6). The main wind direction is south-west and ca. 50 % of the wind direction is between west and south.

Taking into account these foregoing considerations, the following window ventilation strategy has been designed (cf. Figure 9. Answer to question 18). To meet the CO_2 requirements a first hysteresis controller with an upper limit of 1000 ppm and a lower limit of 500 ppm is used. In winter, when indoor temperatures are rather low, window opening might cause a temperature drop below the lower limit. Therefore, ventilation is only allowed when the indoor temperature is above 23 °C and does not fall below 20 °C (thermostat controller below). Our investigation shows that at low occupancy densities and low internal loads, as chosen in the baseline simulation, it might be either too cold or the air quality is insufficient. To prevent CO_2 concentration higher than 1750 ppm (upper limit of category IV, DIN EN 16798-1:2021-4 [12]) a second criterion is implemented to open panels above 1750 ppm regardless of indoor temperatures (hysteresis controller below). To reduce overheating in summer, windows are opened at an upper limit of 26 and a lower limit of 22 °C (hysteresis controller below). At the same time the ambient temperature has to be lower than the internal temperature (thermostat controller below) and below 26 °C (boolean operator below).

Particularly at low ambient temperatures, high indoor air velocities causing discomfortable draft have to be avoided. The opening strategy has to maximize ventilation efficiency at minimum local air velocities during occupation. Therefore, 3 different opening positions allowing intermediate opening widths of 5 and 10 cm

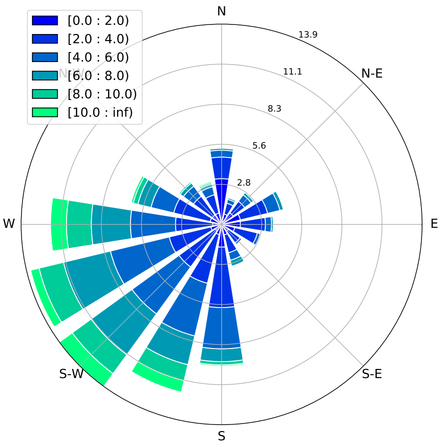


Figure 6: Windrose EPW Brussels. Windspeed v_{wind} in m/s

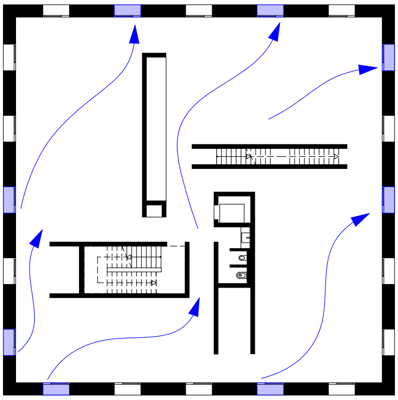


Figure 7: Location of panel openings and ventilation concept

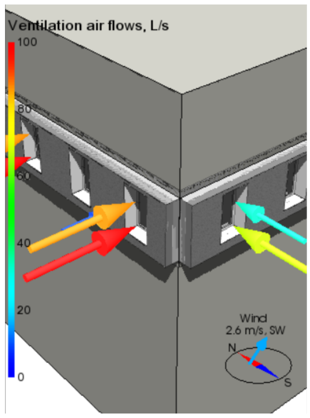


Figure 8: IDA ICE model

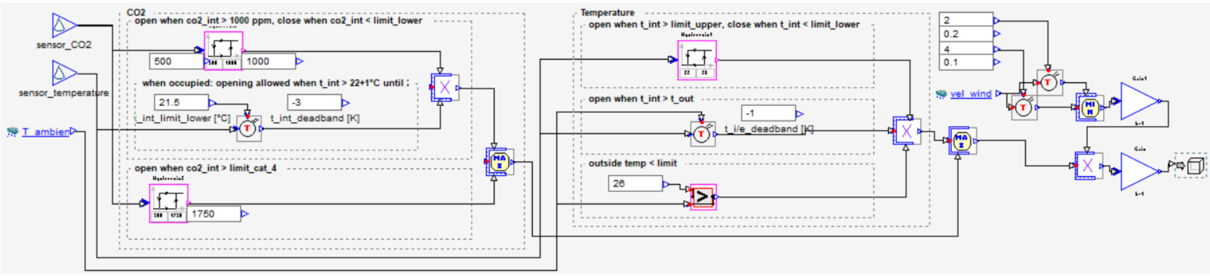


Figure 9: Ventilation controller in IDA ICE

and full opening at 0.29 cm are assumed (cf. Figure 5). Figure 10 shows the resulting air velocities referred to a reference section of B x H = 1.0 x 1.5 m (seated person). In winter half year maximum air velocities of around 0.15 m/s are simulated and stay within the upper limit of 0.21 m/s for category III according to DIN EN 16798-1:2021-04 [12]. Contrary, in summer maximum values increase up to 0.30 m/s. As this is just a rough assumption, local air velocities and draft risk have to be approved in a CFD simulation.

A purely automated concept, even if carefully designed and approved in building simulation might fail in reality, when the user needs and behavior patterns are neglected. While in a self-owned and used building, like in the original case by *Baumschlager Eberle*, users might be "educated" and learn to live with an automated ventilation strategy. It is important to mention the difference between cold air entering in an window self opened or in the case of automatic opening. The acceptance will be very different although the facts are identical. For simplification the thermal simulation does not take into account additional ventilation of e.g. n_{user} = 0.2 h^{-1} to consider an average manual ventilation. For further considerations about the user behavior cf. subsection 3.4.

In our baseline concept the panel openings are independent of the wind direction (answer to question 18). However, when the building was located next to a highway this has to be adapted according to the course of the highway. When the highway is located on the downstream side, panels might be opened as designed. On the contrary, when the highway is located on the upstream side, panel opening would only be allowed when during non-occupied periods (answer to question 19). At this point detailed acoustic calculations are needed to assess the impact on the ventilation strategy.

According to [3] an air tightness at a pressure difference of 50 Pa of n_{50} = 0.51 h^{-1} has been estimated .

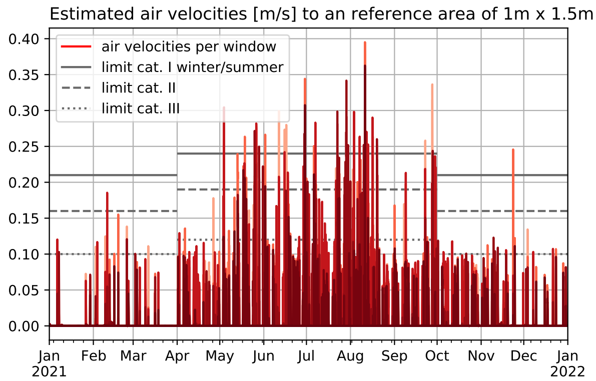


Figure 10: Simulated air velocities near the opening panels

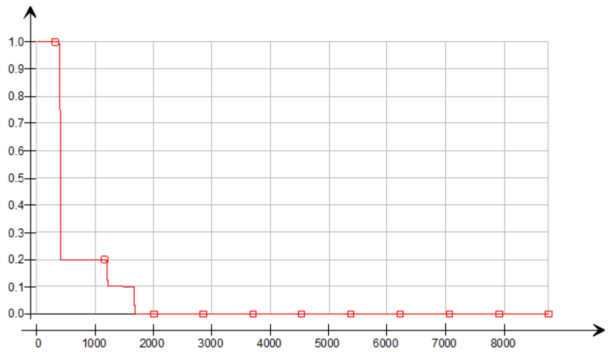


Figure 11: Cumulative distribution function of the opening width of the window over the year

2.6. Metrics for performance assessment

Thermal comfort For thermal comfort, the indoor operative temperature, the CO_2 concentration as indicator for the air quality and the realtive humidity have been chosen [12]. The limits for the operative temperature have been defined according to the *2226* concept with 22 °C as lower and 26 °C as upper limit. The upper limit for the CO_2 concentration is 1000 ppm. For the design of the AHU in subsection 3.3 the limits defined in DIN EN 16798:2021-04 [12] have been used.

Visual comfort To asses the daylight availability and visual comfort the daylight factor (DF), the spatial daylight autonomy (sDA), the daylight glare probability (DGP), the annual sunlight exposure (ASE) and the useful daylight illuminance (UDI) are used. For this study we decided to use the *medium* level described in DIN EN 17037:2019-03 [17] as a reference. To fulfill the requirements a target daylight factor $D_T > 2$ %, a minimum target daylight factor $D_{T,M} > 0.7\%$, a target illuminance $E_T > 500$ lx of at least 50 % of the occupied hours on at least 50 % of the occupied area, a minimum target illuminance $E_{T,M} > 300$ lx at least 50 % of the occupied hours on at least 95 % of the occupied area and a DGP not > 0.38 in more than 5 % of the occupied time of a space (minimum recommendation) have to be fulfilled.

The reference heights have been defined with 0.85 m for daylight simulation and with 1.20 m for glare analysis [17]. Simulations are done with the grid-based method with a 0.5 x 0.5 m grid and an inset of 0.4 m from surrounding walls. A detailed description of the metrics is provided in Appendix D.

Energy performance For the assessment of the energy performance in subsection 3.3 the useful net energy is used. The conversion factors and primary energy factors used are presented in subsection 3.3.

2.7. Modeling software, methods and assumptions

To evaluate thermal comfort and energy the simulation environment IDA ICE 4.8 [18] has been used. In the simulation model one office floor with a net floor area of A = 464 m² is chosen for evaluation. The floor is used in four office areas which are not separated by walls. To ease the simulation a one zone model has been chosen. Drawback of this approach is that only one value per comfort parameters is obtained which cannot be resolved by office section. 60 days of dynamic simulation start-up have been chosen to take into account the high thermal mass.

The 3-D CAD modeling tool Rhinoceros3D [19] is used as design environment. Daylight and artificial lighting analyses have been done with ClimateStudio (CS) [20] which is an a environmental modeling and simulation plugin for Rhino. Details of the input settings are collected in Appendix C.

3. Building Performance

In this chapter, first, the results of the baseline simulation based on the modeling specifications described in section 2 are presented. Second, parameter studies for the climate, wall thickness and window position, glazing type, window area, internal loads and concrete core activation are evaluated.

3.1. Baseline simulation

3.1.1. Thermal comfort and Indoor air quality

Figure 12 shows the comfort assessment for temperature, air quality, relative humidity and the air change rate. The grea shaded area indicates the comfort ranges per variable. Summer and winter period can be clearly divided: Particularly in winter, neither for the operative temperature nor for the air quality the requirements are met. During 982 h/a the operative temperature falls below 22 °C. On the contrary, in warmer periods both indoor temperature and air quality are within the comfort range. Only 86 h/a are exceeding the 26 °C limit, which is a very good value for buildings with fixed shading only and natural ventilation. The relative humidity reaches extreme values of 20 to 70 %, however, since IDA ICE does not take into account moisture buffering, these values are buffered in reality.

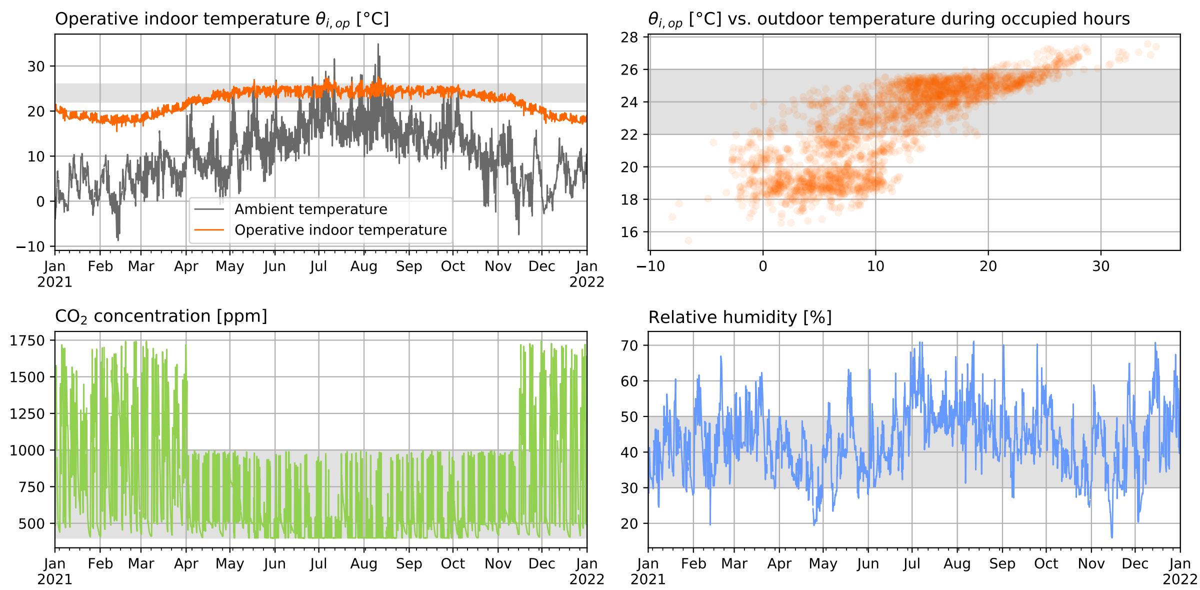


Figure 12: Evaluation of baseline simulation for hourly mean values.

For a deeper understanding the energy balance for a winter and a summer week has been evaluated (cf. Figure 13). For both summer and winter the solar gains are around 10 to 15 W/m² (dark yellow). The energy is mainly stored in internal walls and masses (green). During daytime they absorb energy and during nighttime they release energy. In winter, main losses occur trough windows (dark yellow). The sum of internal loads from occupants, equipment and lighting has a smaller share than solar gains. While the ventilation (magenta) in winter is very short, panels are opened for longer periods in summer. These findings will be taken into account in the parameter studies in subsection 3.2

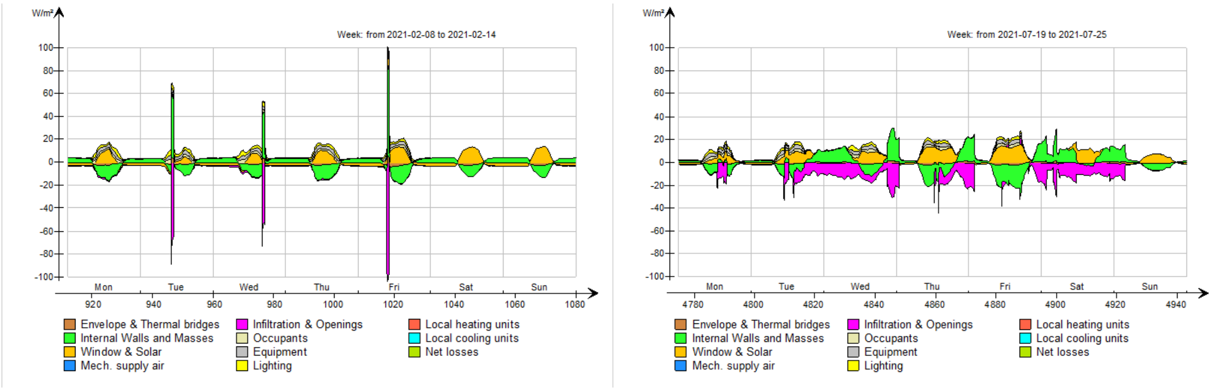


Figure 13: Evaluation of baseline simulation. Energy balance in winter (left) and summer (right).

3.1.2. Daylight availability and visual comfort

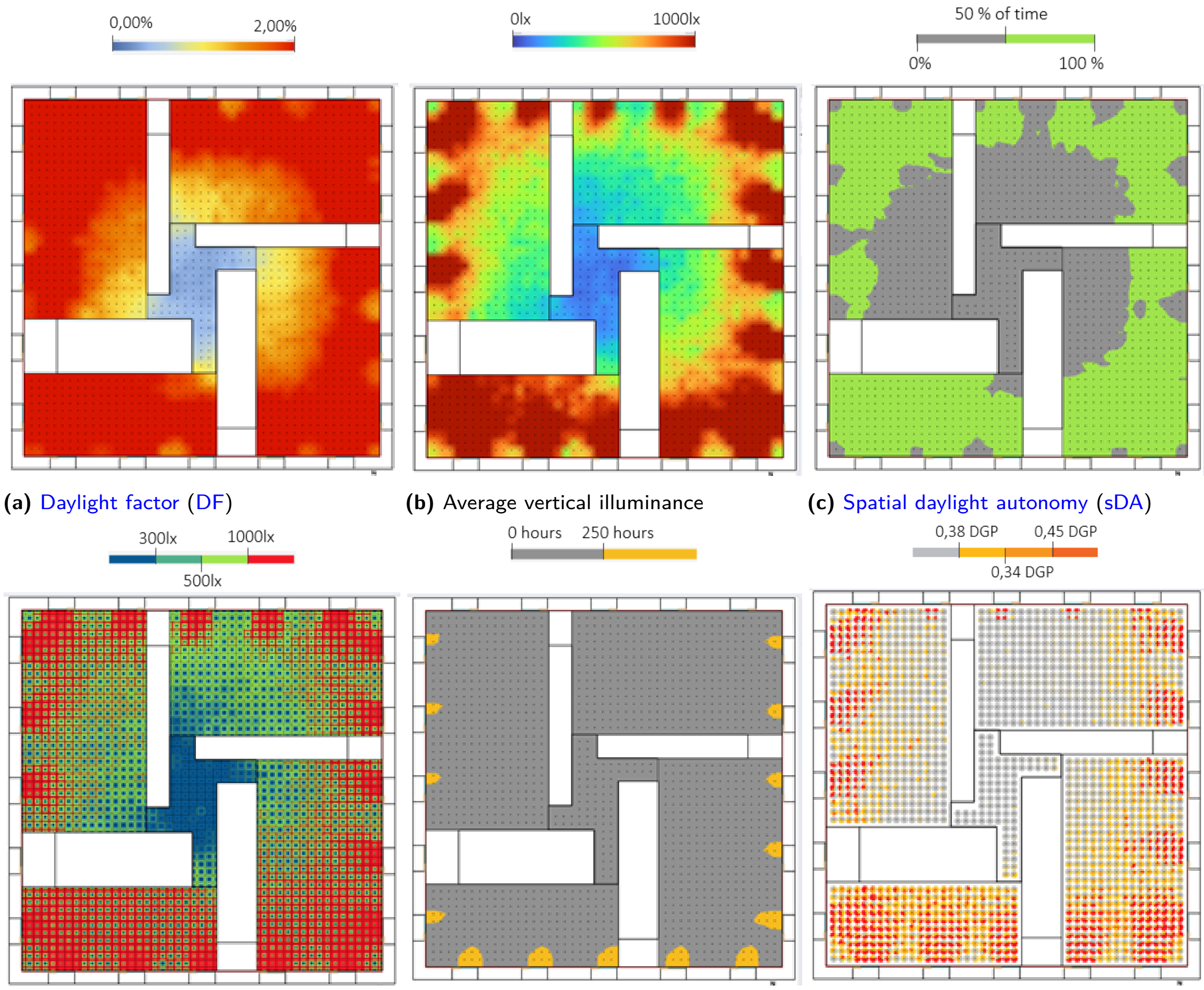
In this chapter the evaluation of daylight metrics is presented for an exemplary office floor. A full evaluation for all floors can be found in Appendix E. First we investigated the influence of the site context (See Table E.1). We observe that near surroundings reduce the DF from 3.0 % (without site context) to 2.6 %. In the following simulations, the spaces are evaluated within site context. In general, the Building *2226* meets the requirements during occupied hours 8 am to 6 pm daylight saving time (DST), except daylight glare probability. The whole building achieves a spatial daylight autonomy of $sDA_{500,50\%} = 54$ %, an average useful daylight illuminance of $UDI_a = 24.4$ %, an annual sunlight exposure of $ASE_{1000,250} = 3.3$ %, an average Illuminance E = 842 lx and a spatial disturbing glare $sDG_{5\%} = 10.1$ %.

The building has an average daylight factor DF = 2.60 % over all floors (cf. Appendix E) and fulfills the minimum target criteria for all office spaces in all floors of $DF_T > 2.00$ % required in DIN EN 17037:2019-03 [17]. Except core spaces, all spaces archives $D_T = 2.00$ % for at least 50 % of space area during occupied hours (answer to question 6). However, the required minimum of 0.5 for the DF uniformity is not achieved except for core spaces. Figure 14a shows the spatial distribution of DF for the 3rd floor. The simulated average illuminance of this exemplary floor at occupied times is avgE = 857 lx (Figure 14b), the spatial daylight autonomy reaches $sDA_{500,50\%} = 56.9$ % (Figure 14c), the share of acceptable useful daylight illuminance $sUDI_a = 25.3$ % (Figure 14d) and the annual sunlight exposure $ASE_{1000,250} = 3.5$ % (Figure 14e). With these values the 3rd floor is a good representation of the whole building. The basic daylight availability requirements except uniformity according to DIN EN 17037:2019-03 [17] are met.

Figure 14f presents the daylight glare probability for the selected office floor. 10 % of the simulated views have a disturbing or an intolerable glare of DGP > 0.38 during at least 5 % of the time ($sDG_{5\%} = 10$ %). Regarding maximum time period, 1 % of the views have a disturbing or an intolerable glare for 35 % of the time ($sDG_{35\%} = 1$ %). Especially south-east and south-west spaces have higher glare problem compared to north-east and north-west spaces (answer to question 8, cf. Appendix E for all floors).

In a next step the influence of blinds is evaluated. The Verosol Silver Screen Beige with an openness factor OF = 3 % and with a light transmittance LT = 3 % is selected. Simulation results show that operable blinds are open for 90.4 % of the occupied time (see Table E.2). ClimateStudio does not support use of blinds for glare evaluations, however it provides another assessment method, which is that operable blinds are closed, if more than 2 % of an occupied area is illuminated by more than 1000 lx of direct sunlight. Models with blinds does not have severe DGP problem regarding exceeding levels of direct sunlight, therefore while the spatial daylight autonomy decreases, the the share of acceptable useful daylight illuminance UDI_a changes slightly compared to base model without blinds, thus the use of blinds increases the visual comfort (answer to question 8).

For an office area, glare is investigated in more detail. 12th of February 4:30 pm is selected as an investigation point in time. Figure 15 shows that a person at a selected point with a north-north-west view direction (expressed with dashed-lines in Figure 15) experiencing intolerable level of glare with DGP = 0.64, as well as a luminance from window surfaces L_V = 2500 cd/m^2. Also, the eye level vertival illuminance E_V = 2026 lx is far beyond the limits for visual comfort.



(a) Daylight factor (DF) **(b)** Average vertical illuminance **(c)** Spatial daylight autonomy (sDA)

(d) Useful daylight illuminance (UDI) **(e)** Annual sunlight exposure (ASE) **(f)** Spatial disturbing glare (sDG)

Figure 14: Baseline simulation: Daylight metrics for 3rd floor.

This office area is also evaluated in terms of view-out availability (cf. Figure E.7 for geometry). Horizontal sight angles range from 5° to 16°, the outside distance of the nearest neighbor building is mostly higher than 50 m and at least two layers of outside environment are included in the same view. This space almost meets the medium level of recommendation for view-out evaluation.

To check the visual comfort performance of the existing artificial lighting, first it is evaluated if the artificial lighting provides sufficient light for specific tasks in the office. For a selected point in time (mid-night), illuminance simulations are run. Luminaries are placed based on the interior space photographs [21] (cf. Appendix C for selected luminaries). The baseline office model has 1 free-standing up-light for each of the two work stations per office. Figure 16 shows that in the baseline simulation the artificial lighting fails to provide the required level of illuminance of 500 lx. Also, the illumination on the desk surfaces has a low uniformity with values between 125 lx and 470 lx (answer to question 9). To improve the task specific artificial lighting, the free-standing up-lights are doubled for each of the works stations and 500 lx is achieved. Also, the average illuminance of the whole office area increased from 339 lx to 443 lx by the new lighting design. Addition to that to see, if artificial lighting causes any glare problem, renders are created at the same points where daylight glare is evaluated for

Figure 15: Daylight render and point in time DGP for the north-west office at the 3rd floor.

both of the models. Results show that person at that point experience only imperceptible level of glare (answer to question 9). Figure 16 shows the comparison of the baseline and alternative models for a point in time illuminance and glare renders.

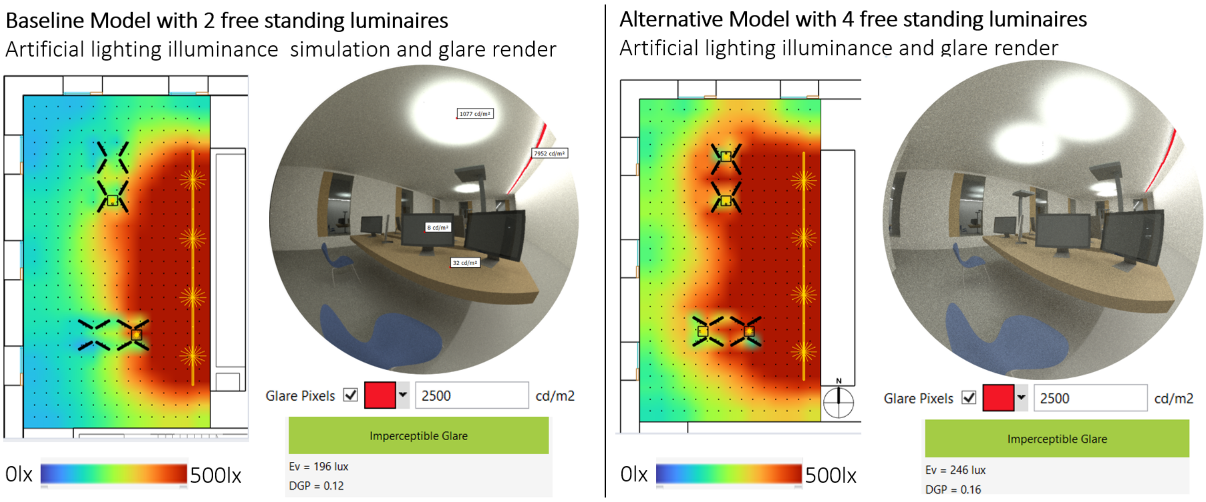


Figure 16: Comparison of artificial light illuminance and glare renders for the baseline (left) and alternative luminary models (right) at mid-night.

3.2. Parameter studies for indoor comfort

3.2.1. Climate

A set of climate data files has been developed in subsection 2.1. Figure 17 shows the time series of the operative temperature. The orange curve represents the operative temperature for the EPW Brussels data and the different grey curves the values for the PVGIS weather. It becomes clear that particularly in winter the minimum of the daily mean temperatures vary between ca. 15 and 20 °C. In summer maximum values are more similar which means that the ventilation concept designed in subsection 2.5 is able to maintain the maximum of 26 °C. Also in the lower graphs the variation according to the lower and upper limits can be shown. To conclude it can be shown that for such concepts different weather data sets have to be used to assure the designed concept. "Designing based on average" is not sufficient to guarantee comfort. Normally the backup system is responsible to fill the gap under extreme conditions.

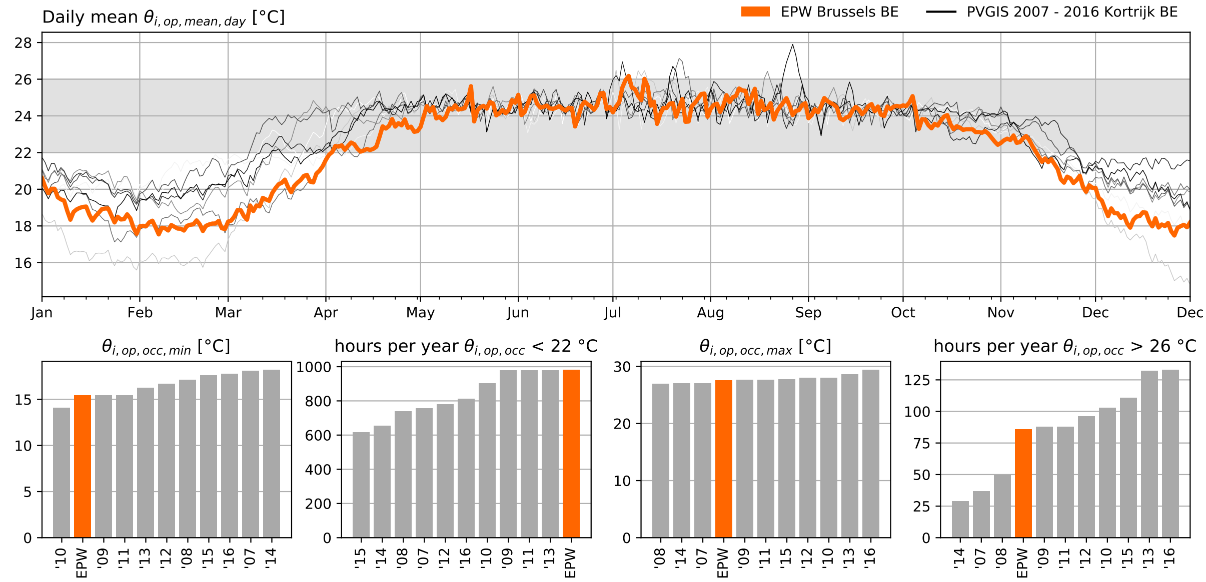


Figure 17: Evaluation of operative indoor temperatures under different climatic conditions

3.2.2. Window geometry and glazing properties

Wall thickness and window position The original building design is without any movable external shading elements. In Figure 18 we can see the position of the window flush mount on the wall inside guaranteeing a natural shading especially at high solar altitudes during summer. We investigated different scenarios S01 to S05 of the window position within the window reveal to investigate the impact on the transmitted solar energy (cf. Figure 19). We notice that the monthly transmitted solar energy is the lowest when the window is located on the inner side of the wall (S05) compared to other window positions S01 to S04 (answer to question 11). This is in line with the purpose behind the wall design of 0.813 m depth. It is not only serving as a thermal storage element, but also the deep position of the window in the wall guarantees a natural shading element. This also decreases the transmitted solar energy combined with the high-performance triple glazing window system. To increase indoor temperatures in winter, a smaller recess depth of the window reveal would be favorable. However, our simulation results show that indoor temperatures can not be raised significantly towards 22 °C (not presented here in detail).

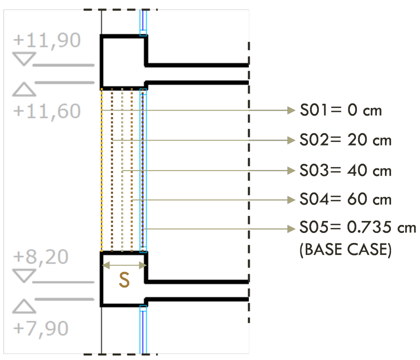


Figure 18: Section view of different window positions.

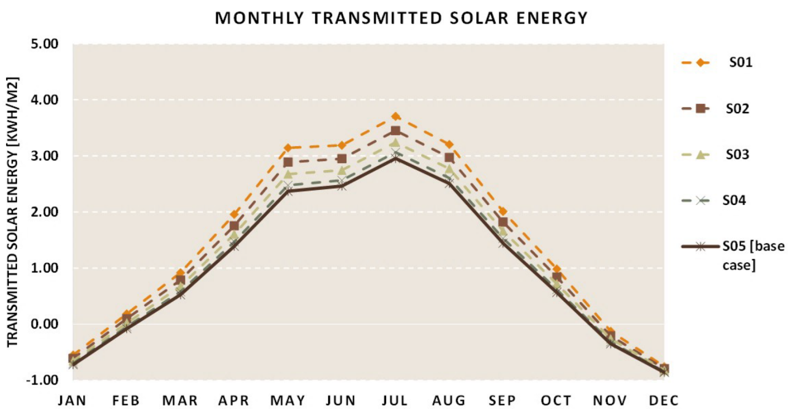


Figure 19: Monthly-averaged transmitted solar energy kWh/m^{2}a for different window positions within the window reveal.

The wall thickness is also an important parameter for the daylight performance of the offices. To assess the impact of the depth of the window reveal a simulation with an alternative wall thickness of 0.51 m has been investigated in daylight simulation for the 3rd floor (cf. Figure E.9, representing an ETICS construction[3], 2nd column of subfigures in Figure 20). Blinds are considered as always open during the simulations (for other settings see Appendix C). According to the simulation results, with a wall thickness of 0.51 m the spatial daylight autonomy $sDA_{500,50\ \%}$ increases from 56.0 % to 68.6 % (answer to question 7). On the contrary, the average share of acceptable useful daylight illuminance UDI_a decreasees slightly from 25.2 % to 24.7 %. These results show that although the daylight availability increases in space, visual comfort does not increase in parallel (Figure 20b and Figure 20c) since the additional daylight gained by a more narrow wall is causing excessive levels of light higher than 1000 lx.

Glazing type Starting from the default glazing type with a visible total light transmittance $T_{vis,tot} = 74$ % (Figure 5 and Appendix C) we investigated the impact of varying $T_{vis,tot}$, while maintaining other light related glazing properties. Compared to the baseline with a spatial daylight autonomy $sDA_{500,50\%} = 56.9$, a glazing with lower $T_{vis,tot} = 60.0$ % results in a lower spatial daylight autonomy of $sDA_{500,50\%} = 40.0$ % while a higher $T_{vis,tot} = 83.0$ % results in a higher $sDA_{500,50\%} = 69.3$ % (Figure 20a, second column of subfigures in Figure 20, answer to question 7). Blinds are considered as always open during the simulations.

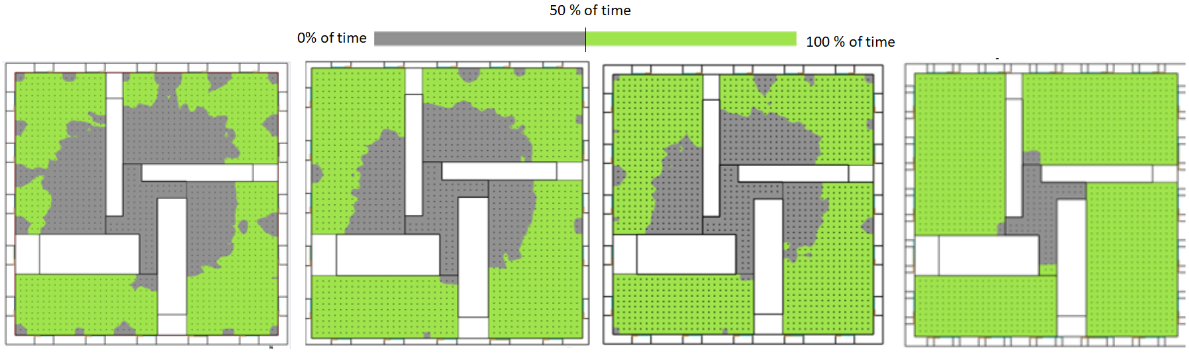
On the contrary, results are not directly proportional for useful daylight illuminance (UDI) and daylight glare probability (DGP). A glazing with $T_{vis,tot} = 60.0$ % results in a slightly lower average share of acceptable useful daylight illuminance $UDI_a = 23.70$ % (not included in Figure 20). A glazing with a higher $T_{vis,tot} = 83.0$ % leads to a slightly lower average useful daylight illuminance $UDI_a = 25.1$ % than the baseline model. Additionally, the sDG indicates that the baseline model with $T_{vis,tot} = 74.0$ % glazing reaches the limits regarding daylight glare probability. We observe a spatial disturbing glare of $sDG_{5\%} = 10.1$ %, which is almost the limit for visual comfort.

Window area Last parameter considered is the window area with a focus on spatial daylight autonomy. Compared to the baseline model with a glazing width of $w = 1.18$ m (glass to wall ratio 18 %) we doubled the window width to $w = 2.36$ m (36 % glass to wall ratio, cf. Figure E.8). Blinds are considered as always open. Our simulation results show that the spatial daylight autonomy increases from $sDA_{500,50\ \%} = 56.9$ % in the baseline to $sDA_{500,50\ \%} = 93.0$ % after doubling the window width (Figure 20a, right column of subfigures in Figure 20).

But varying the glass to wall ratio also reveals that higher levels of daylight do not lead necessarily to a higher level of visual comfort: On the one hand, by increasing the glass to wall ratio, the daylight availability is continuously increasing (answer to question 7) as well as the average share of acceptable useful daylight illuminance UDI_a. On the other hand the spatial disturbing glare $sDG_{5\%}$ are exceeding the thresholds of the comfortable range. By doubling the window the $ASE_{1000,250}$ is exceeding the limit value of 10 % (not included in Figure 20). Also, the daylight glare probability $sDG_{5\%} = 44.7$ % is far beyond the target limits. Figure 20 (right column of subfigures) shows the daylight metrics for the alternative window width.

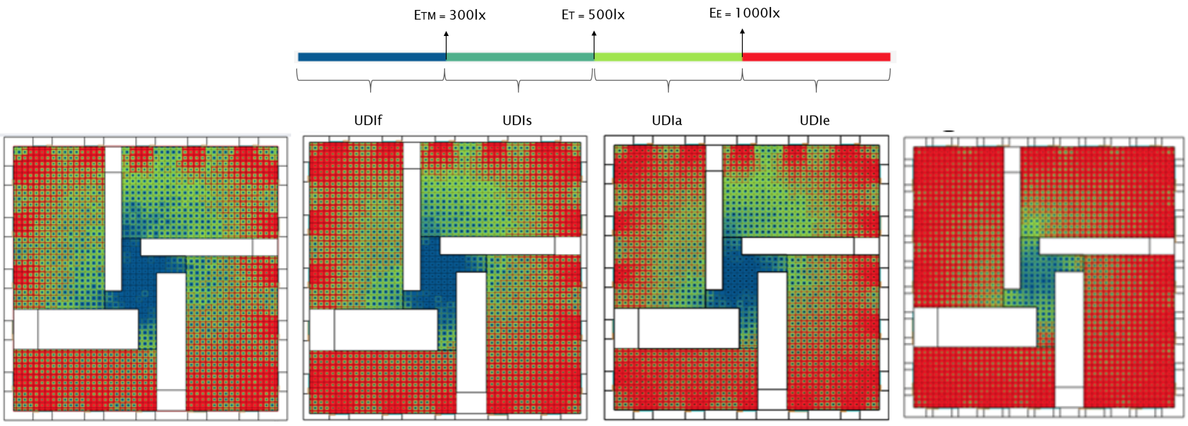
[3] While in subsubsection 2.3.1 and Table B.1 an ETICS with unchanged wall thickness of 0.813 m is described, here a reduction of the wall thickness to 0.51 m is assumed. Typically, an ETICS construction allows an optimized wall composition regarding the total thickness which is underlined by the evaluation of the areal heat capacity presented in Figure 4.

Default	**Wall thickness**	**Glazing**	**Window area**
Wall thickness t = 0.81 m	t = 0.51 m		
$T_{vis,tot}$ = 0.74		$T_{vis,tot}$ = 83.0 %	
glazing width w = 1.18 m			w = 2.36 m



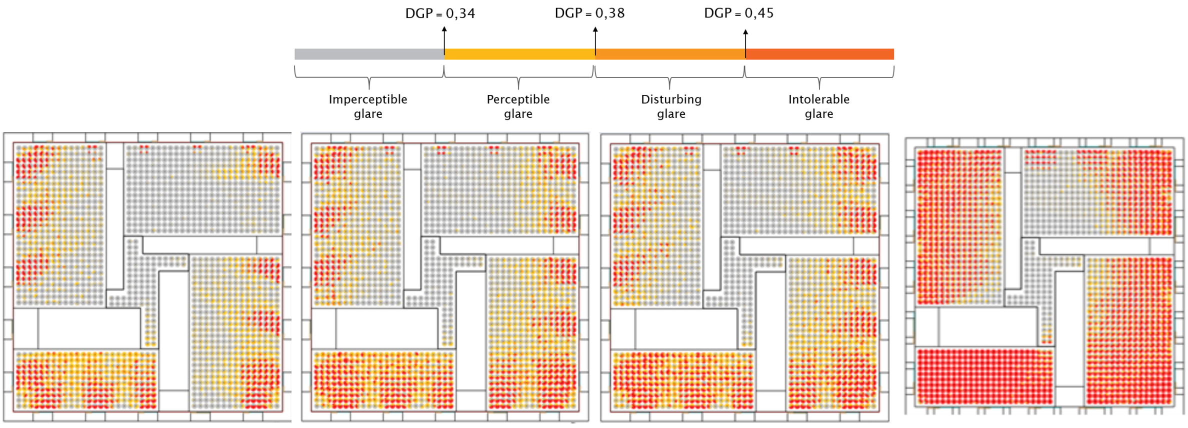
$sDA_{500,50\ \%}$ = 56.9 %	$sDA_{500,50\ \%}$ = 68.6 %	$sDA_{500,50\ \%}$ = 69.3 %	$sDA_{500,50\ \%}$ = 93.0 %

(a) Spatial daylight autonomy (sDA)



UDI_a = 25.2 %	UDI_a = 24.7 %	UDI_a = 25.1 %	UDI_a = 18.1 %

(b) Useful daylight illuminance (UDI)



$sDG_{5\%}$ = 10.1 %	$sDG_{5\%}$ = 12.9 %	$sDG_{5\%}$ = 13.3 %	$sDG_{5\%}$ = 44.7 %

(c) Daylight glare probability (DGP)

Figure 20: Parameter studies: Daylight metrics as a function of wall thickness, glazing type and window area for the 3rd floor.

3.2.3. Internal loads

As mentioned in subsection 2.4 and shown in Figure 13 the internal loads are relatively low due to the low occupancy rate. To investigate if the low winter indoor temperatures occur due to "lacking" internal loads three scenarios have been investigated: 1. Higher internal loads from equipment of 150 W per person compared to 100 W in the baseline 2. lower internal loads for equipment of 50 W and 3. an occupancy of 8 person instead of the fully occupied space (16 person). The applied schedule (cf Figure B.2) is not changed. Figure 21 shows that the effect of these substantial changes is in a range of ± 1.5 K. This underlines first, that the building design is relatively robust against changes of the occupancy but also second, that the discomfort in winter is not due to missing internal loads.

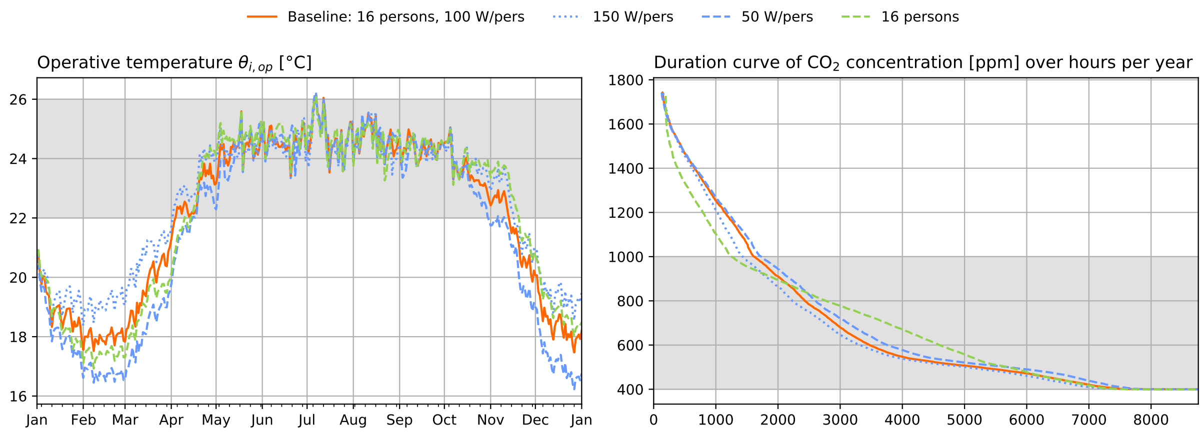


Figure 21: Evaluation of different internal loads

3.3. Energy performance

The original design of building 2226 in Lustenau (Austria) has no heating, cooling or mechanical ventilation system. In order to keep the temperature within the comfort range of 22 to 26 °C, the net energy and primary heating demand for the following cases has been investigated:

Radiators and fan coil As a conventional solution radiators and fan coils are applied to keep temperatures within the range of 22 to 26 °C. The systems are activated on weekdays from 6 am to 6 pm. The resulting energy indicators are included in subsection 3.3.

Air handling unit An alternative AHU with heating, cooling, humidification and dehumidification has been designed in IDA ICE (answer to question 16). Figure 22 depicts the chosen components (enthalpy wheel, heating coil, cooling coil, evaporative humidifier, two fans) with the outside air on the left and the room on the right side.

An individual controller has been programmed (cf. Figure B.3) to keep the room air temperature and the relative humidity within comfort ranges according to DIN EN 16798-1:2021-04 [12] (category I: indoor operative temperature $21.0 < \theta_{i,op} < 25.5$ °C, relative humidity 30 % $< \phi_i <$ 50 %, category II: 20.0 °C $< \theta_{i,op} <$ 26.0 °C, relative humidity 25.0 °C $< \phi_i <$ 60 %, cf. Table B.9 and B.16 in [12]). Depending on the conditions in the extract air setpoints for the different components are calculated (h-x-control) to reach to target temperature and humidity calculated by the controller[4]. Supply temperatures and humidities have been limited to 18 to 36 °C and 30 to 90 %, respectively. Figure 23 shows the air condition states at after each component.

[4]The hx-control is implemented in the programming language Neutral Model Format (NMF) [22] within IDA ICE.

The AHU is designed as a VAV system to vary the fresh air rate according to the aimed indoor air quality (category I[5]: < 950 ppm, category II: < 1200 ppm, cf. Table B.9 in [12]). First, the controller tries to reach the target state by adjusting the supply air temperature. Second, the air volume is increased if the target state can not be reached. The resulting net and primary energy demands for the heating, cooling and reheating coil, as well as the electricity needed for fans are presented in Figure 26 (answer to question 16).

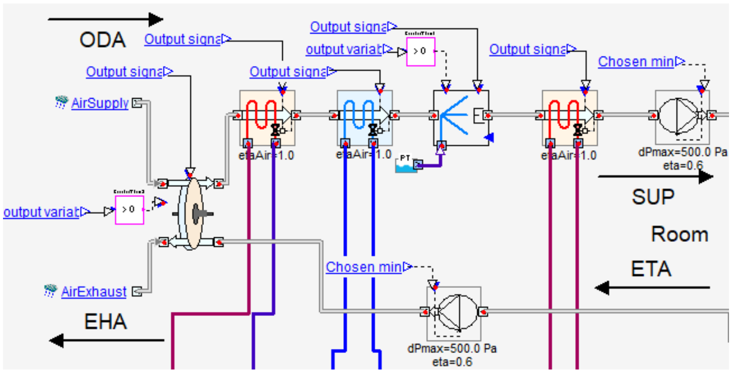


Figure 22: Air handling unit in IDA ICE

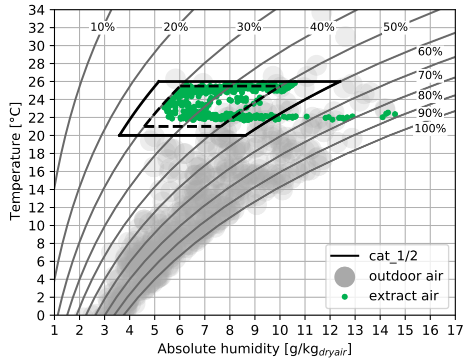


Figure 23: Mollier hx diagramm for IAQ 2.

Concrete core heating and cooling (CCHC) Introducing a CCHC as a low temperature system activating the thermal building mass opens up the possibility of introducing heat pumps and flexible operation and control. In the CCHC model, water pipes are embedded on the middle level (10 cm) of the concrete layer in the ceiling and they cover 50 % of the surface area. Both the ceiling and floor slabs are equipped with the system and CCHC is operable for heating and cooling. We assume an area specific flow rate of 10 l/m²h. A geothermal heat pump system is used heating/cooling system with an assumed average COP = 4.35. The CCHC is operated periodically from 6 pm to 6 am to load the mass during night time for the next day. Continues operation mode would lead to small temperature differences and increased power demand for pumps. For the control strategy a base case and a flexible operation are investigated as follows (answer to question 14):

Base case In this control strategy, the supply temperature of the CCHC is optimized based on the mean outdoor temperature. By this optimization, the aim is to narrow down the daily operative temperature change during occupation time and to create stable indoor temperatures. In this context, the supply temperature ranges between 30 °C to 19 °C according to the outdoor temperature. These supply temperatures have been optimized and defined in a series of preliminary simulation runs (not included in the report).

Flexible operation The base represents a typical control strategy. However, by referring to the main competition question, an advanced control strategy is needed for an advanced building operation. In this purpose, building-grid interaction is examined as second strategy. The rising penetration of renewable energy sources (RES) increases the loads in the electricity grids. Buildings can assist the grid by Building-Grid Interaction (Building energy flexibility) to stabilize the loads [23]. The correlation between the energy price and CO_2 free electricity generation plays an important role in this strategy. If surplus electricity is supplied to grid, building utilizes CO_2 free electricity with cheaper price. Therefore, the building mass can be loaded thermally more via CCHC in this period. Vice versa, the building is supposed to reduce its energy demand without jeopardizing the thermal comfort. Therefore, we introduce a flexible operation taking in to account the day-ahead electricity price of Belgium.

According to [24] the electricity unit price in Belgium is 0.27 EUR/kWh if the building uses a regular electricity tariff. In the day-ahead market, the price changes based on supply-demand balance. The price data of EPEX

[5] An outdoor CO_2 concentration of 400 ppm is assumed.

for January and July [25] are used for flexible operation. The same supply temperature is taken as in the base case during expensive electricity periods. However, when electricity is cheaper, the temperature band is increased or decreased by 1 K to 31 or 17 °C, respectively. Thus, the concrete slab can be loaded warmer or cooler and keep the indoor thermal comfort in a more narrow band.

Thermal comfort The CCHC system mostly keeps the indoor temperature between 22 to 26 °C band. Figure 25 shows that the indoor thermal comfort is improved compared to the baseline model. On the other side, quick temperature drops are observed which is caused by natural ventilation developed in subsection 2.5. After this period, the increment of the temperature in a short period is tracked, as well. The resulting energy demands are presented and compared in Figure 26.

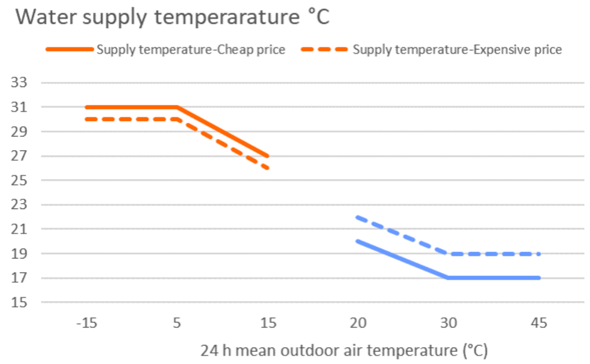


Figure 24: Water supply temperatures [°C] for base case and flexible operation of CCHC

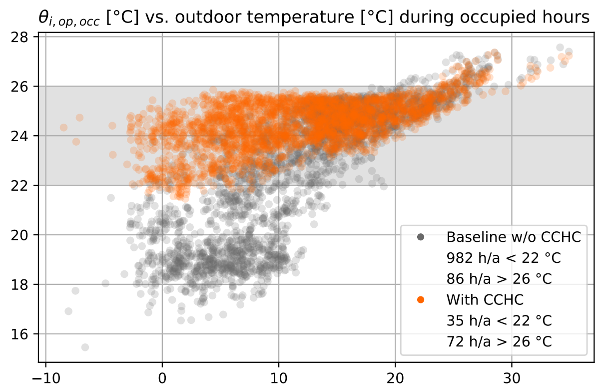


Figure 25: Comparison of operative temperatures with and without CCHC.

Energy demand The resulting area-related net and primary energy demands for radiators and fan coils, CCHC and the AHU including fan power and lighting are compared in Figure 26. For the conversion from net to primary energy we assume that radiators and fan coils as well as the air handling unit coils have to be supplied with conventional high or low temperature generators, respectively. For heating we assume a gas boiler with a COP = 0.9 and for cooling a compression chiller with EER = 3. On the contrary, we assume that the Concrete core heating and cooling can be supplied with a heat pump on low temperature levels for both heating and cooling. We assume a seasonal performance factor $COP_{seasonal} = 3.5$ for heating and that direct cooling without reversible heat pump is possible with an estimated $COP_{cool,direct} = 10$. Hitchin et.al. present the range of primary energy factors for different European countries [26]. On this basis a primary energy factor $PEF_{gas} = 1.1$ and $PEF_{electricity} = 2.5$ have been assumed.

Radiators and fan coil The simulated area specific net energy demand of one office floor is 10.0 kWh/m²a for heating and 2.8 kWh/m²a for cooling (answer to question 12).

Concrete core heating and cooling (answer to question 15) In the baseline strategy energy demands stay on the same level with 11.0 kWh/m²a for heating and 1.4 kWh/m²a for cooling. With a heat pump and direct cooling the primary energy demand decreases to 7.9 kWh/m²a for heating and 0.3 kWh/m²a for cooling. The purchased energy is calculated as 360 EUR.

As shown in previous studies (e.g. in the framework of IEA EBC Annex 67 [27]) flexible operation might lead to increased energy consumption. In our case considering flexible operation the energy demand for heating and cooling is increasing by 90 % for heating and 70 % for cooling. The energy costs increase to 640 EUR. This increase illustrates that future buildings which are able to communicate and stabilize the electricity grid will have an increased energy demand. In our example the primary energy demand increases in parallel. However, the share of electricity generated by RES is also increasing every year, accordingly, which results in lower primary energy factors. In the coming years, the electricity grid will need more support from buildings due to the rising share of RES, thus, the day-ahead prices and primary energy factor will be lower. As implying to the main competition question, building-grid interaction is evaluated as a potential control strategy.

Air handling unit (Answer to question 16) With the designed AHU the heating demand can be reduced by 80 % (cat. 1) to 90 % (cat. 2) due to heat recovery compared to radiators and fan coils. The sum of the primary energy demand is 25 % lower for category II compared to category I.

Lighting The energy demand for lighting (inputs described in subsection 2.4) is 1.9 kWh/m² for floor lamps is the office area and 5 kWh/m²a for general lighting (answer to question 9). Typically the demand is lower for general lighting. In our case this is due to an advanced automated dimming control for floor lamps and a simple "alwalys on" for general lighting.

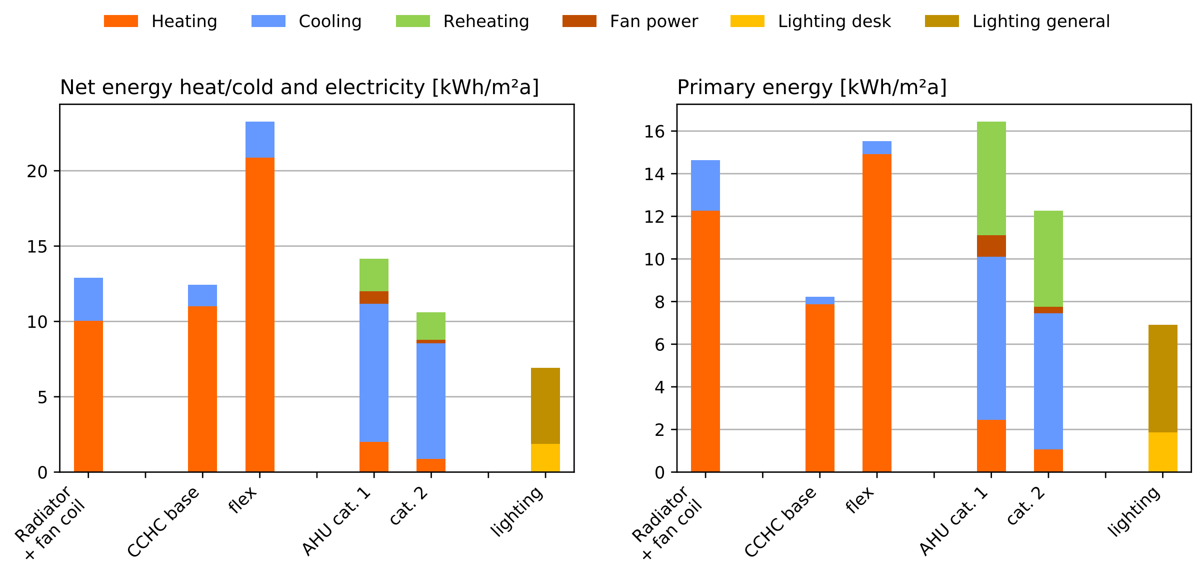


Figure 26: Energy performance for technical systems and applications.

3.4. Reflections on user behavior

In the absence of movable shading systems, the user influence on comfort and energy use is smaller compared to normal office buildings. When window opening is the only way to actively influence temperatures and air quality the questions how users accept automated ventilation systems, how they "disturb" these concepts by manually opening windows and how they react when it is either too cold or air quality is insufficient are becoming important. In fact, people generally like to have control over their environment and they like having access to fresh air, breezes and the outdoor environment.

Occupant behavior is proven to have a significant impact on energy consumption in buildings (cf. publications in the framework of IEA-EBC Annex 66 and 79 [28]. Most of the building energy systems are designed without a realistic view of the occupant and their behaviors. However, several studies investigated occupant control of windows and how to account the occupant behavior in building design and building performance simulation. For instance, Borgeson et. al. [29] found that automated building systems should be responsive to specific patterns of window control such as models that can account for greater window operation at occupant arrival and departure, the tendency for windows to stay in their current state, seasonal variations and of course thermal comfort and ventilation. Ackerly and Brager [30] proposed a new policy of window signaling system (with recommendations based on the study findings) that advises building occupants when to open and close windows (such as green or red visible lights) for balancing the comfort benefits of manual windows with the efficiency benefits of window automation. This policy can be adapted to the building 2226 window control concept. However, Karjalainen [31] found that occupant behavior can be diminished greatly via robust building design solutions which make buildings less sensitive to occupant behavior. In our study, building 2226 has proved its resilience and robustness under different variations of design parameters (see subsection 3.2).

4. Conclusions

The present study provides a full overview about thermal and visual comfort and the energy performance of the *2226* building concept for the new location in Kortrijk, Belgium. A low-tech concept without heating or cooling system is a showcase project for the need and the power of building simulation. Conventional planning tools and rules of thumb are not able to compensate lacking experience of such an approach. Only the simulator can put together the different parts of building physics, control strategies and daylighting. The study is a very good example for the need of building simulation to assure design decisions. According to measured indoor thermal comfort presented in [3] both monitored indoor temperatures and CO_2 concentrations mainly stay within the aimed limits in the real building. On the contrary, according to our simulation results, the originally designed concept could not be approved for the new location. Particularly in winter temperatures drop below the 22 °C threshold with daily means around 18 °C and the indoor CO_2 concentration exceeds 1000 ppm. The dilemma is that it is either too cold or air quality is insufficient. Different parameter studies have been done to investigate the impact of the climate, the wall and window geometry and glazing parameters. Varying climate data sets and internal loads show a bandwidth of about ± 2 K for winter temperatures. However, the minimum of 22 °C is not reached in any simulation.

In terms of daylight availability, the building generally meets the medium requirements, except for the uniformity. To reach a uniform distribution of daylight designing daylight openings on the opposite walls instead of neighbor walls of the space would be needed which is not possible for the existing layout. Also, some openings on the interior walls as light bridge gaps to link corner spaces in terms of daylight can be considered. Another possible solution would be to increase the reflectance of the ceilings and the interior walls (especially on the opposite of the window surfaces). Regarding daylight only, approaches like smaller window sizes or glazing with lower transmittance on the south facade would lead to a more uniform distribution aver the floor space. However, this would reduce solar gains in winter and is therefore not compatible with the building concept.

About the visual comfort, our results show that approximately 10 % of users might experience disturbing and/or intolerable glare especially in the south-east and south-west corner spaces. Based on the analyses, the best solution is the use of interior blinds to prevent glare problems without decreasing the useful daylight illuminance (UDI). In some areas of the existing building, manually movable curtains are already in use. Since summer thermal comfort is not critical, exterior blinds are not needed at the new location. Thus, we recommend to complete the combo glazing - artificial lighting - solar shading by internal blinds only, added by supplementary floor lamps if needed (answer to question 10).

Coming back to the main competition question how to adopt the concept to the new location we see the greatest potential in the introduction of a Concrete core heating and cooling system. On the one hand this allows to guarantee thermal comfort in winter and keeping the automated natural ventilation concept. On the other hand the activation of the building mass together with a heat pump makes the building ready for building grid interaction as future requirement. As stated in the introduction and subsection 3.4 aspects the user behavior have to be carefully considered, particularly in buildings that are not used by the owner together with the experiences gained in the real project.

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A. Challenge sub questions

Building Envelope

1. Check the thermal transmittance of the outside wall. Design an alternative wall composition with an External Thermal Insulation Composite System (ETICS). What do you learn?

   see subsubsection 2.3.1

   With the wall composition given in Table B.1 and heat transmission resistances of $R_{s,i}$ = 0.13 m²K/W and $R_{s,e}$ = 0.04 m²K/W the thermal transmittance of the outside wall is

   $U_{wall} = \frac{1}{R_{s,i}+\sum\frac{d}{\lambda}+R_{s,e}} = \frac{1}{0.13+\frac{0.01}{0.7}+\frac{0.38}{0.11}+\frac{0.018}{0.38}+\frac{0.38}{0.09}+\frac{0.025}{1.0}+0.04} = 0.12\ W/m^2K$

2. Use the dynamic thermal characteristics (ISO 13786:2007 Thermal performance of building components - Dynamic thermal characteristics - Calculation methods) to evaluate alternative wall compositions. What do you learn?

   see subsubsection 2.3.1

3. Calculate the overall envelope thermal transmittance (wall + glazing + frame).

   With a outer wall length of l = 24 m, a floor height of h = 3.70 m and 5 windows with 1.63 x 2.80 m (A_{window} = 4.564 m²) the resulting areas are

   A_{wall} = 65.98 m² and $A_{windows}$ = 22.82 m

   with U_{wall} = 0.12 W/m²K

   and U_{window} = 0.63 W/m²K (incl. frame)

   the resulting total thermal transmittance $H'_{wall+window}$ is

   $H'_{wall+window} = \frac{0.12W/m^2K\cdot 65.98m^2+0.63W/m^2K\cdot 22.82m^2}{65.98m^2+22.82m^2} = 0.25\ W/m^2K$

   According to [2] the overall thermal transmittance of the building envelope is H' = 0.233 W/m²K which is in line with our result since in an overall assessment roof and floor slab are compensation the higher U-Value of the windows.

4. Calculate the linear thermal transmittance of the floor joint according to EN ISO 10211:2017 Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations.

   -

5. Do a life cycle analysis of the original wall composition (ISO 15686-5 Buildings and constructed assets - Service life planning Part 5: Life-cycle costing).

   -

Visual Comfort (light)

6. Calculate the spatial distribution of the daylight factor (EN 17037:2019 Daylight in Buildings).

   see subsubsection 3.1.2

7. Calculate the spatial distribution of daylight autonomy (sDa) for the office level as a function of wall thickness (with and without ETICS) and as a function of glazing type (EN 17037:2019 Daylight in Buildings). How is the comfort level? Analyse the impact of the window area on the daylight autonomy. The blinds should be considered as always open at this stage.

   see subsubsection 3.2.2

8. Calculate the daylight glare probability (DGP) (EN 17037:2019 Daylight in Buildings). What is the impact of using the interior blind (Verosol silverscreen)?

   see subsubsection 3.1.2

9. Check the energy and visual comfort performance of the artificial lighting system (with a method of your choice, e.g., GR, UGR). Calculate the electricity use for general lighting and for task lighting.

   see subsubsection 3.1.2 for visual comfort and subsection 3.3 paragraph "Lighting" for electricity use.

10. Optimize the combo glazing - artificial lighting - solar shading for thermal and visual comfort. Present a control system.

    see section 4

Thermal Comfort

11. What is the transmitted monthly solar energy as a function of the window position (depth of the wall)?

    see subsubsection 3.2.2

12. What is the yearly net energy demand for heating of an office floor?

    see subsection 3.3

13. Evaluate the thermal comfort in summer and winter time for different occupancy schedules (EN 15232 Appendix A).

    see subsubsection 3.2.3

14. Introduce a concrete core activation system and design the control system.

    see subsection 3.3 paragraph "Concrete core heating and cooling"

15. In which way can a geothermal heat pump with concrete core activation enhance the thermal comfort? What is the primary energy consumption for heating in that case?

    see subsection 3.3.

Indoor Air Quality

16. Design an alternative air handling unit that includes humidification, dehumidification, filters,heating, cooling. Calculate the fan energy use, and energy demand for humidification as a function of the required comfort class A and B, required indoor air quality IDA 1 and IDA 2 (EN 16798-1:2019).

    see Figure 22, Figure 23, subsection 2.5 and subsection 3.3

17. Calculate the distribution of pressure coefficients on relevant windows as a function of the wind direction.

    see Figure B.1

18. Design a window opening strategy as a function of wind direction and wind speed. Give a cumulative distribution function of the opening width of the window over the year.

    see subsection 2.5 and Figure 11.

19. How would you change the concept of this building, related to IAQ, if it were to be situated next to a highway?

    see subsection 2.5 second to last paragraph.

Acoustic Comfort

20. What is the reverberation time in an office?

    -

21. How can you enhance the acoustical comfort?

    -

22. What is the impact on the thermal comfort of these changes to enhance the acoustical comfort?

    -

23. Which potential synergy do

    -

B. Additional figures and tables

Table B.1: Opaque constructions according to [1, 2, 3] [1]

		layer internal to external			
		d [cm]	λ [W/mK]	ρ [kg/m^3]	c [J/kgK]
External wall Default d = 0.81 m U = 0.12 W/m²K	gypsum plaster	1.0	0.7	1400	1000
	brick	38.0	0.11	700	840
	light plaster	1.8	0.38	1000	1000
	brick	38.0	0.09	600	840
	lime plaster	2.5	1.00	1800	1000
External wall ETICS d = 0.81 m U = 0.12 W/m²K	gypsum plaster	1.0	0.7	1400	1000
	reinf. concrete	45.0	2.5	2400	1000
	insulation	33.0	0.42	160	2100
	lime plaster	2.5	1.00	1800	1000
External wall Timber structure d = 0.81 m U = 0.12 W/m²K	gypsum plaster	1.0	0.7	1400	1000
	timber	55.0	0.18	700	1600
	insulation	21.0	0.42	160	2100
	lime plaster	2.5	1.00	1800	1000
Ceiling	gypsum plaster	2.5	0.07	1400	1000
	brick	0.38	0.11	700	840
	light plaster	1.8	0.38	1000	1000
	brick	0.38	0.09	600	840
	lime plaster	2.5	1.00	1800	1000
Internal wall d = 0.26 m	gypsum plaster	2.5	0.07	1400	1000
	brick	0.38	0.11	700	840
	gypsum plaster	2.5	0.07	1400	1000
Roof, U = 0.1 W/m²K					
Floor slab					

[1] roof and floor slab are not used in building simulation

Face \ Angle	0	45	90	135	180	225	270	315	Face azi...
Building body									
f1	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	0.0
f2	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	90.0
f3	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	180.0
f4	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	270.0
Crawl space	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Roof	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0

Figure B.1: IDA ICE pressure coefficients

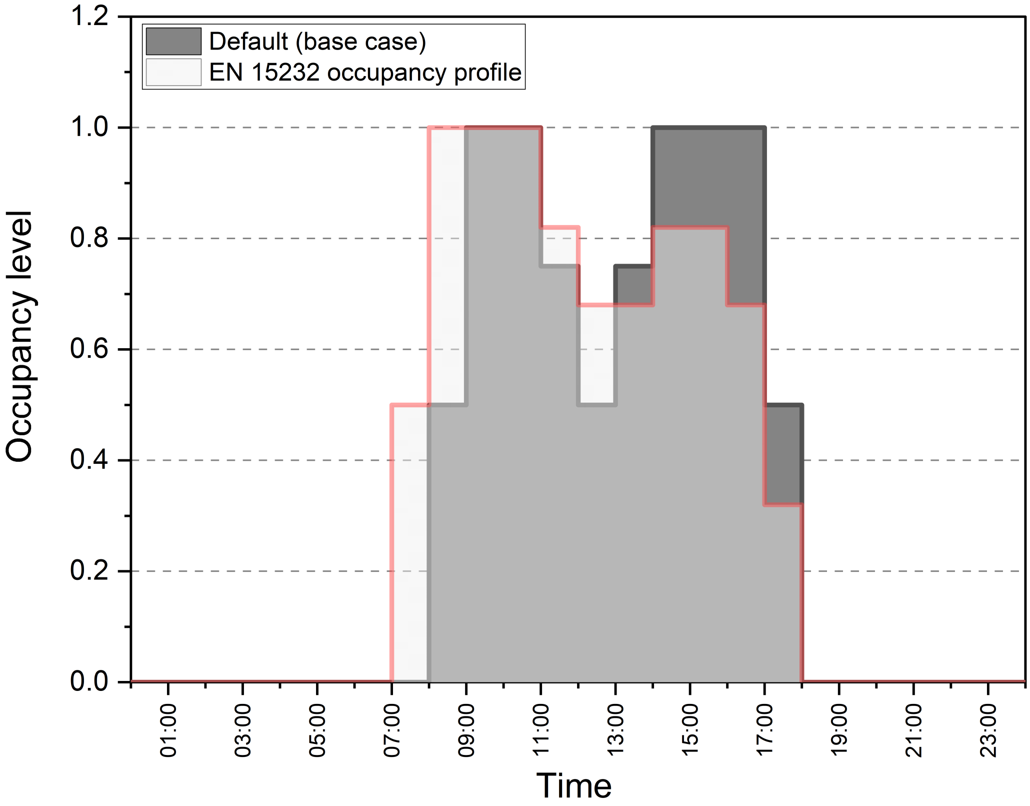

Figure B.2: Occupancy profile

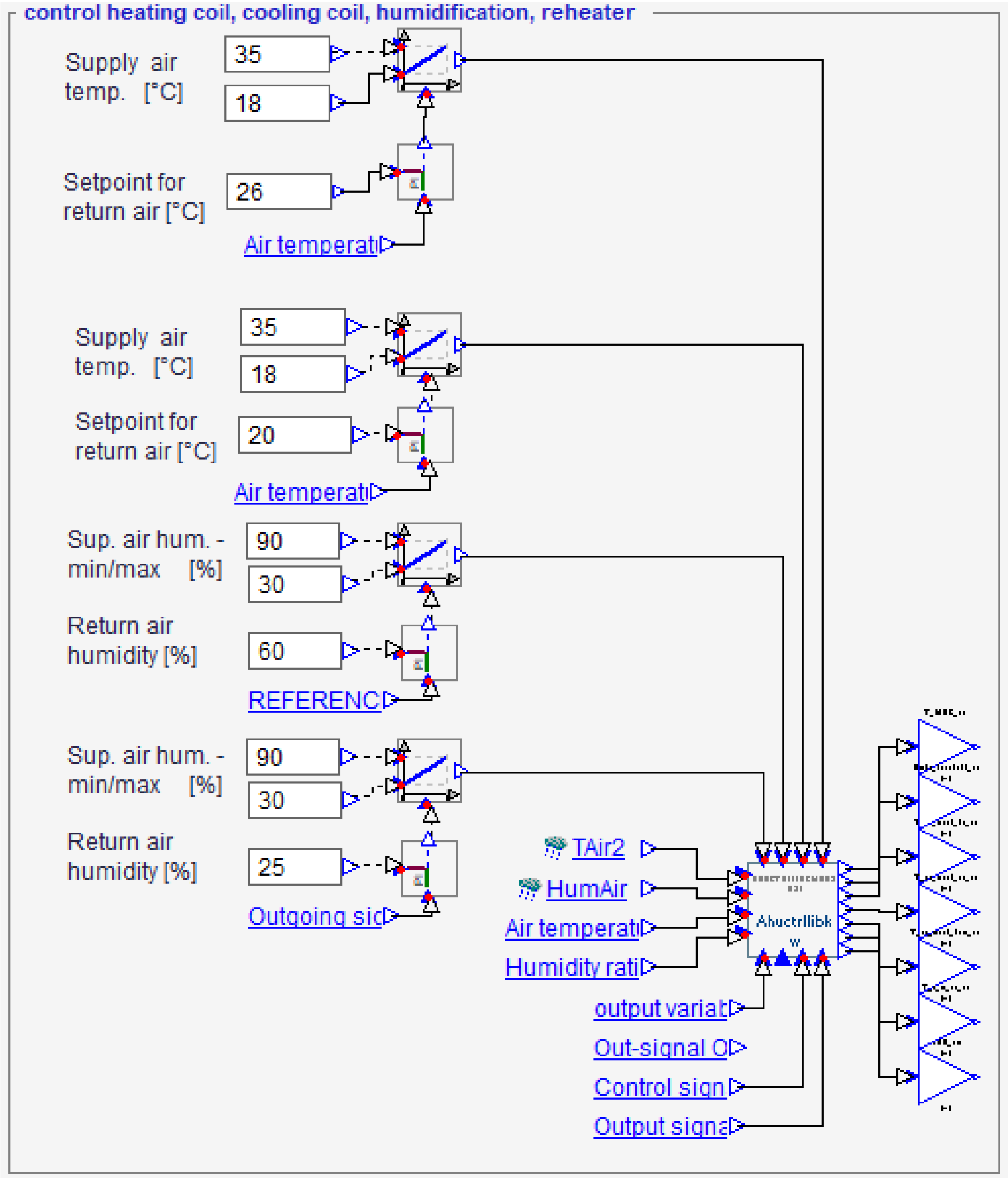

Figure B.3: AHU controller in IDA ICE

C. Daylight input settings

Weather Data

- EnergyPlus weather (EPW) [5]

Sky Models

- CIE Overcast Sky Model for Daylight Factor [17]
- Perez all-weather Sky Model from weather data for sDA, ASE, UDI, DGP, avgE [17]

Architectural Model

- All space and facade details are modeled within 2 cm tolerance: wall thickness, frames, mullions, interior partitions, ceilings [1], furniture [21].

Investigated Spaces

- Whole building for general evaluation
- 3rd floor for parameter evaluations - in detail north-west office

Opaque Materials and Rvis-tot

- Outside nearby ground surface: Concrete exterior floor with 18.14 % Rvis-tot [1, 32]
- Neighbor buildings: Concrete exterior wall with 25,83 % Rvis-tot [1, 32]
- Nearby tress: Matte green leaves with 8.54 % Rvis-tot [1, 32]
- Building 2226 - Roof with 25.88 % Rvis-tot [1, 32]
- Building 2226 - Exterior wall surface: White exterior plaster facade with 64.11 % Rvis-tot [1, 32]
- Building 2226 - Interior wall surface: White plaster finishing with 86.62 % Rvis-tot [1, 32]
- Building 2226 - Ceiling finish: White plaster ceiling finishing with 89.90 % Rvis-tot [1, 32]
- Building 2226 - Floor finishing: Light grey painted floor with 37.08 % Rvis-tot [1, 32]
- Building 2226 - Widow frames and openings: Light brown wooden frames with 37.46 % Rvis-tot [1, 32]
- Furniture - Desks & Tables: Light brown wood table with 32.95 % Rvis-tot [21, 32]
- Furniture - Chairs: Blue magenta rubber body with 14.08 % Rvis-tot and metal legs with 50.70 % Rvis-tot [21, 32]
- Furniture - Lockers - Black wood with 4.28 % Rvis-tot [21, 32]
- Furniture - Monitors: Clear glass screen with 87.70 % Tvis-tot and 8.40 % Rvis-front, Dupont black screen frame with 0.34 % Rvis-tot and metallic aluminum body with 20.01 % Rvis-tot [21, 32]

Glazing Materials, Tvis-tot, Rvis-front, Rvis-back

- Building 2226 Window glazing: Triple glazing (4-14-4-14-4) Argon filled with 74 % Tvis-tot and with 18.80 % Rvis-front and 16.40 % Rvis-back [1, 33]

Reference Plane Grid and Sensor Positions

- For DF, sDA, ASE, UDA: 0.85 m sensor height, 0.5 m sensor spacing, 0.45 m sensor inset [17]
- For DGP: 1.2m sensor height, 0.5 m sensor spacing, 0.45 m sensor inset [17]
- For glare renders: 1.2 m sensor Height, selected orientation, fisheye lens with opening angle of 180°.

Target and limit values for daylighting evaluations metrics

- Daylight factor: DF 2 % and DFM=0.7 % ; as well DF Uniformity $>$ 0.5 [17]

- sDA300lux,50 % ≥ 95 % and sDA500lux,50 % ≥ 50 %. (Level of Recommendation is medium) [17, 34]
- ASE1000,250 < 10 %, [34, 35]
- UDI limit values: ETM = 300 lx, ET = 500 lx and EE = 1000 lx [17, 34, 36, 35]
- $DGP_{5\%}$ < 0.45 (level of recommendation is MIN.) and DGP5 % < 0.35 (level of recommendation is HIGH) [17] Luminance < 2500 cd/m2 [37]

Limit values for View-out Comfort according to level of recommendation

- Level of recommendation minimum: Horizontal sight angle > 14°, outside distance of the view > 6.0 m, at least a landscape view is included [17]
- Level of recommendation medium: Horizontal sight angle > 28°, outside distance of the view > 20.0 m, L landscape view is and one additional layer (sky or ground) included in the same view opening [17]
- Level of recommendation high: Horizontal sight angle > 54°, outside distance of the view > 50.0 m, all layers are included in the same view opening [17]

Luminaries

- Luminaries for task lighting in offices: ID-S ID-S 150 W i HIT-DE with 150 W free-standing up-light [38]
- Luminaries for general lighting in office LINARIA Led [39]

Reference Plane Grid and Sensor Positions

- For Point in time illuminance: 0.85 m sensor Height, 0.5 m sensor spacing, 0,45 m sensor inset [17]
- For Glare: 1.2 m sensor height, 0.5 m sensor spacing, 0.45 m sensor inset [17]
- For glare renders: 1.2 m sensor height, selected orientation, fisheye lens with opening angle of 180°.

Target and Limit values for artificial lighting metrics

- Em = 500 lx for work station in an office space and Em > 300 lx for meeting room [37, 40]
- Luminance < 2500 cd/m2 [37]
- Etask Uniformity > 0.7 and Etask surroundings uniformity > 0.5 [40]

D. Description of daylight metrics

DIN EN 17037:2019-03 [17] proposes to use the daylight factor to assess the natural light supply in a space. daylight factor (DF) represents the amount of daylight that space might receive compared to what available from sky. DF is the ratio between two illuminance value, one is an inside illuminance E_i at an upward facing unobstructed point on a horizontal surface in a space and the second is an outside illuminance E_o of an upward facing point under CIE overcast sky, which provide illuminance values for diffuse light and do not include direct sunlight. Accordingly, DF described with an equation, DF = (E_i / E_o).100 %. DIN EN 17037:2019-03 [17] describes two levels of daylight factor, which are target daylight factor D_T and minimum target daylight factor D_{TM}. Depending on the external average diffuse horizontal illuminance and the level of average illuminance value of an interior space, standard recommends different D_T values for different regions, in our case the recommended values of DF for a building in Brussel with vertical openings are 2 % for D_T and 0.7 % for $D_{T,m}$. For dynamic calculation (e.g. annual dynamic calculations) standard recommends the D_T to be achieved at least 50 % of the area of a space during occupied hours. Also, in the standard it is mentioned that DF uniformity, which ratio of minimum DF to average DF, is generally expected higher than 0.5.

Besides the daylight factor, calculation of illuminance levels on the reference plane using climatic data, in the course of the year and related to space, sDA metric is used. sDA is a percentage of the area that meet a minimum horizontal daylight illuminance level for a specified fraction of time [34]. DIN EN 17037:2019-03 [17] recommends different levels for the evaluation of daylight availability in a space. In this study, medium level of recommendation is selected and evaluated. According to the medium level, for minimum target illuminance $E_{T,M}$ a space with vertical openings should have minimum 300 lx at least 50 % of the occupied hours, at least 95% of the occupied area. This is expressed as an abbreviation of $sDA_{300,50\%} = 95$ %. For target illuminance E_T, a space should have minimum 500 lx at least 50% of the occupied hours, at least 50 % of the occupied area. And this is expressed with an abbreviation of $sDA_{500,50\%} = 50\%$.

To support the sDA metric, for it does not has an upper limit for illuminance, IES developed an accompanying metric entitled ASE, which is a metric describes the potential for visual discomfort in interior environment [36]. This metric is not mentioned in DIN EN 17037:2019-03 [17], on the other hand some of the green building certification systems, such as LEED uses this metric and according to that if the more than 10% of the space has a 1000 lx or higher illuminance at least 250 hours in a year, which is described with abbreviation of ASE1000,250 > 10 %, then this space will be disqualified for LEED certificate.

Another climate-based annual illuminance metric used is UDI, which is described as a fraction of time across a daylighting study period where the illuminance at a point lies between selected minimum and maximum levels, typically 100 lx and 3000 lx [36]. By mean of that metric, it is possible to set ranges for daylight availability evaluation. In this study, a version of UDI, which is adapted to space is used. The aimed UDI UDI_a is a percentage of a space area that stays between aimed and excessive horizontal daylight illuminance for a specified fraction of time. Additionally, UDI_f refers to a fraction of a space which is failed to meet min target illuminance level, UDI_s lux refers to a fraction of a space which stays in a range of minimum and target illuminance levels and UDI_e refers to a fraction of a space which has higher level of illuminance than the defined limit values. As a combination of recommended minimum and medium illuminance levels for sDA, values of 300 lx for E_{TM} and 500 lx for E_T are set for UDI, also because the 1000 lx is used for the evaluation of ASE, upper limit of excessive illuminance E_E is set as 1000 lx.

DIN EN 17037:2019-03 [17] provides the DGP metric as an assessment of glare discomfort. The minimum recommendation for glare protection is DGP for occupied space does not exceed a value of 0.45 in more than 5% of the occupied time of a space. DGP coefficients defines the ranges from imperceptible glare to intolerable glare.

sDG is a version of DGP applied to a space and views. sDG refers to fraction of space – in other word views - that has disturbing or intolerable glare probability ($DGP_{5\%} > 0.38$) at least 5% of the occupied time ($sDG_{5\%}$). For instance, $sDG_{5\%} = 10\%$ means that 10 % of the views have a disturbing glare at least 5 % of the occupied time.

About sensor height, the reference plane of the space is at a height of 1.2 m above the ground, which represent the eye height of a siting office person. Again, the sensor spacing is set as 0.5 m, also the sensor inset is taken as 0.45 m.

Based on the daylight glare probability (DGP) patterns, specifics days and times (points in time) and views in spaces are selected and Radiance renders are created. DGP, luminance and eye level vertical illuminance (Ev) values are presented. 2500 cd/m2 is set as a limit value for luminance [37]. The camera type is a fisheye lens with opening angle of 180° is used for renders.

For the assessment of view-out, which is one of the important visual comfort indicators according to DIN EN 17037:2019-03 [17]; horizontal sight angle, outside distance of the view and the visible layers of outside environment such as sky, landscape and ground are included in the visual comfort evaluations.

E. Supplementary figures and tables for daylight analysis

Table E.1: Daylight availability and visual comfort results with and without site context

	With site context (Figure 2)	Without site context
mean DF	2.6 %	3.0 %
$sDA_{500,50}$ %	54.1 %	67.0 %
avg UDIa	24.40 %	25.5 %
$ASE_{1000,250}$	3.30 %	3.6 %
avg Lux	842	949
$sDG_{5\%}$	10.1 %	15.0 %

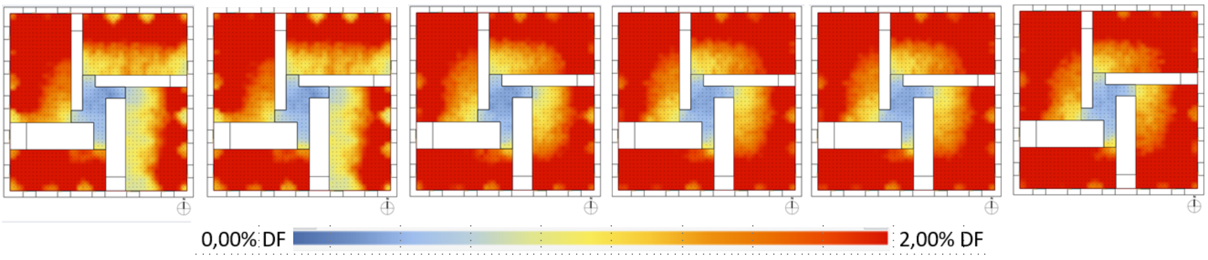

Figure E.1: Spatial Distribution of Daylight Factor for 1st floor (left) to 5th foor (right).

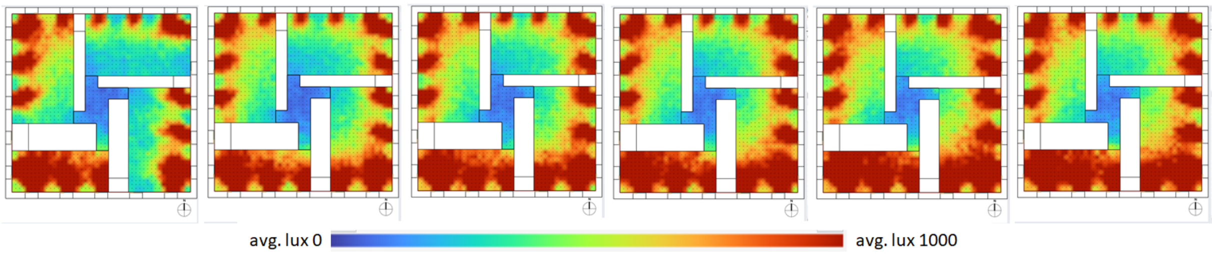

Figure E.2: Average Illuminance for 1st floor (left) to 5th foor (right).

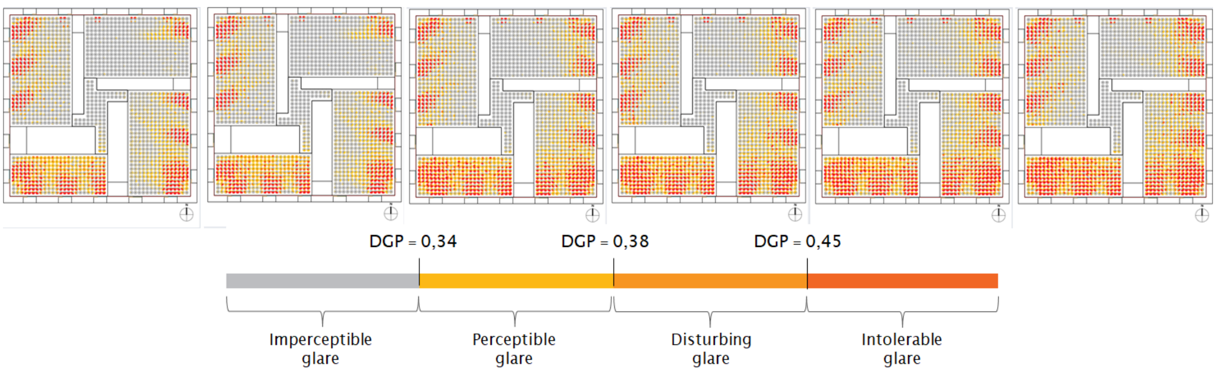

Figure E.3: Spatial Disturbing Glare for 1st floor (left) to 5th foor (right).

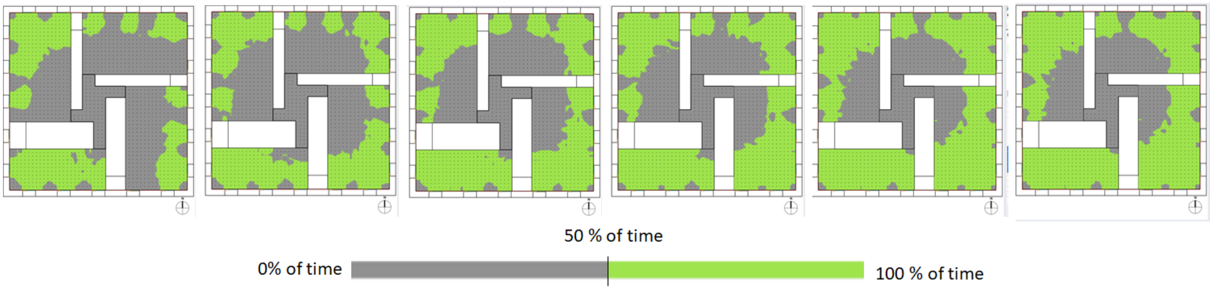

Figure E.4: Spatial Daylight Autonomy (sDA) for 1st floor (left) to 5th foor (right).

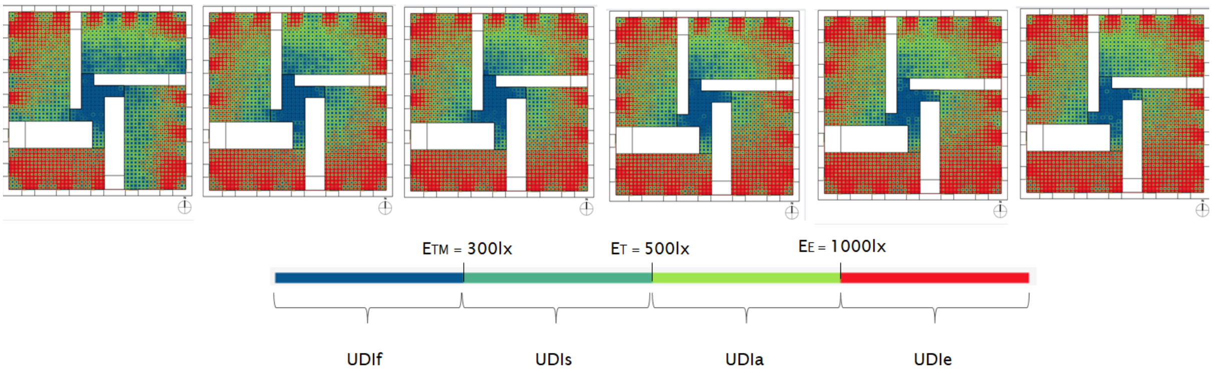

Figure E.5: Useful Daylight Illuminance (UDI) for 1st floor (left) to 5th foor (right).

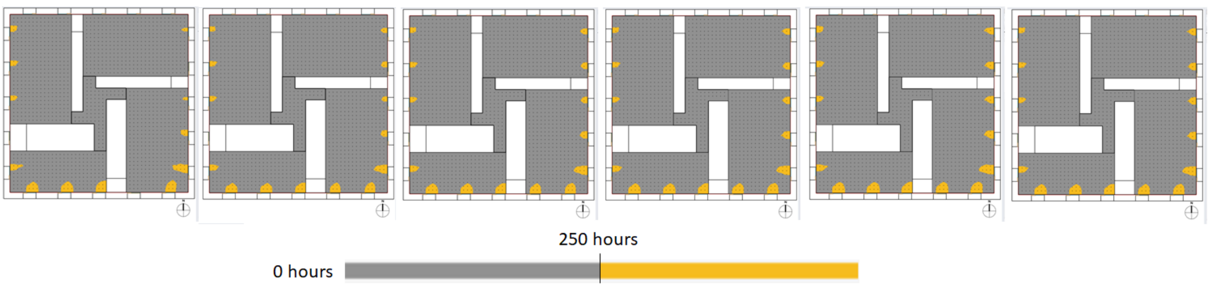

Figure E.6: Annual Sunlight Exposure for 1st floor (left) to 5th foor (right).

Table E.2: Comparison of the baseline model with and without blinds for the 3rd floor

	Baseline without blinds	With blinds
$sDA_{500,50\%}$	56.9 %	27.5 %
avgerage UDI_a	25.2 %	24.9 %
$sDG_{5\%}$	10.1 %	n/a

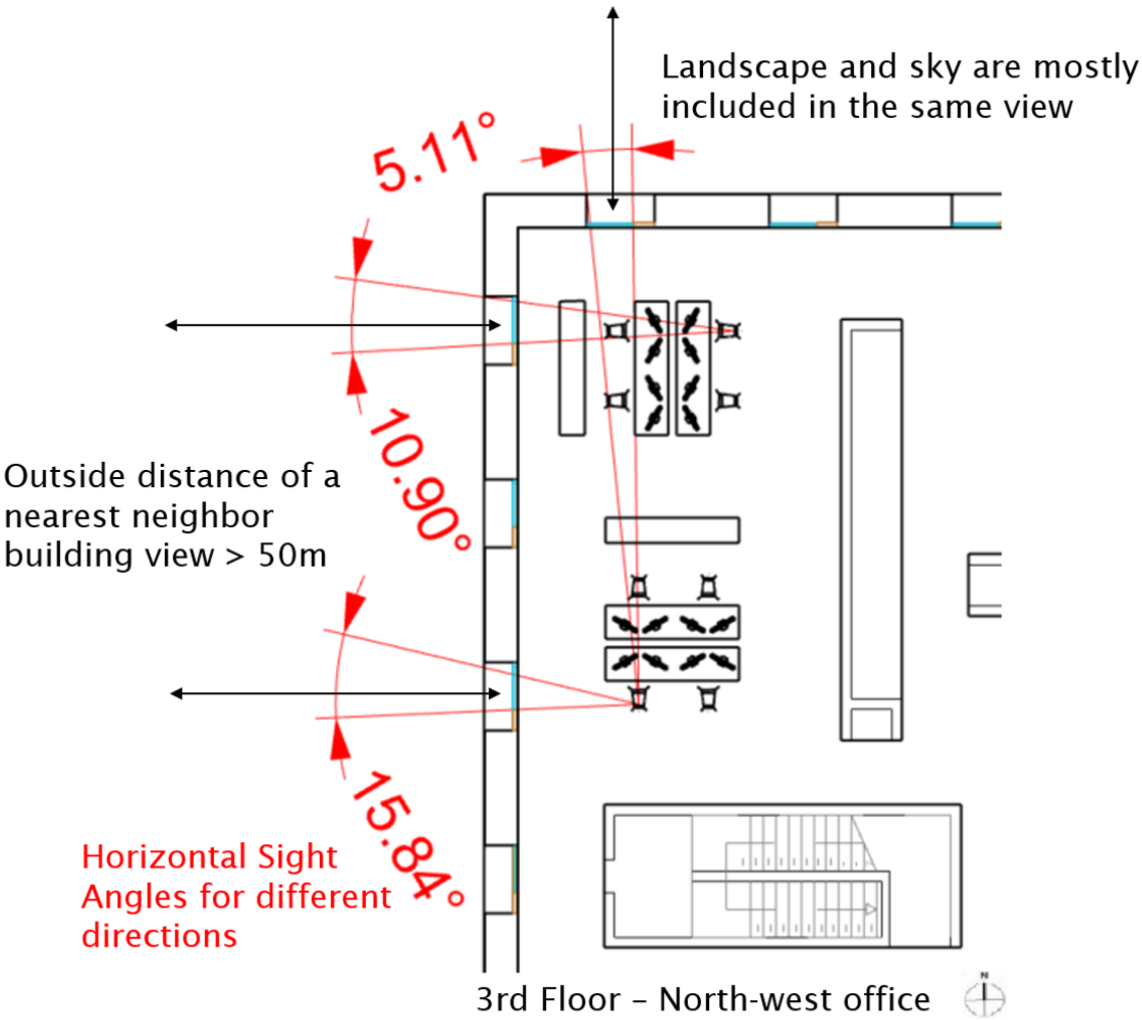

Figure E.7: View-out evaluation for the 3rd Floor Office

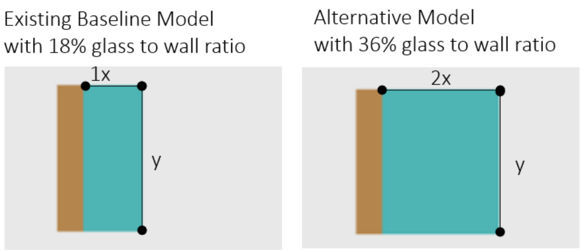

Figure E.8: Variation of the glass to wall ratio for daylight analysis.

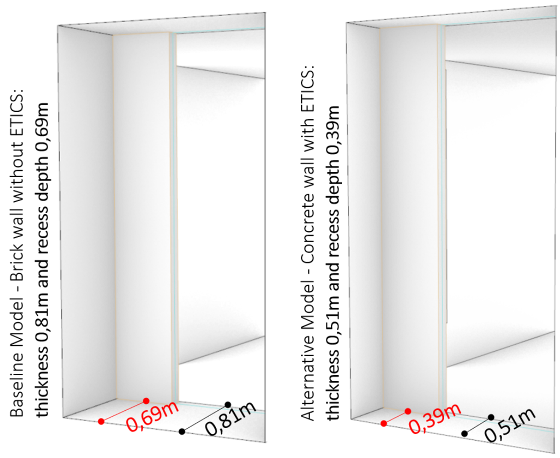

Figure E.9: Variation of the wall thickness for daylight analysis.