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CONVERGE: low energy with active passiveness in a transparent highly occupied building

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Abstract
This research gives an overview of the current comfort and energy performance, and optional future design of highly transparent and lightweight buildings. The transparent Co-Creation Centre in the Green Village at the TU Delft, has a combination of active and passive climate control measures. The aim of the research is to show how transparent buildings with a high glass/floor percentage (here 122 %) perform and how these could be optimized. An overview of the research project and system integration is presented, with the focus on energy, comfort and working of the BMS-system. Energy and comfort performances are measured and simulated. Validation has been executed of daylight, solar heat access, and thermal performances. A large Phase Change Material (PCM) buffer in the air handling unit reduces the heating and cooling demand. Making use of passive qualities of the outdoor and indoor air temperature and solar energy requires a more complex control strategy than usual. A Model Predictive Control (MPC) strategy has been investigated and can optimize the energy consumption.

Keywords. transparency, passive, PCM, ventilation

1. Introduction

Transparency is since long mainstream in architecture. However, this may lead to a higher heating and cooling load due to a lower insulation of the transparent material and its higher solar transmission. The variability of solar load also leads to an unstable indoor climate. These factors make it more difficult to use passive or active climate control strategies. The climate control system will become more complex and less robust. A high degree of transparency will also effect indoor visual comfort, due to high luminance levels and sharp contrasts between sunlit and shaded areas.

The new fully transparent building, the Co-Creation Centre, see figure 1, was erected at TU Delft, Green Village [1] in 2020. The Co-Creation Centre is both a meeting centre and a research facility. The building consists of large meeting space, with a service cabin connected to it. The meeting space is used for different functions like conferences, educational and office functions. The occupancy is extremely variable from low to very high. The large glass hall can be seen in figure 1 at the left side. The service centre with a kitchen, toilets and ICT-functions at the right side.

The fully transparent triple glazed façades are state of the art in glass engineering, the columns are even of glass. The building has large overhangs and automatic outdoor sunshades to prevent overheating. The building was initially designed for 30 people but was redesigned to hold 240 people in a meeting setting (prior to the introduction of Covid restrictions). A so-called climate tower, visible on the left in figure 1, makes sure that the building is comfortable. The building, with PV panels on the tower, aims to become energy neutral or positive, which is even better than the Dutch BENG-standard. The building is also a research facility to investigate if a transparent building could be passively heated, cooled and ventilated without loss of comfort. The building has an extensive sensor network for continuous monitoring. This paper describes the building and all its climate controls and shows the first results of the investigation.

Fig. 1 – Co-Creation Centre with blinds down and climate tower at the South-side.

2. The building and its control options

2.1 The building

The building has a limited size (315 m^2). The fully transparent façades consist of triple glazing with a U-value of 0.53 W/m^2K. The building has 34 PV-panels of 300 Wp on the climate tower, leading to 6,000 – 7,000 kWh/y electricity production per year. However, on the circa 400 m^2 roof much more panels could be installed.

In winter the building is heated by the sun through the transparent façade and by preheated displacement ventilation via the floor. Heating is provided by an air-based heat pump in the climate tower. The climate tower was originally designed as a solar chimney, but later reconfigured as a large air handling unit. The ventilation is controlled by the indoor CO_2 concentration, to minimize the amount of air changes in the heating season. A counter-flow heat exchanger further reduces the heating energy necessary for ventilation.

In summer blinds are used to reduce the solar load from the sun, see figure 1. Overhangs and trees reduce the amount of sun in summer too. A PCM battery with 1,170 panels (2,106 kg, 181 kWh) of calcium chloride hexahydrate with a phase change temperature between 20 and 23 °C adds additional cooling or heating power to building. The PCM battery can be cooled by ventilation at night and heated up by warm return air. In the cooling season skylights and doors can also be used for natural ventilation during the day and cooling at night. Extra cooling is also possible via the heat pump with return air or the ground as its source.

2.1 Passiveness

The degree of passiveness is here defined as the time of the year that the building does not need additional electricity for heating, cooling and ventilation while maintaining a comfortable indoor climate. The energy necessary for controlling the blinds and the airflow and for opening the skylights is not considered in this definition of passiveness. Several key performance indicators, such as energy consumption, indoor temperature, illuminance, and CO_2-levels are measured. Furthermore, occupants' comfort is evaluated. However, due to Covid-19 restrictions, this is only indicative at this stage of the research.

2.2 Control options

The following main control options are available:

Blind control: the blinds can be individually controlled for all four facades, to all tilt angles and to all vertical heights. Four different shading control strategies are being developed and evaluated: (a) fixed passive strategies; (b) sun-tracking dynamic control; (c) energy-based dynamic control; and (d) visual comfort-based dynamic control. The first strategy (a) is based on passive lighting control provided by fixed shading elements, such as the overhangs and the deciduous trees behind the building. Strategy (b) is based on a traditional sun-tracking algorithm, which controls the tilt of the lamellas so that they always block direct sunlight. Strategy (c) controls the blinds based on the amount of available solar energy and on the amount of heat that is required within the building at any specific moment. On a hot summer day this behaves similarly to the sun-tracking control mode, but on a colder day, the blinds are more open to let more sunlight inside and heat the building. The last control strategy (d), still in development, is controlling the blinds based on the combined requirements of preventing discomfort glare and guaranteeing a view out whenever possible. The control of the blinds is based on illuminance data read by sensors installed on the Co-Creation Centre roof and on simulation data from synchronous daylight modelling algorithms.

Indoor thermal comfort: the indoor thermal comfort is controlled by the air temperature set-point. A different set-point is chosen for summer and winter. The air temperature set-point takes also the radiant temperature of the glass into account maintaining the operative midwinter-temperature above 21 ^{o}C.

Fresh air supply: the airflow is firstly controlled based on the CO_2 concentration when the building is occupied. When the CO_2 concentration is below 800 ppm (Covid values) the airflow can follow different paths through the climate tower.

Airflow control for passive heating and cooling: the heat exchanger can be enabled between 0 and 100 %.

Exhaust air can either pass or not pass through the PCM.

Airflow control for PCM heating and cooling: the air can pass through the PCM to heat up or cool down the inlet air. The air can pass through the PCM with an airflow percentage between 0 and 100 %. This is the control strategy when the building is occupied. When the building is unoccupied or when the indoor air is within the temperature boundaries for thermal comfort, (part of) the air can pass through the PCM to heat up or cool down the PCM to store heat or cold.

Airflow control as a source of the heat-pump: a limitation is that the exhaust air is the source of the heat-pump, requiring an increased indoor and outdoor airflow to obtain enough heating power of the heat pump.

Heating and cooling via water flowing via piles in the ground: soon the heat pump will be connected to energy stored in the ground via energy piles under the building. The energy piles are able to replace the outdoor condenser and are expected to increase the COP of the heat pump significant. The cold in the ground can also cool the building indirectly without using the heat-pump.

Controlled natural ventilation: rooflights can be automatically controlled for cooling in summer. The doors can be opened manually to further increase air exchange rate. It is estimated that the building does not need HVAC for 20-30% of the year, while keeping CO_2-levels and temperatures within comfort-range.

2.3 PID and MPC

The control system includes an automatic operation mechanism to deal with the dynamics of people occupancy and heat exchanges across the building. The controller relies on the temperature measurements collected in situ and algorithms implemented to optimally follow the set of strategies presented in Section 2.2. The purpose is keeping the tracking error e (the difference between the temperatures read by the sensors and the desired value) close to zero. While several methods can be considered, a PID (Proportional-Integral-Derivative) controller has currently been implemented since it is known to be an accurate and reliable control method [2]. The PID continuously balances selected inputs (e.g. shades aperture, ventilation flow rates, and heat pump power) by a correction factor u that depends on the tracking error feedback as follows:

$$u = K_\mathrm{p} e + K_\mathrm{i} \int_0^t e\, dt + K_\mathrm{p} \frac{de}{dt} \qquad (1)$$

where K_p and K_i are control parameters tuned for the current controller.

Moreover, a MPC (Model Predictive Control) has been theoretically investigated through MATLAB simulations [3], as it shows promising results when evaluating the control performance in comparison to PID controller. With MPC, the controller draws on system models and on the SQP (Sequential Quadratic Programming) method [4] to determine the set of optimal inputs that minimize an objective function over a selected time horizon, such that:

$$\min_{\mathrm{x}} \sum_{0}^{t} \dot{q}_{\mathrm{hp}} + e^2 \qquad (2)$$

where x is the controllable input, and $\dot{q}_{\mathrm{hp}}$ the heat pump power consumption. Therefore, the MPC builds on the capability of knowing the system dynamic in advance instead of acting over sensor feedback, which is certainly helpful when dealing with different disturbances and heat capacities.

3. Methods of research and design

3.1 Set-points

The measurements are performed with dummy persons in the room to simulate the internal heat production of 30 persons. The dummy persons are spread over the room, creating a more or less realistic situation. The occupancy times are 9:00 - 17:00 h in the measurement periods. The air temperature set-points have the following values:

Tab. 1 – Set-points during the measurements °C

season	min/max occupied	min/max unoccupied
spring	20/23	15/25
summer	20/23	15/30
autumn	20/23	15/25
winter	21/23	18/25

The set-points for occupied hours are based on Category A or B of the EN 15251. Ultimately an adaptive control strategy will be implemented to reduce energy even more. Outside occupancy time temperatures may be lower or higher to save energy or load the PCM-battery.

3.2 Measurements

More than 100 sensors are used in the building and integrated in the online Priva Display website. Figure 2 gives an indication of all the sensors and controls. The sensors log measurements every 5 minutes, except for the energy sensors which log measurements every 15 minutes. Additional measurements were also manually collected to validate the simulations, besides the long-term data series recorded by the sensor network.

Weather data are measured at a weather station established on the roof of the Co-Creation Centre and by a pyranometer managed by the faculty of EWI of the Delft University of Technology. Four illuminance sensors are place on the Co-Creation Centre roof:

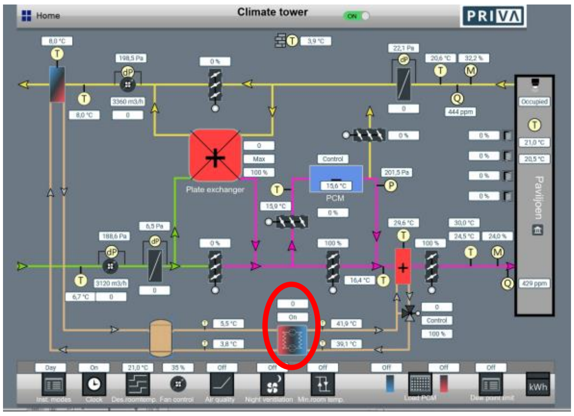

Fig. 2 – Schematic overview of the climate tower and the sensors on the accompanying Priva website. The red box in the middle is the heat exchanger, the blue box the PCM-battery and at the bottom, circled, the air to air heat-pump can be seen.

one is positioned horizontally and looks upward, while the other three are positioned vertically and respectively look towards the East, South, and West directions (approximately, as the longitudinal axis of the building is tilted of -22° from due North). The focus of this evaluation is only on the thermal and comfort achievements in relation to the energy consumption. Occupant feedback was also collected but due to Covid 19 and in this stage of the project the results only consist of random samples.

3.2 Simulations

Simulations with DesignBuilder, Phoenics (CFD), Radiance, and Matlab/Python were used for calibration and yearly predictions of energy and comfort. Also, the effect of the cooling set-point was investigated. The thermal behaviour of the PCM-battery is predicted via a CFD- (Phoenics) and MATLAB-model. These models are discussed in more details elsewhere [5].

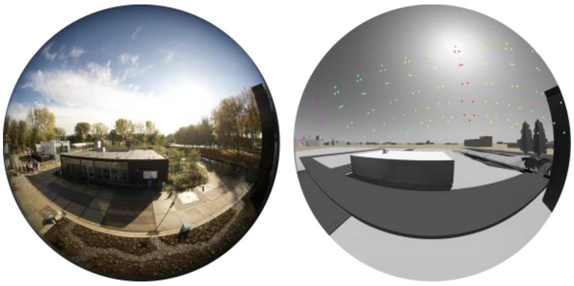

Fig. 3 – Fisheyephotograph taken from the viewpoint of the South facing illuminance sensor (left) and virtual reconstruction of the same scene used for Radiance simulations (right).

Radiance was used to simulate the illuminance reaching of each of the four outdoor illuminance sensors, as a first step towards the validation of the blind control algorithms. This step allowed the quantification of errors due to the luminance distribution model used within the simulation (Perez All-Weather) and to the modelling of the environment surrounding the Co-Creation Centre.

4. Results

4.1 Measurements

Measurements with the same internal heat over two weeks in spring, summer, autumn and winter are executed. The exact period of measuring was depending on the availability of the building.

Summer temperatures

Measurements in the summer period are presented in figure 4. The set-point for the maximum temperature was 23 °C during working hours. The minimum temperature set-point was 15 °C. The highest indoor temperatures are in the weekend, without occupancy.

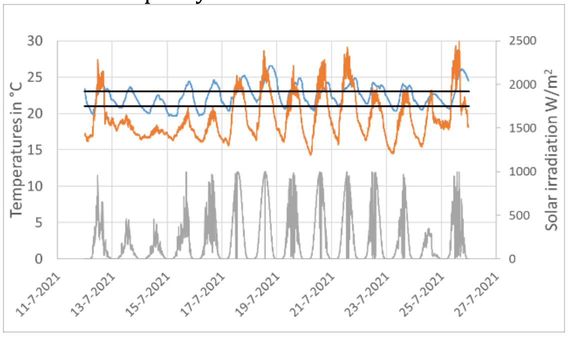

Fig. 4 – Measurements 12 – 25 July 2021. The line at the top is the indoor temperature (blue) and in the middle, the outdoor temperature (orange). The lower line is the solar irradiation (W/m²). The two black lines are the boundary conditions for occupied weekdays.

Occupants last summer often experienced the space as "too cold" suggesting that the cooling set-point of 23 °C could be higher.

Autumn temperatures

In autumn, the temperature drop between day and night is only around 3 °C, see figure 5. The blinds are mostly closed, but the blind settings were not optimized at that time.

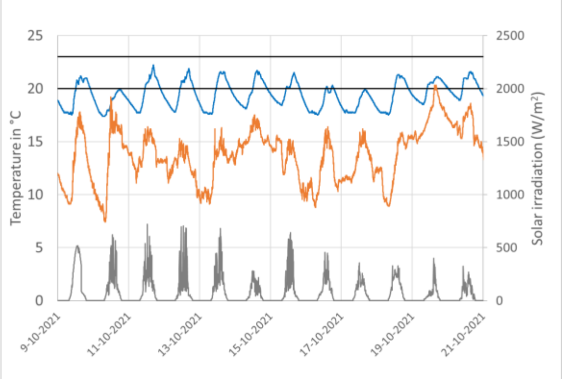

Fig. 5 - Measurements 9 – 21 October 2021. The line at the top is the indoor temperature (blue) and, in the middle, the outdoor temperature (orange). The lower line is the solar irradiation (W/m²). The two black lines are the boundary conditions for occupied weekdays.

The building is heated by the heat-pump, as shown in figure 6. Here the air temperature of the air coming from the heat-pump is shown to reach 35 °C.

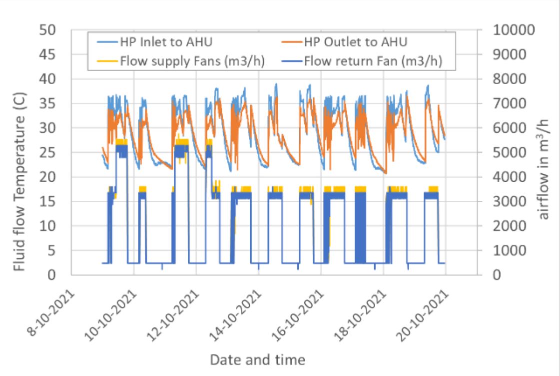

Fig. 6 - Autumn measurement period (9 – 21 October). The fluid flow temperatures (around 35 °C) to and from the heat-pump to the heat exchanger (HP inlet and outlet to AHU) which heats up the air to the room and the air flows via the fans (m^3/h) are presented.

The air flows (3,000 to 5,500 m^3/h) are very large for the limited simulated amount of people (30) inside, see figure 6. With 30 m^3/h per person, 900 m^3/h would have been sufficient.

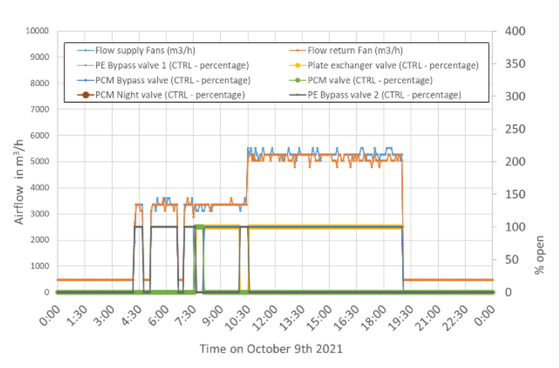

Fig. 7 – Control actions on October 9th.

In the following section some initial problems with fine-tuning of a complex climate system are presented. The measurements in figure 6 show an airflow of more than 3,500 m^3/h in the early morning. In more detail, see figures 7 and 8, on Saturday October 9th the building valve opens at around 4:00 a.m. when the inside temperature is below 18°C. This is caused by the heat-pump only working when there is an air flow. At 4:00 am the temperature of the airflow from the heat-pump (supply temperature) rises when the heat-pump starts to work. The heat-pump tries to keep the indoor temperature above 20 °C within the occupied time, i.e. from 7:30 h (figure 8, yellow line in the middle). Under the night setting, when the building is unoccupied, the heat exchanger was not used. As a result, the heat-pump needs to heat the cold outside air instead of air preheated by the heat exchanger. Figure 7 shows that during occupancy, i.e. from 7:30 onwards, the heat exchanger is active except for the short period when the airflow rate increases, around 10:00. Figure 8 shows the measured temperatures as a result of all the control actions shown in figure 7. The stored heat in the PCM is only checked at the start of the day for the 9th of October but is not actively used. The PCM temperature is slightly higher than the average outside air temperature.

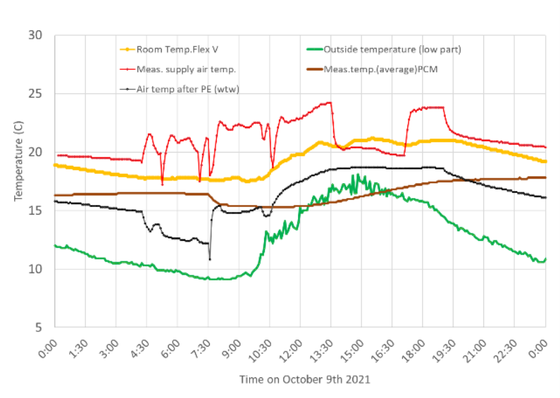

Fig. 8 - Temperature measurements at 9th October.

Another not yet logical control setting is a combination of using the heat exchanger first to load the PCM with internal heat, making this less efficient (not visible in these figures).

Winter measurements

Measurements of the heat-pump for a whole year show a total electrical energy consumption for heating and cooling of 12,700 kWh (40 kWh/m^2), excluding the energy for the fans in the condenser. The energy consumption is expected to become much lower once the ventilation is optimized and the ground storage is connected to the heat-pump.

Noise

A disadvantage of the current design is the choice of a high efficiency fan with a too small diameter. The diameter of the fan is 0.31 m, whereas a 0.62 m diameter and a maximum velocity of 10 m/s would be more appropriate for a low pressure and low noise system. The maximum velocity in the fan is 37 m/s at 10,800 m^3/h with a measured pressure difference of 2,000 Pa. The noise level, based on manufacturer data, is 87.6 dB(A) at 8,000 m^3/h. On top of that there is an Aeolian sound effect caused by one of the ventilation grilles. An air flow of circa 6,000 m^3/h produces circa 52 dB(A) at 49 m distance outside, whereas the Dutch Building Code requires 40 dB(A), and 37 dB(A) within the building. 6,000 m^3/h should already be sufficient for the high maximum number of 240 occupants.

Solar access results

Global horizontal irradiance is recorded by a commercial pyranometer installed on the Co-Creation Centre roof. Measurements collected by this device were compared to irradiances measured by a research-grade pyranometer installed on the roof of one of the nearby campus buildings. Figure 9 shows the correlation between the two datasets, for measurements collected during the July test weeks. The bias error is zero, indicating a good agreement between the two instruments overall. However, there is a noticeable scatter ($R^2=0.72$) and a relative Mean Absolute Error (rMAE) of 22%. Measurements recorded during high sun altitude instances seem to be particularly affected by errors and under-prediction.

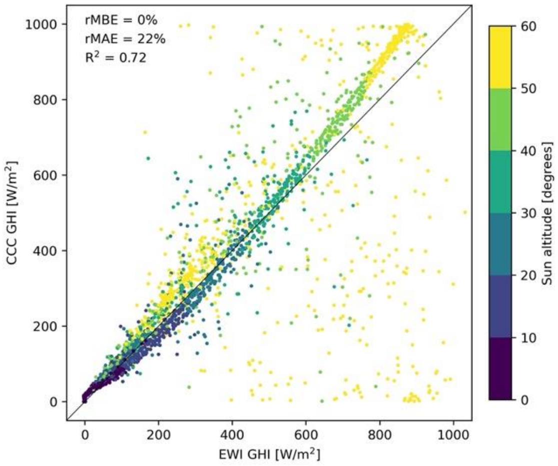

Fig. 9 – Scatterplot showing the correlation between Global Horizontal Irradiance (GHI) values (in W/m^2) recorded by a research grade pyranometer on a building on campus (EWI) and by the commercial pyranometer installed on the CCC roof.

4.2 Simulations

DesignBuilder-simulations

For the DesignBuilder calibration simulations and the yearly energy demand the 2021 data of the weather station of Rotterdam Airport has been used, as provided by the KNMI [6].

Heating Season (winter)

DesignBuilder simulations of the winter show that the temperature is allowed to drop to as low as 10 - 12 °C at night. Even with a low heating capacity of 15 kW and heating starting 3 hours before occupancy time, the required comfort-temperature can be realized. The large diurnal temperature drop shows a potential weakness of the concept of a lightweight building with fully glazed facades. In buildings with sufficient thermal mass and a limited glass percentage the diurnal swing in winter would only be several degrees, whereas the Co Creation Centre can reach a 10 °C temperature drop. The air-to-air heat-pump should - after optimization - lead to an yearly energy consumption for heating of minimal 6,500 kWh/y (20 kWh/m^2y) with a COP of circa 2. However, this COP-value will become much higher with a COP of circa 5 with a connection to the storage in the ground in combination with an efficient running PCM-battery (COP > 27 [5]). Simulation results shows that most of the heating is provided by the sun. In order to reduce the heating energy more, a façade with 30 % glass, combined with an opaque part with a U-value of 0.2 W/m^2 would lead to a thermal heating energy consumption of only 5,000 kWh instead of 13,000 kWh, with almost the same usage of electrical lighting energy (70 kWh above 1030 kWh). A transparent design with adaptive façade isolation could be a future option.

Cooling Season (summer)

At a cooling set-point of 26 °C and a low average occupancy of 30 people (9:00 - 17:00 h) the simulated thermal cooling energy consumption is only 300 kWh/y. Due to the low g-value of the glass with outside louvres (design value g=0.03), a large overhang and trees on the West-side, the solar transmission in summer is very low when the louvres are down. This prevents overheating.

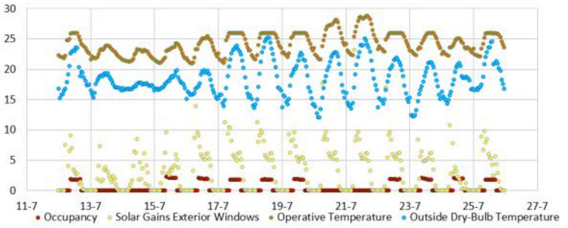

Fig. 10 – DesignBuilder simulations for 12 – 25 July. The cooling set-point is 26/27 °C (adaptive range Category C). The operative temperature is shown at the top with the outdoor temperature below that line. The solar gains are low in summer: maximal circa 10 kW, due to usage of the blinds (circles at the underside). The dark line below those circles is the internal heat load. The left axis shows temperatures or kW's.

Cooling set-points

The energy-consumption for heating remains almost the same, so choosing a higher set-point is energy-efficient. The cooling load due to the sun in the cooling season is around 50 % lower due to a full row of high trees at the West-side, see figure 1. Most of the heat loss is caused by transmission through the 5 m high triple glazing with a U-value of 0.53 W/m^2K. The CO_2-level based ventilation (a maximum of 1200 ppm only at very low outdoor temperatures) is, apart from the isolation of the glass, the most relevant parameter to reduce the heating energy. The limited heat loss through ventilation explains the fact that, without a heat exchanger, the thermal energy consumption increases only from 45 to 54 kWh/m^2. In table 2 the results of DesignBuilder simulations are presented. The set-points for cooling have almost no effect on the discomfort hours that comply with the EN 15251 Category C.

Tab. 2 – Set-points, thermal energy and comfort*

Set-point cooling	Cooling Energy kWh	Heating Energy kWh	Hours Cat. C EN 15251
26 °C	300	13,116	7,5
25 °C	1,078	13,078	8,0
24 °C	3,165	12,916	5,5
23 °C	3,565	12,809	5.5

*The blinds go down at an inside temperature above 21 °C, combined with a solar tracking-mode of the blinds. There are 30 persons inside, Mo – Fri from 9:00 - 17:00 h. The CO_2-level is maximal 1200 ppm.

The simulated amount of energy that can be stored in the PCM-battery is 181 kWh for one load. When 1200 kWh = 600 sunny hours of 20 kW could be delivered in the heating season in the simulated year of 2021 (see table 2) the heat-pump would not be necessary. However, in the months November till the end of February there is not enough sun at all times. The heat pump still has to run to compensate for the sunless days as can be seen in figure 11:

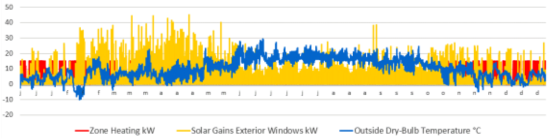

Fig. 11 – DesignBuilder-simulations of the whole year. The set-point for cooling is 26/27 ºC (adaptive range Category C). Red = heating load (kW), yellow solar load and blue outside temperature. The left axis shows temperatures or kW's.

The operative temperature is not presented here but is at least 20 °C during occupancy. The solar gains are high in the heating season, maximum circa 40 kW, the number of leaves on the trees is then decisive.

Radiance simulations

As shown in figure 12, the simulations performed for the outdoor illuminance sensors resulted in relatively small errors (relative Mean Bias Errors, rMBEs, lower than 7% and rMAEs lower than 27%). except for the West looking sensor.

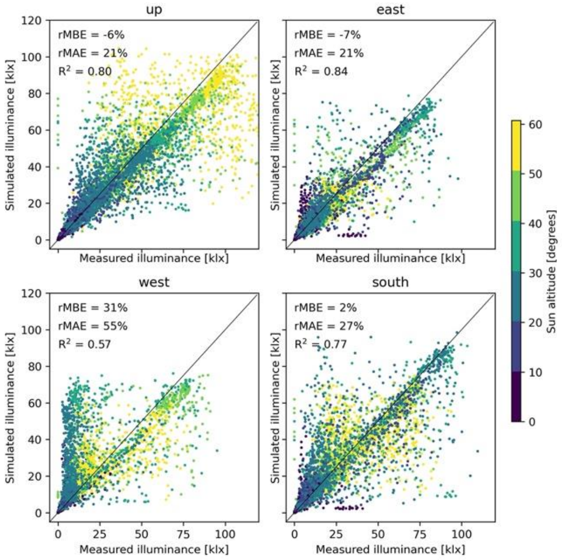

Fig. 12 – Scatterplots showing the correlation between measured and simulated illuminances for the four roof sensors. The points colour indicates the sun altitude at the time of measurement.

Such sensor is significantly obstructed by trees, a challenging element for the correct modelling of the environment. During the middle of the day errors are less pronounced but simulation results are characterised by more frequent fluctuations than measured values. To exemplify the role of obstructions on results, figure 13 shows measured and simulated illuminance data for a clear sky day within one of the test periods (July 18th 2021). It can be noticed that for low sun altitudes (morning and evening) the obstructions on the horizon lead to more discrepancies between measurements and simulations, especially noticeable for the East and West looking sensors. These might be due to the luminance distribution model implemented in the simulation.

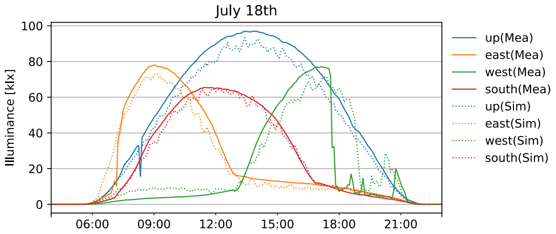

Fig. 13 – Example of illuminance data recorded by the four roof sensors (solid lines) and corresponding results from the simulation (dotted lines), during a clear day (July 18th). The results for the west looking sensor are affected by nearby obstructing trees.

5. Evaluation

5.1 Overheating?

At the start of the project, it was expected that overheating would be a major problem, but due to a very effective sunshade, the opposite is true and reduction of heat loss via the façade and ventilation needs more attention to reach the goal of delivering an almost passive building.

5.2 All air system for a fully glazed system?

The indoor climate is based on an all-air system-principle. Even though this is often seen as too energy-intensive, for buildings with a low heating and cooling load this is a realistic option again. The building has displacement ventilation via perforated tiles under the carpet, making the contaminant removal efficiency favourable as well. A comfortable climate for 240 occupants was a main design starting point, which could be realized. For the default usage with a number of 30 persons a much lower air flow (≥ 750 m^3/h) will be already sufficient.

5.3. Heating using an air-based heat pump

In the current design the air flow is connected to the heat-pump which uses the return air as a heat source. The heat-pump requires a minimal air flow of circa 3,400 m^3/h, which is circa 1/3 of the ventilation capacity. It is also more difficult than expected to heat up the building because of the low capacity (surface) of the heat exchanger in the supply air. The building makes use of a low-pressure cross flow heat exchanger with a high efficiency of 93 %. According to DesignBuilder a reduction of heat recovery efficiency from the current 93 % to, for instance, 70 % for a twin-coil would have limited effect on energy consumption. A twin-coil could be an option for a design substantially based on buoyancy forces.

5.4. *Climate Tower*

The usage of the natural pressure difference (buoyancy) is very limited within this design because fresh, but cold, outdoor air enters via the top of the chimney and leaves the building at ceiling height. The original design was based on a low position of the air inlet at floor level and exhaust at the top.

5.5 Energy and visual comfort

With high outside temperatures a high solar load is unwanted. When the outside temperatures are low a higher solar load inside will reduce the heating load of the heat-pump. A high glass percentage produces contrast differences giving the occupants the feeling that there is insufficient light in the centre of the building which leads to occupants turning on the artificial lighting [7]. This effect is increased by the black and grey colours of the ceiling and floor. The dark colours also reduce the reflections of the floor, blinds and ceiling, making the lighting less efficient. On top of that, with closed louvres a spectacular "mausoleum"-effect is created. An entirely different atmosphere can be created with lighter colours and natural materials as can be seen in the house of Philip Johnson and the Barcelona gallery of Mies van der Rohe. At high wind-velocities the outdoor sunshade cannot be used so indoor sunshade will shortly be added to prevent glare and this could make the interior less dark. The mausoleum effect can also partly be compensated by opening louvres in a strategic way, i.e. opening the blinds at the sides where the sun is not shining or only blocking only the direct solar beams. The combination of lighter colours and a smart control in DesignBuilder reduces the electrical energy for lighting (> 300 lux, 3 W/m^2 LED) from the measured 3,500 kWh to 1,000 kWh.

6. Conclusion and recommendations

It should be possible to design a lightweight fully glazed building with an acceptable to good visual comfort, which can be energy positive against a limited amount of solar panels. At the moment the heating energy is too high, but this is probably due to unnecessary ventilation at the start and an unconnected energy storage in the ground for the heat pump. On top of that electricity consumption for lighting is much higher than expected.

A building with a lower glass percentage would lead to less heating and cooling energy, lower investment and maintenance costs and an easier to realize good visual comfort. This also depends on the glass-floor ratio, window-height and thermal mass, so there is no final answer.

Architects need to have very good reasons to design fully transparent buildings and in some circumstances these are realistic. Partly transparent buildings, where transparency is an added value on strategic locations, is often a better choice [8, 9]. A comparable building-design with a more limited heat loss could have, for instance, even better isolating glass or screens at the in- or outside. In order to realize an even better energy positive building with a good thermal and visual comfort, optimization of all components need more attention. Additional options are: reduction of resistance of the ventilation system, using buoyancy, a modulating heat-pump, a larger heat exchanger for air supply and a light-coloured interior. Complexity reduction of the installations and a more user-friendly control system (BMS) are other connected relevant issues for sustainable transparent designs of the future.

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The datasets generated during and/or analysed during the current study are not available, because it requires specific data-acquisition rights and skills, but the authors will make every reasonable effort to make them available in the near future.