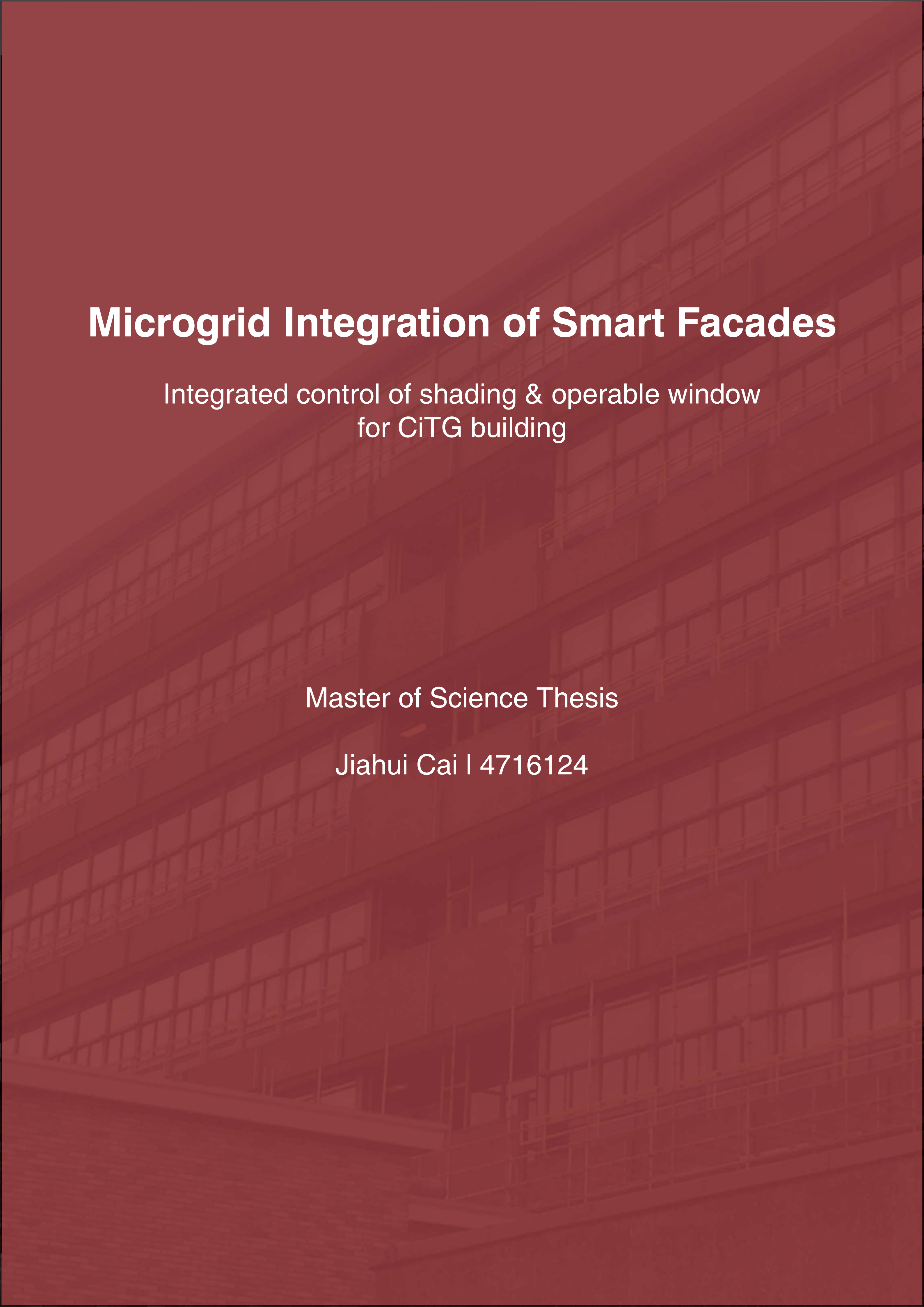

Microgrid Integration of Smart Facades

Integrated control of shading & operable window
for CiTG building

Master of Science Thesis

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Microgrid Integration of Smart facades
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Acknowledgement

During the study of Building Technology, I gained an interest in facade and climate design. For my final practice, I’ve chosen ‘Microgrid Integration of Smart facades’ as my graduation topic, in which I developed a control strategy for the east facade of CEG building. During the entire process, from research, concept forming to final design, I gained more insight to how the control could facilitate better thermal comfort and energy efficiency, understood more about how the use of computer program aided to the design and its limitation, as well as learned more about the facade industry development.

Here, I would like to express my gratitude to my teachers Juan F. Azcárate-Aguerre, and Peter van den Engel for guiding me during the entire process of the graduation thesis. Also many thanks to Tillmann Klein, Truus Hordijk and Willem van der Spoel for providing advice and help for my design problems.

Abstract

This project aims to design the integrated control of shading and operable windows for CEG east facade to improve the thermal comfort with respect to energy consumption.

The design stage focused on the thermal advantages that the integrated control of shading and operable window brought to the CEG building. The controls are simulated in the EnergyPlus engine with DesignBuilder interface. The output data of temperature distribution and heating demand of the two proposals were used to compare for choosing the best control strategy during the operating stage. One proposal was using the old glazing materials and the other one was replacing the whole facade. After choosing the final solution (new construction), the effectiveness of shading and operable window control, the visual and ventilation performance of the integrated control, the possible energy deviation, the design refinement were conducted.

The final control had a total discomfort occurrence of 39.5 hours, heating demand of 36.10kWh/m2 and lighting demand of 11.17kWh/m2. Compared with the simulation of the existing situation with new construction, it reduced 79% of discomfort hours and 38% of heating demand.

Content

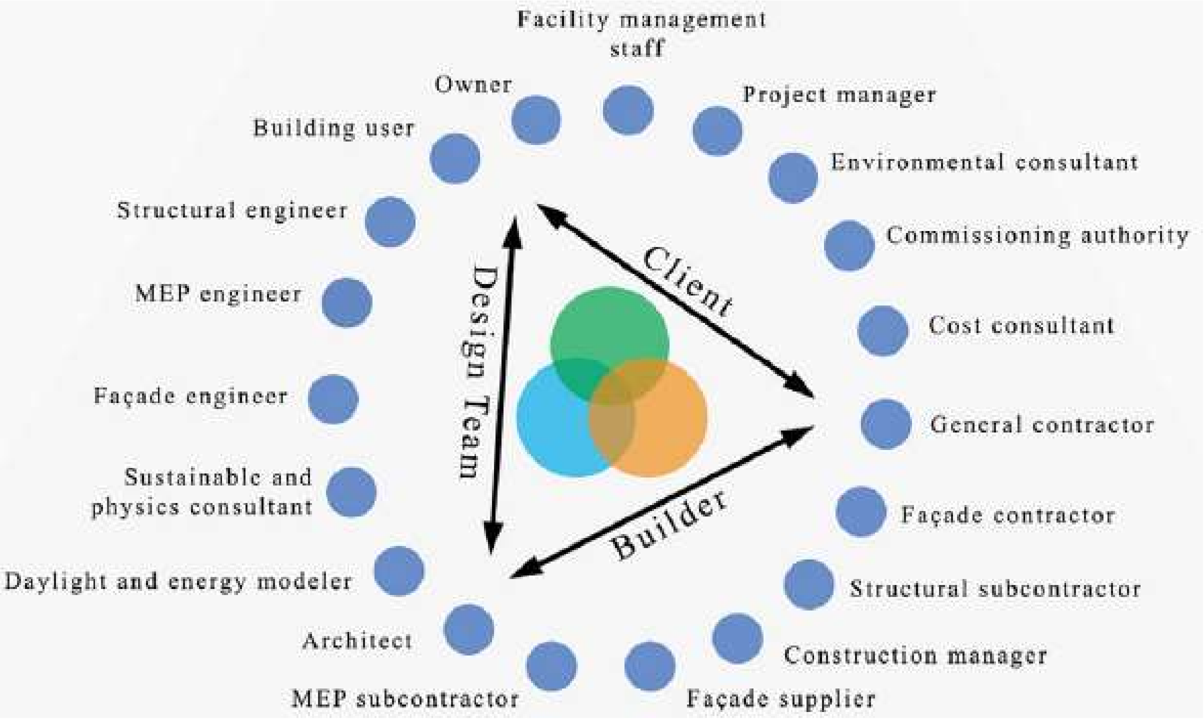
Introduction

1.1 Smart facade

By the innovation in materials, components and systems, smart facades (SF) can deal with the changing climatic conditions, concerning energy saving, energy harvesting and thermal comfort. Among them, the idea of integrating building services into facade, has come out since 1970s, which includes ventilation, heating, cooling, lighting and shading, automated windows and PV cells (Klein, 2013). However, the application of SF is not widespread due to the conflicts existed in these three aspects, façade delivery and operation stakeholders, multi-disciplines of facades and buildings, as well as facades operation objectives (Attia, 2018).

Figure 1. Generic stakeholder for smart facade

source: (Attia, Bilir, et al., 2018)



The realization of micro-grid integration, Internet of Things and Industry 4.0, is alleviating the conflicts and enhancing the communication in designing, constructing and operating phrases of SF, which could lead to the increase of the intelligent in SF and building system and the decrease of the cost in its life cycle. Under this context, to benefit from SF in the operating phrase, an optimized control strategy plays a significant role. In terms of it, there are two challenges.

First, a large portion of researches focuses on the façade's performance in terms of materials. Fewer evaluations were on the component level and rarely on the building level. For example, EN 13830 prescribes the performance expectation of facades but only focuses on calculation methods in individual function instead of addressing SF on facade system or building level (Attia, Bilir, et al., 2018), which may generate conflicts between different functions and between the collaboration with the building system. Therefore, different functions of SF, should be designed and controlled holistically with the building system to optimize the indoor comfort and the energy consumption by heating, cooling, lighting and ventilation.

Second, the automatic control of SF and user feedback are also conflicting in many cases. In one hand, facility managers control the building systems to ensure general good indoor environmental quality (IEQ) and to achieve high energy efficiency, and on the other hand, building occupants are seeking localized control for their personal preference (Attia, Luna Navarro, et al., 2018). The conflict may be possible to be solved by combining manual and automatic control, in a way that increases the effectiveness of control systems and allows more flexibility for personal control.

1.2 The CEG building

The faculty of Civil Engineering and Geosciences(CEG) in Delft University of Technology was designed by Van den Broek and Bakema and built in 1970s. It has a length of 260 meters and an area of 66600m2.

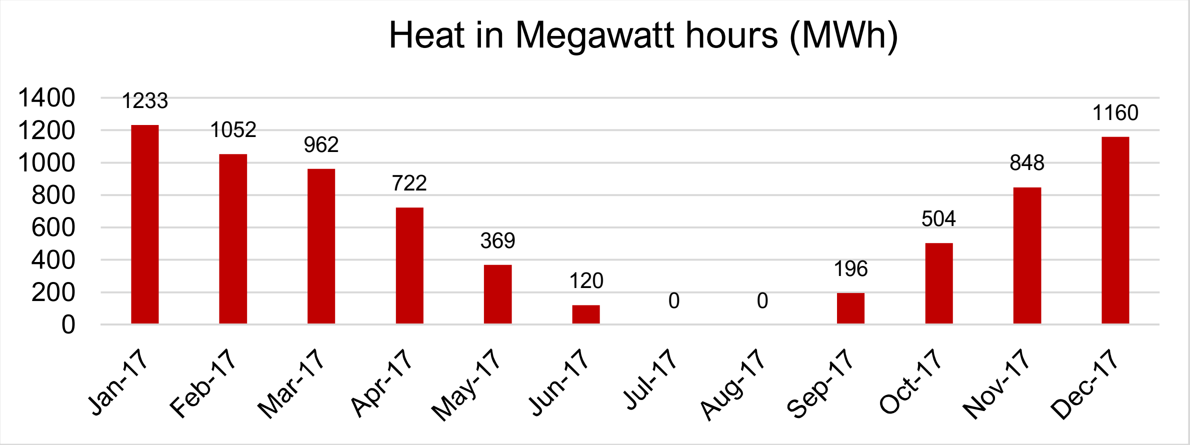
Figure 2. Impression of CEG (West side)

source: https://www.tudelft.nl/citg/

From the second floor to the sixth floor, the rooms on the west and east side are mainly used as offices. Inside those rooms, there's no fresh air system, air conditioning and mechanical ventilation. So the rooms only have natural ventilation using the manually operable window. Besides, the rooms have radiators with thermostatic valve or standard value for the heating system. The water temperature in the heating system depends on the outdoor temperature and the ambient temperature measured in four rooms in the building. Referring to the campus 'Energy Monitor', the heating consumption was 107.60kWh per square meter in 2017(Figure 3), which was relatively high compared with BENG (50 kWh/m2) (BENG, 2012).

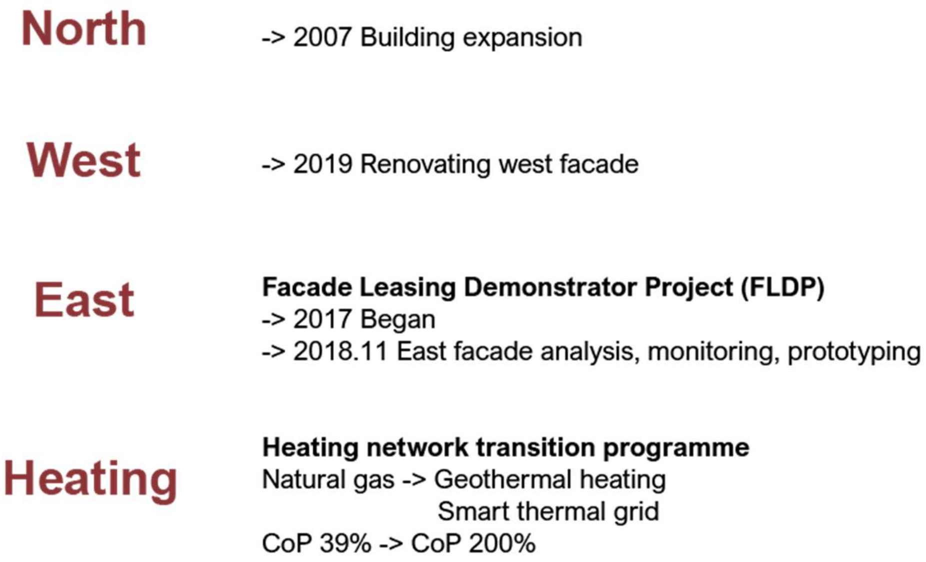
Figure 3. Heating consumption of CEG in 2017.

Source: http://emonitor.tudelft.nl/index.php/portfolio/23/



Considering the energy consumption and comfort are not fulfilling today's requirements, several projects are underway or done at this faculty and in its surroundings. The north expansion of the building was built in 2007 and the west facade is under renovation nowadays (Figure 2 & Figure 5). The 'Heating network transition' programme is implementing in CEG, in which a smart thermal grid will be developed and prepared for the connection to sustainable sources like geothermal energy.

Figure 4. Renovation project brief



North	-> 2007 Building expansion
West	-> 2019 Renovating west facade
East	**Facade Leasing Demonstrator Project (FLDP)** -> 2017 Began -> 2018.11 East facade analysis, monitoring, prototyping
Heating	**Heating network transition programme** Natural gas -> Geothermal heating Smart thermal grid CoP 39% -> CoP 200%

Figure 5. West facade in shading condition

Source: http://emonitor.tudelft.nl/index.php/portfolio/23/

For the east facade, Another programme called Facade Leasing Demonstrator Project (FLDP) has been conducted since 2017 for future retrofit. In 2018, the project team installed a monitor system (OfficeVitae) from the second floor to the sixth floor and a facade prototype inside one of the rooms. The facade analysis is conducting these days with TU Munich.

- The east facade

The east facade was unobstructed since the surrounding buildings' heights were low (Figure 6). A 0.75m concrete overhang and a manually operable internal shading were installed. The existing east facade panel consists of a frame with U-value of 2.2 W/m2K, single glazing with g-value of 0.81 and U-value of 5.42 W/m2K.

Figure 6 East facade context

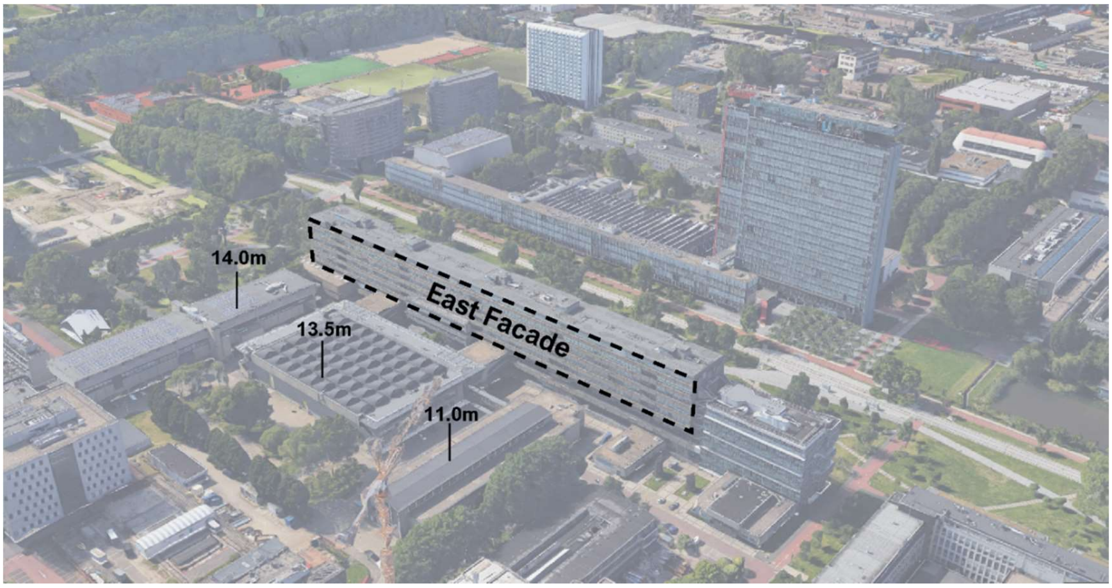


Figure 7. The east facade


(a) Look from inside

(b) Look from outside
Source: (Azcárate-Aguerre, Klein, & Heijer, 2018)

Figure 8. Available control of the east facade

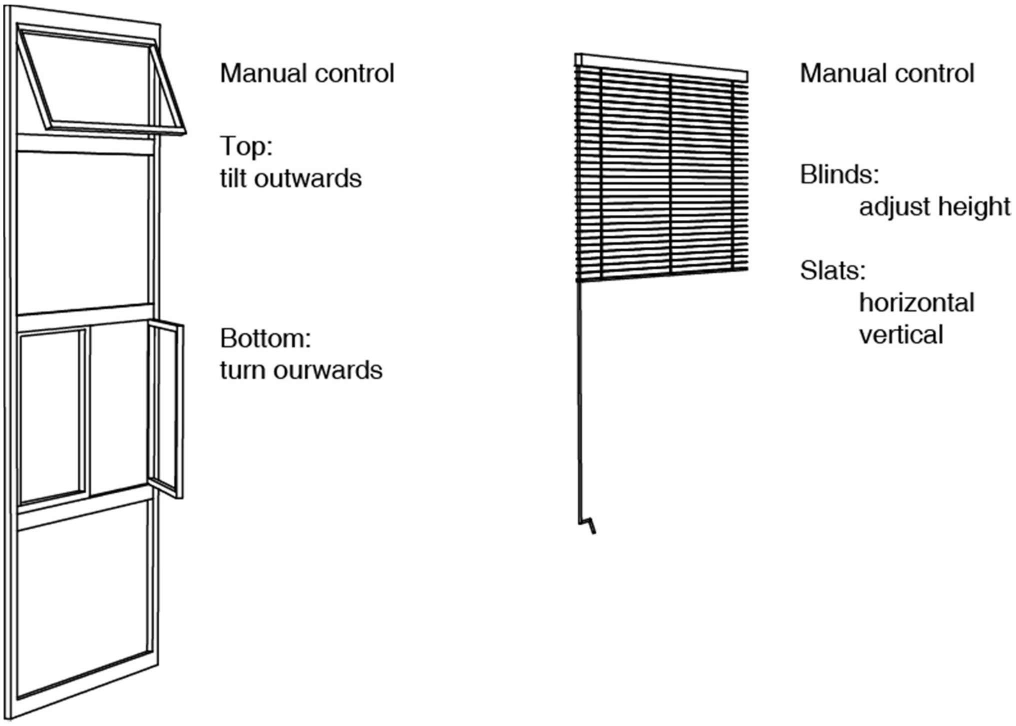


Figure 9. Shading of the east facade

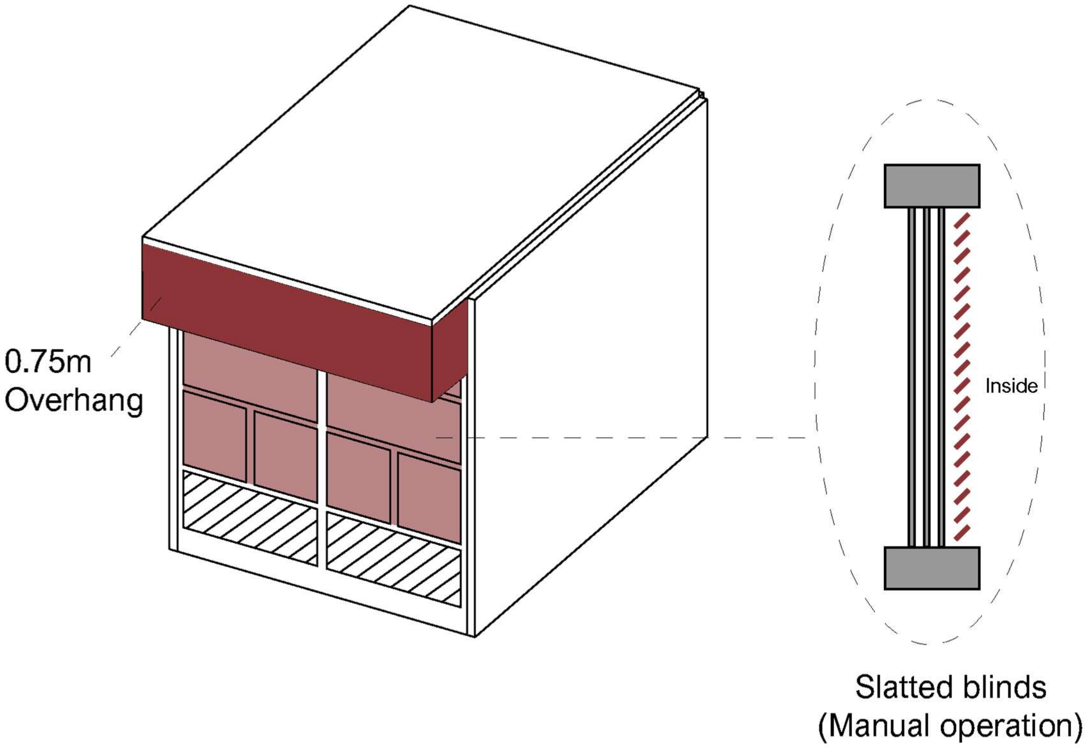
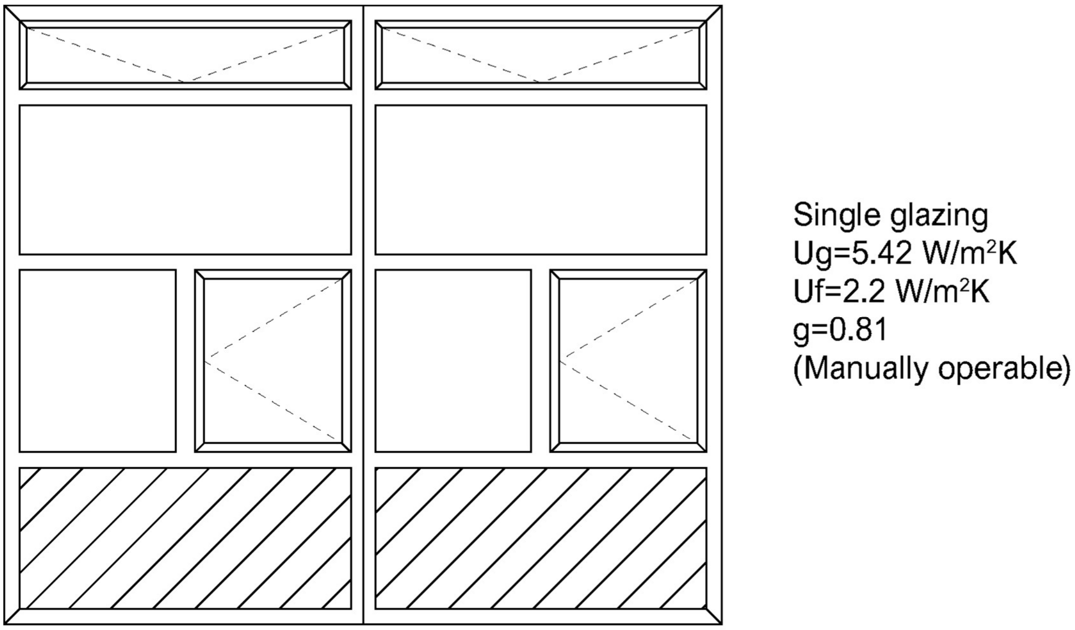


Figure 10. Existing facade configuration



1.3 Problem statement & Objective

The integrated control of smart facade has great potential in indoor comfort and energy efficiency. The CEG east facade has poor thermal performance and energy consumption, which is considering to be replaced by the proposed facade panel. The problem is:

The CEG east facade has poor thermal performance and energy consumption and needs a solution to fulfill the indoor comfort requirement.

The goal of this project is to design the control for the integration of shading and operable windows in CEG east facade to maximize its contribution to the indoor comfort. The energy consumption of the control strategy should be evaluated.

1.4 Research question

The integrated control of smart facade for maintaining visual comfort, thermal comfort and air quality has a great impact on user's well-being and productivity. With the drop of the cost, automated control of solar shading and window openings would have more and more advantages in sustainable development. Proper control of the automatic operable windows and shading, it could represent better lighting, ventilation and less energy demand for lighting heating and cooling.

As for CEG, the main research question is:

- **How can the integrated control of smart facade contribute to the indoor comfort for the east of CEG?**

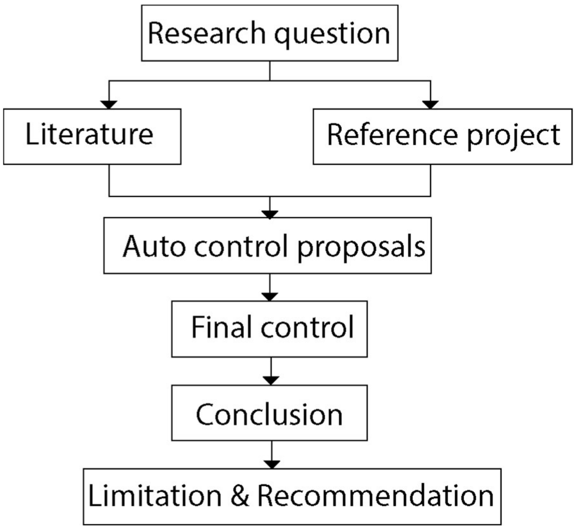
The proposed facade panel by FLDP has solar shading and operable windows for integrated control. The rooms attached to the east facade of CEG mainly are offices.

The following sub-questions are based on the preset functions.

- **What are the factors that influence office indoor comfort related to solar shading?**
- **How to control solar shading for the sake of indoor comfort?**
- **What are the factors that influence office indoor comfort related to operable window?**
- **How to control operable window for the sake of indoor comfort?**
- **How can the shading and operable window control be integrated to reach the most effective for CEG?**
- **What is the energy impact of the design solution?**

1.5 Approach and methodology

Figure 11 Research process



- General research:

At this stage, the research methods were desktop research and discussion with Juan F Azcárate-Aguerre and Jens Böke. After choosing the general topic ‘Micro-grid Integration of Smart facades’, to narrow down the research topic and finalize the design objective, the research focused on the current development of smart facade, including facade integrated technology, prototypes and applications, existing problems in different aspects.

- Research for design

At this stage, detailed research was based on the research question and the design objective. The methods were desktop research, case study and site visit. Theories and control strategies on shading and natural ventilation in office facade were conducted followed by case studies, which were the reference project for the design.

- Design

After setting up the environment condition and the basic facade input, simulations would be built step by step to optimize the control strategy (to fulfil the design requirement, mainly thermal comfort). Therefore, the uncertainty in the outputs can be allocated to uncertainty in the inputs of the process models. After choosing the final control from different proposals, the performance of the final control and the refinements were added to complete the design.

Literature

2.1 Indoor comfort criteria

This section would focus on the comfort criteria in terms of office shading and operable window control.

2.1.1 Solar shading

- Illuminance (E)

  Illuminance describes the amount of light on a surface which used as a reference measurement of the performance of a lighting system as related to the activity (Designing Buildings Wiki, 2017). Typically for work-plane illuminance, it means the illuminance on a work surface which normally is 0.8m above the floor. The Illuminance requirement for office is summed up in Table 1.

Table 1 Work-plane illuminance recommendation for offices

Source	Value [lux]	Note
EN12464-1	100-300	Computer based task
	200-600	Paper based task
	1280-1800	Maximum values
CIBSE	< 500	Office with Vider Display Terminals
	1500	Maximum value

- Useful Daylight Illuminance (UDI)

  UDI is retrieved by computing the percentage of occupied hours that daylight illuminance on the work-plane falls within certain bounds (Loonen, R.C.G.M, 2018). As shown in Table 2, illuminances between inferior limit and autonomy value are considered supplementary which need artificial lighting, illuminances between autonomy value and superior limit are considered autonomous which are useful but might be too bright at some times. (Rodrigo Mogárrio Freitas Leal, 2016).

Table 2 UDI reference

source: (Rodrigo Mogárrio Freitas Leal, 2016)

Source	Inferior limit [lux]	Autonomy value [lux]	Superior limit [lux]
Bellia et al. (2015); Chaiwiwatworakul & Chirarattananon (2013); Gilani et al. (2015); Hu & Olbina (2011); Manzan (2014); Mardaljevic (2006); Mardaljevic & Nabil (2005); Nabil & Mardaljevic (2006); Olbina & Hu (2012); Ramos & Ghisi (2010); Reinhart et al. (2006); Reinhart & Weissman (2012); Shen & Tzempelikos (2013); Tzempelikos & Shen (2013); Zelenay (2011)	100	500	2000
Mardaljevic et al. (2012)	100	300	3000
Hachem et al. (2014)	300	500	2500
David et al. (2011)	300	300	8000

- Daylight factor (DF)

DF is the ratio of Illuminance on the indoors workplane to the simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of an overcast sky. In architecture design, DF is to determine whether light is sufficient for occupants to carry out normal activities (Wikipedia, 2017). The DF requirement for office tasks during working hours is shown in Table 3. Usually, the over-lit phenomenon happens at 0-6 m from the window and under-lit phenomenon happens at the deep of the room.

Table 3 DF performance indicators for facade

Source	Threshold	Note
CIBSE (2002)	DF< 2%	Too dark for paper and computer work.
	2%≤DF ≤5%	Sufficient for both paper (sedentary) and computer (detail) works. Maximal DF of 5% is required for avoiding glare for these two types of work.
	>5%	Causing glare for both paper and computer works.
Szokolay (2003)	Minimum 2% of DF on work-plane	Artificial lighting generally not required except at dawn and dusk.

- Daylight glare index (DGI) & Daylight glare probability (DGP)

Glare is a phenomenon that shows difficulty in seeing, which can be caused by too much brightness or too high luminance ratios. It can be evaluated by visual comfort probability, unified glare rating, DGI and DGP these four indexes, among which DGI and DGP are the most common indexes for shading evaluation.

DGI, is the sum of glare contribution of each bright source based on subjective ratings from human subjects in a day-lit office space. It is computed based on the average window luminance and does not take into account the direct light. So it should be carefully used when the light source occupies a big portion of the field of view or when the wall luminance is similar to window luminance (Bellia et al., 2008). The most used DGI value is 22 (Dinapradipta, 2015).

DGP is a probability that an occupant will be dissatisfied with the visual environment. According to a comparative study of Jakubiec &Reinhart, DGP is the most robust glare index under a wide range of ambient conditions (Jakubiec &Reinhart, 2011).

Table 4 Glare performance indicators for facade

Source	Threshold	Note
Wienold (2009)	DGI ⩽22 ∈ [24-26] ⩾28	Comfortable Uncomfortable Intolerable
Wienold & Christoffersen(2009)	DGP ⩽0.35 ∈ (0.35-0.4]	Imperceptible Perceptible, 95% of office time should lower than this limit
Fisekis et al.(2003)	∈ (0.4-0.45] >0.45	Disturbing Intolerable

- Solar radiation (SR)

The most effective way to control overheating is to reduce the amount of solar radiation from reaching the window. So it is more of thermal control when using SR for evaluating shading devices. For facade manufacturers, they prefer the use of solar heat gain coefficients (SHGC) in USA and g-values in Europe. Generally, a higher g-value will be beneficial in cooler climates and a lower g-value will be beneficial in warmer climates. Typically g-values will range between 0.2 and 0.7(Designing Buildings Wiki). When related to control strategies, direct solar radiation is commonly used but the values differ in individual cases. Somfy company suggested a setpoint of 150 W direct vertical solar radiation on the facade shading.

2.1.2 Operable window

- Airflow rate

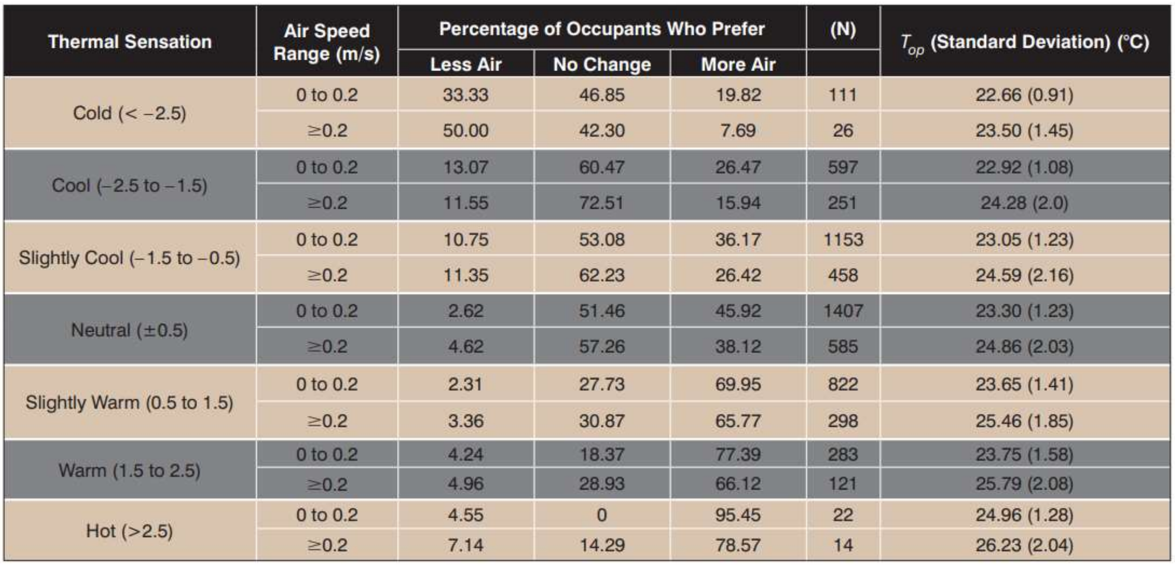
It is important to be able to predict the airflow rate through the windows so that the right amount of fresh air could be supplied to the rooms in the building and also avoid unnecessary consumption for heating (Larsen & Heiselberg, 2008). According to EN 13142, the minimum airflow rate for office buildings is 6.5 l/s per person or 1.25 l/s,m2 (Shitole, 2012), which is similar to the Dutch standard, 25 m3/h per person (Nederlands normalisatie instituut, 2013). According to EN 15251, the recommended airflow rate for single office (non-polluted) in category II is 2.1 l/s,m2 and a minimum of 0.1 to 0.2 l/s,m2 for unoccupied period. (Category II represents a normal level of expectation, to be used for new buildings and renovations.)

- Air velocity

In ASHRAE standard, air velocity of 0.2m/s is the draught limit (ASHRAE 55, 2004). In Dutch energy efficient office buildings, the draught rate of 15% is acceptable in office buildings (Scholten, 2015). However, Table 7 is the occupants' air movement preferences research results by Arens et al., which is not paralleled with the ASHRAE standard. When the air velocity was larger than 0.2 m/s and high operative temperature was presented, many people still wanted to increase air velocity. Only when people felt cold and the air velocity was larger than 0.2m/s, the percentage of people wanted less air reached 50% (Arens, Turner, Zhang, & Paliaga, 2009).

Table 5 Air movement preferences by thermal sensation and for two ranges of air velocity, n=6,148.

Source: (Arens et al., 2009)



Thermal Sensation	Air Speed Range (m/s)	Percentage of Occupants Who Prefer			(N)	T_{op} (Standard Deviation) (°C)
		Less Air	No Change	More Air		
Cold (< −2.5)	0 to 0.2	33.33	46.85	19.82	111	22.66 (0.91)
	≥0.2	50.00	42.30	7.69	26	23.50 (1.45)
Cool (−2.5 to −1.5)	0 to 0.2	13.07	60.47	26.47	597	22.92 (1.08)
	≥0.2	11.55	72.51	15.94	251	24.28 (2.0)
Slightly Cool (−1.5 to −0.5)	0 to 0.2	10.75	53.08	36.17	1153	23.05 (1.23)
	≥0.2	11.35	62.23	26.42	458	24.59 (2.16)
Neutral (±0.5)	0 to 0.2	2.62	51.46	45.92	1407	23.30 (1.23)
	≥0.2	4.62	57.26	38.12	585	24.86 (2.03)
Slightly Warm (0.5 to 1.5)	0 to 0.2	2.31	27.73	69.95	822	23.65 (1.41)
	≥0.2	3.36	30.87	65.77	298	25.46 (1.85)
Warm (1.5 to 2.5)	0 to 0.2	4.24	18.37	77.39	283	23.75 (1.58)
	≥0.2	4.96	28.93	66.12	121	25.79 (2.08)
Hot (>2.5)	0 to 0.2	4.55	0	95.45	22	24.96 (1.28)
	≥0.2	7.14	14.29	78.57	14	26.23 (2.04)

- CO2

Natural ventilation is not only used for maintaining thermal comfort, but also for indoor air quality (IAQ). CO2 concentration is one of the criteria. According to EN 13779, high IAQ is achieved with less than 400 ppm above outdoors, medium quality in a range between 400 and 600 ppm, moderate IAQ from 600 to 1000 ppm and low IAQ above 1000 ppm. 1200 ppm is the upper limit for the design of ventilation.

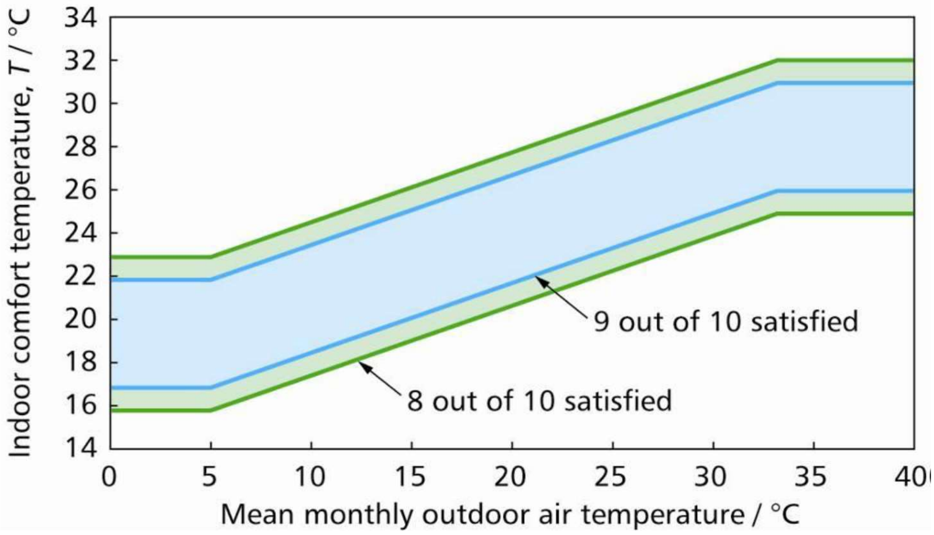
2.1.3 Combination

- Temperature

According to EN 15251, the comfortable indoor temperature for office in category II ranges from 20℃ to 24℃ for heating and from 23℃ to 26℃ for cooling due to the clothing insulation difference. The recommended setpoint for heating and cooling are 20℃ and 26℃. Figure 12 shows the 80 percent and 90 percent acceptable operative temperature ranges for the buildings that are only ventilated by windows.

Figure 12. Acceptable operative temperature ranges for naturally conditioned spaces.

Source: (ASHRAE 55, 2004)



2.2 Solar shading control

2.2.1 Shading principle

In EnergyPlus, the total solar gain is calculated by the given equation (Figure13). Figure 14 shows the expressions of the transmittance and the absorptance in the combination of glazing and external shading, which is referred as ‘sys’ (EnergyPlus Development Team, 2010).

Figure 13. Equation of the total solar gain

$$Q_{so} = \alpha \cdot \left(I_b \cdot \cos\theta \cdot \frac{S_s}{S} + I_s F_{ss} + I_g F_{sg}\right)$$

Where,
α: Solar absorptance of the surface;
θ: Angle of incidence of the sun’s rays;
S: Area of the surface;
Ss： Sunlit area;
Ib: Intensity of beam (direct) radiation;
Is : Intensity of sky diffuse radiation;
Ig : Intensity of ground reflected diffuse radiation;
Fss : Angle factor between the surface and the sky;
Fsg : Angle factor between the surface and the ground;

Figure 14. Expressions of glazing and external shading combination

$$T_{sys}(\emptyset) = T_{1,N}^{dif} \frac{\tau_{sh}}{1 - R_f^{dif} \rho_{sh}}$$

$$T_{sys}^{dif} = T_{1,N}^{dif} \frac{\tau_{sh}}{1 - R_f^{dif} \rho_{sh}}$$

$$A_{j,f}^{sys}(\emptyset) = A_{j,f}^{dif} \frac{\tau_{sh}}{1 - R_f \rho_{sh}}, \qquad j = 1\ to\ N$$

$$A_{j,f}^{dif,sys} = A_{j,f}^{dif} \frac{\tau_{sh}}{1 - R_f \rho_{sh}}, \qquad j = 1\ to\ N$$

$$A_{j,b}^{dif,sys} = A_{j,b}^{dif} \frac{T_{1,N}^{dif} \rho_{sh}}{1 - R_f \rho_{sh}}, \qquad j = 1\ to\ N$$

$$\alpha_{sh}^{sys} = \alpha_{sh} \left(1 + \frac{\tau_{sh} R_f}{1 - R_f \rho_{sh}}\right)$$

The functions of shadings include blocking direct sunlight to prevent glare and reduce heat and allowing diffuse light to enter the space therefore reduce lighting consumption (Shen & Tzempelikos, 2012). Shutters, blinds and awnings and EC windows are all dynamic shadings which can be controlled automatically and manually at facade system level or can be integrated into the BMS level to vary solar exposure in multiple zones. They can be made from various materials like glass, plastic and metal. They can be in different shapes and different location related to the facade. For blinds, the properties are determined by slat geometry, slat optical properties and the profile angle, which would affect the solar transmittance, reflectance and absorptance of the facade.

2.2.2 Control strategy

Table 6 is a summary of the blinds control strategies sorted by indexes of visual comfort from researches of Rodrigo's (Rodrigo Mogárrio Freitas Leal, 2016) and Correia et al. (Correia, Leal, & Andersen, 2012). The references inside the table are listed in Appendix 1.

Table 6 Summary of shading control strategies

Automated control strategies of shading

Parameter	Source	Stimulus	Action
Solar radiation(SR)	[2][12][21]	$SR_{vertical} > 300$ W/m2	Ajust height
	[24]	$SR_{vertical} > 200$ W/m2	Close blinds
	[13]	$SR_{direct\ on\ workplane} > 50$W/m2	Close blinds
	[1]	$SR_{vertical} > 250$ W/m2	Ajust height
	[19]	$SR_{vertical} + SR_{diffuse} > 200$ W/m2	Close blinds
Daylight glare index(DGI) /Daylight glare probability(DGP)	[19]	DGI> 20	Close blinds
	[26]	DGI<= 22	Ajust slat angle
	[25]	DGI> 22	Close blinds
	[8]	DGI> 24	Ajust height
	[6][7]	DGP> 40%	Ajust slat angle
Illuminance(E)	[9][10]	$E_{workplane} > 1800$ lux	Close shades
	[28]	$E_{workplane} = 500$ lux	Ajust slat angle
	[27]	E >= 2000lux	Ajust slat angle
	[23]	$E_{vertical} > 30$ klux or $E_{workplane} \neq$ 570-670 lux	Ajust slat angle
	[16]	$E_{window} > 1800$ lux	Ajust blinds height
	[15]	$E_{window} > 5000$ lux	Close shading
	[11]	$E_{Visual\ field} > 1000$ lux	Close shading
	[23]	E > 538 lux	Ajust slat angle
	[20]	E ≠ 485-675 lux	Ajust slat angle
	[4]	DGI> 20 or $SR_{direct} > 94.5$ W/m2	Close blinds
Solar radiation(SR) + Daylight glare index(GDI)	[17]	DGI> 19 or $SR_{direct\ in\ summer} > 94.5$ W/m2	Close blinds
Illuminance(E) + Daylight glare index(GDI)	[18]	DGI > 22 and $E_{workplane} < 1800$ lux	Ajust height
Solar radiation(SR) + Illuminance(E)	[29]	SR_{direct} exists or $E_{morning} > 793$ lux or $E_{morning} > 696$ lux	Ajust slat angle

Manual control of shading

Parameter	Source	Stimulus	Action
Illuminance(E)	[5]	$SR_{vertical} > 233$ W/m2	Close blinds
Solar radiation(SR) + Illuminance(E)	[14]	$E_{window} > 4466$ lux; or $E_{background} > 225$ lux; or $E_{window\ average} > 890$ lux; $SR_{vertical} > 13$ W/m2 all with probability of action of 50%	Close blinds
Solar radiation(SR) + Solar gains（SG）+ Illuminanc	[3]	$SR_{direct} > 50$ W/m2 or SG > 50 klux(450 W/m2) or $E_{window} > 25$ klux	Ajust height

The previous studies use different values as thresholds to adjust the shadings. There is no unified criteria for shading control, for examples, Tzempelikos & Athienitis (2007) assumed that the shading is lowered when direct solar radiation presents on building facade while Lee and Selkowitz (1995) suggested that the blinds should close when direct solar radiation is exceeding 94.5 W/m2.

A large portion of shading control strategies does not use metrics such as DF or g-value. They only consider outdoor condition (the 'Stimulus') and lighting condition but do not take office schedule or thermal condition into account, as well as have not integrated with BMS.

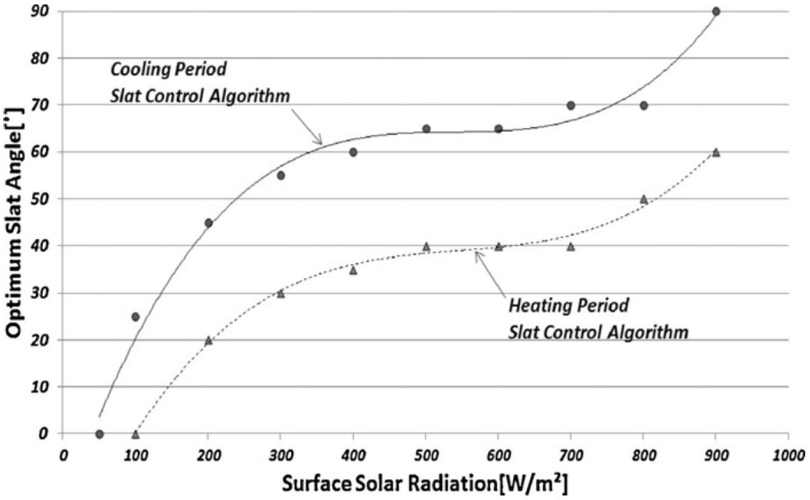
Table 7 Control strategy of the slat-type blind

source: (Oh et al., 2012)

Control	Description
Blinds	SRdirect > 50W/m2, downward; SRdirect ⩽50W/m2, upward. (The SR causing no glare is no larger than 50W/m2)
Slat angle	Follow 'slat angle control algorithm'

Figure 15. Slat angle control algorithm in heating & cooling modes

source: (Oh et al., 2012)



As a supplement in this part, Oh et al. (2011) developed a slat angle control algorithm in heating and cooling modes(Figure 15) and used it in the control of the double-sided reflected blind which collaborated with a dimmable lighting system. The whole control strategy is shown in Table 7. By simulation, this control strategy showed 29.2% reduction in the heating, cooling and lighting loads and 99.7% reduction in glare (Oh, Lee, & Yoon, 2012).

2.2.3 Assessment

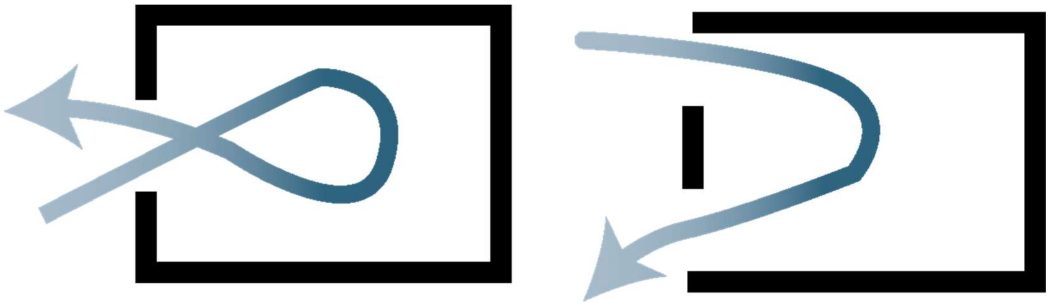
Different shading control strategies diverse performance. The author did not find any research that concluded one specific type of shading (e.g. blind, shade, awning) had better performance in different cases. Regarding performance, external shading could reduce indoor air temperature from 2.5°C to 4.5°C (Kumar et al., 2005). Shadings with automatic control perform better than with manual control or no control in energy saving (Liu, Wittchen, & Heiselberg, 2015), even though it slightly increased the lighting demand. The energy demand can be reduced by 16% in Nielsen et al.'s simulation (2011), 7–17% in Kim 's study (2009) and 50% decrease in annual cooling in Tzempelikos & Athienitis's research (2007). More specifically, by using blinds dynamic control, it could save energy of 3.4%-22.7% in Elzeyadi's simulation (2017) and 5%-14% in Hammad & Abu-hijleh's research (2010).

2.3 Operable window control

2.3.1 Ventilation principle

Natural ventilation is based on pressure difference which could be induced by wind and buoyancy. It's normally divided into three types, single-sided ventilation, cross ventilation and stack ventilation.

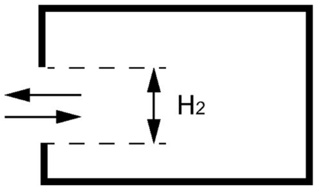
Figure 16. Single-sided ventilation



As it is shown in Figure 16, single-sided ventilation happens in a closed space where all openings are on one facade only (Dascalaki et al., 1995), which was mostly used in this project context.

Figure 17. Equation of single-sided ventilation airflow

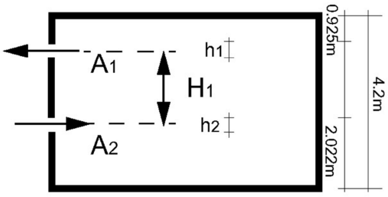
Type A Single-sided ventilation with one opening



Wind effect: $Q = 0.025AV$

Buoyancy effect: $Q = \frac{C_d A}{3}(\frac{\Delta T g H_2}{T_{avg}})^{1/2}$

Type B Single-sided ventilation with two openings



Wind effect: $Q = 0.025AV$

Buoyancy effect: $Q = C_d A \left[\frac{\varepsilon\sqrt{2}}{(1+\varepsilon)(1+\epsilon^2)^{\frac{1}{2}}}\right]\left(\frac{\Delta T g H_1}{T_{avg}}\right)^{\frac{1}{2}}$

$\varepsilon = \frac{A_1}{A_2};$

$A = A_1 + A_2$

The equation (Figure 17) shows the buoyancy driven ventilation is affected by the temperature difference of indoor and outdoor, the window configuration such as opening ways, aspect ratio and area. The wind-driven ventilation is affected by, wind direction and wind velocity. The latter two are related to the location, building shape and building height.

Natural ventilation is not only used for ensuring indoor air quality, but also for cooling down the building by the cold outdoor air, which is more and more common because of its energy saving effect. Night cooling is one of the passive cooling techniques, which could decrease the peak temperature for free running buildings and the cooling load of air-conditioning buildings (Psomasa, Fiorentini, Kokogiannakis, & Heiselberg, 2017). However, it is not suitable for all climates and types of buildings. For example, Kukadia (1998) concluded that natural night ventilation is only suitable in buildings with sufficient thermal mass of 75–100 kg/m2 of floor space and internal gains under 30 W/m2 of floor area.

In Western Europe, during spring and autumn time, it may be too cool in the early morning while internal and glazing heat gains cause overheating in the late afternoon.

Heating and cooling may be needed alternatively (Moeseke, Bruye, & De, 2007). Integrating natural ventilation for thermal comfort among four seasons could be a robust solution.

2.3.2 Control strategy

Table 8 is a summary of the automatic window control strategies in reality sorted by stimulus. In most cases, the main stimuli that trigger automatic windows to open or close are indoor temperature and CO2 levels, corresponding to the two main functions of natural ventilation, which are to maintain good IAQ and to improve thermal comfort in summer by increased daytime air velocity and nighttime ventilation rates. Wind speed is a modifier to protect the window from being damaged. In terms of schedule, during occupied and unoccupied hour, the ventilation system usually works differently, so does during four seasons. Normally, in winters, ventilation is only used to limit the CO2 levels. Cooling by natural ventilation is only used in summer. The action is mainly adjusting the percentage of ope

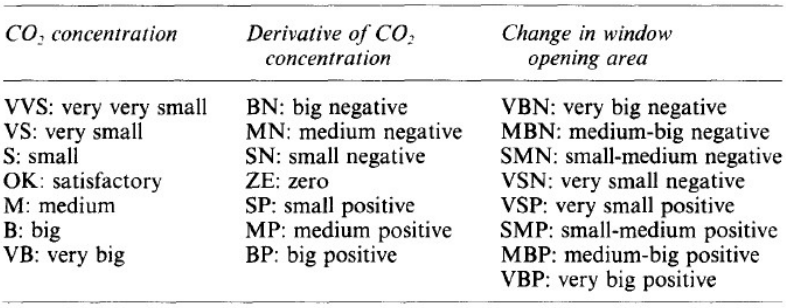
Table 8 Summary of automatic window control strategies

Source	Base case	Stimulus	Stimulus detail	Action
Osso'Dell, R., Iannone, F., Pierucci, A. &Rinaldi, A. (2015)	A residential building in Bari	Temperature & Humidity	T indoor > T optimal; T indoor – 3°C < T outdoor < T indoor. Or if: R.H. indoor (relative indoor humidity) > 70%; absolute indoor humidity > absolute outdoor humidity.	Open tilt windows
Brager, G., Borgeson, S. & Lee, L., (2007)	Federal building in San Francisco	Pressure difference & Wind speed	If ΔP > 60 or Vwind > 20m/s, open < = 52.5%; If ΔP > 130 or Vwind > 25m/s, open < = 13.7%; If ΔP > 300 or Vwind > 30m/s,open < = 3.4%; If heating is on or it is raining, open < = 22.2%; If both sides are in cooling mode, open > = 17.3%;	Adjust opening sizes
	A school in UK	Temperature & Airflow rate	T < 21°C, close louvers; 21°C < T < 22°C, open 25%; 22°C < T < 23°C, open 50%; 23°C < T < 24°C, open 75%; 24°C < T < 25°C, open 100%; T>25°C, open 100%. In the same time, Q < 7m3/s, reduce 0% Q > 7m3/s, reduce 33% Q > 9m3/s, reduce 66% Q > 11m3/s, reduce100%	Adjust opening sizes
	A school in Netherlands	Temperature & C02	The inlet grills automatically controlled, while the windows are entirely manually controlled by the users. Winter During daytime: If CO2 > 700 ppm: open grill 1 If CO2 > 1000 ppm: open grill 2 If CO2 > 1300 ppm: switch on fan During nighttime: Close grills Summer During daytime: If > 700 ppm: open grill 1 & 2 If > 1300 ppm: switch on fan During nighttime, open grills when: Tinternal ≥ Texternal + 2°C & Texternal > 15°C & Tinternal > 20°C	Adjust opening sizes
	Scottish Parliamentary building in UK	Temperature	T < 10°C, control by operator terminal; 10°C <T < 22°C, close window; 22°C < T < 24°C, open high level glazed panel; 24°C < T < 26°C, open lobby glazed panel; T > 35°C, control by operator terminal;	

As a supplement in this part, Dounis et al. (1996) simulated the control of indoor air quality in free cooling buildings. The performances were a little better compared with the time when the building was normally used. However, a fuzzy control logic behind it is worth for design reference (see Table 9 & Table 10). Fuzzy logic concepts can be used to translate imprecise linguistic rules into mathematical terms, which can improve the creation of automatic control strategies (Velasco, Hernandez, Marrugo, & Diaz, 2015).

Table 9 Linguistic representation of the fuzzy sets

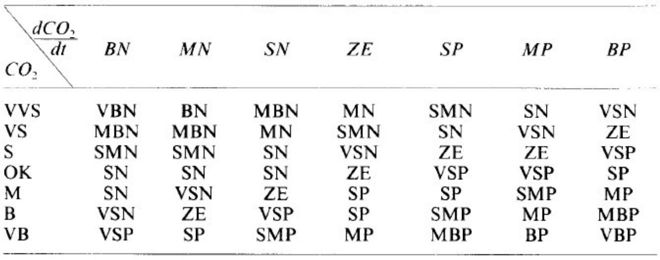
Source: (Dounis et al., 1996)



CO_2 concentration	Derivative of CO_2 concentration	Change in window opening area
VVS: very very small	BN: big negative	VBN: very big negative
VS: very small	MN: medium negative	MBN: medium-big negative
S: small	SN: small negative	SMN: small-medium negative
OK: satisfactory	ZE: zero	VSN: very small negative
M: medium	SP: small positive	VSP: very small positive
B: big	MP: medium positive	SMP: small-medium positive
VB: very big	BP: big positive	MBP: medium-big positive
		VBP: very big positive

Table 10 Control rules

Source: (Dounis et al., 1996)



$\frac{dCO_2}{dt}$ / CO_2	BN	MN	SN	ZE	SP	MP	BP
VVS	VBN	BN	MBN	MN	SMN	SN	VSN
VS	MBN	MBN	MN	SMN	SN	VSN	ZE
S	SMN	SMN	SN	VSN	ZE	ZE	VSP
OK	SN	SN	SN	ZE	VSP	VSP	SP
M	SN	VSN	ZE	SP	SP	SMP	MP
B	VSN	ZE	VSP	SP	SMP	MP	MBP
VB	VSP	SP	SMP	MP	MBP	BP	VBP

2.3.3 Assessment

From performance point of view, natural ventilation for passive cooling is significantly reduce overheating hours and the automatic control allow the reduction of energy consumptions for cooling and peak cooling power (Osso'Dell et al., 2015). For examples, Waterland School in Netherlands received an energy reduction of 20% compared to the Dutch building regulation (Brager et al., 2007). The Liberty Tower of Meiji University in Tokyo reduced 17% of cooling demand and an office building in Denmark used 40 kWh/m2 of primary energy per year while using VAV system would consume 50 kWh/m2 per year (Schulze & Eicker, 2013). As for night cooling, it reduced the indoor temperature by 1.2℃ for a building in German when occupied, by between 1.5 and 2℃ in France compared to a reference room and by between 1.8 and 3℃ in an office building in Greece (Schulze & Eicker, 2013). Night cooling could reduce cooling demand from 12% to 54% with an air change rate of 8 per hour (Blondeau et al.,1997).

Reference project

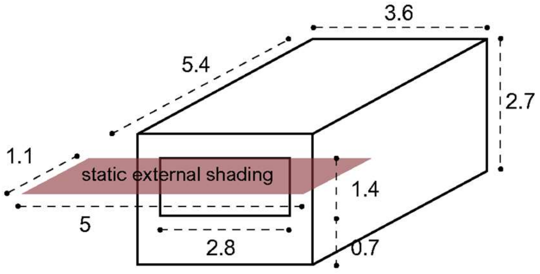
3.1 Case study – Day cooling

This case uses the control strategies of static external shading and day cooling by single-sided natural ventilation for a south-oriented office room in Belgium.

3.1.1 Base case

Figure 18 The basic settings of the modelled office

Room thermal mass:	365 kg for 1m2 gross floor
External wall:	U = 0.33 W/m2K
South WWR:	40%
Glazing:	
U-value	2.95W/m2K
Solar factor	0.77
Frame:	
U-value	6.48W/m2K
Frame/glazing ratio	0.3
Internal gain:	35W/m2
Infiltration rate:	0.2 ach
Heating setpoint:	20.5℃ in occupied hours; 15℃ at night; turned off from May to September.
The occupied time:	8 am to 6 pm/everyday with a reduction factor: 0.5 (8 am to 9 am, 12 am to 2 pm, 5 pm to 6 pm).



Geometry and dimension of the modelled office

The basic settings are described in Figure 18. To point out, the internal gains consist of two people (70W each) with their computer (100W each) and a printer (140W), with a lighting gain of 10W/m2 in a 19m2 office module. External air is preheated to 13℃ when outside temperature is lower than 13℃.

3.1.2 Control strategy

The control is only active from 7am to 6pm between March 1st and December 1st.
Air change rate is initially set at 4 ach for day cooling, including air rate of 1 ach for air quality, in total Air change rate of 4 ach is sufficient for cooling without generating discomfort like draught

.

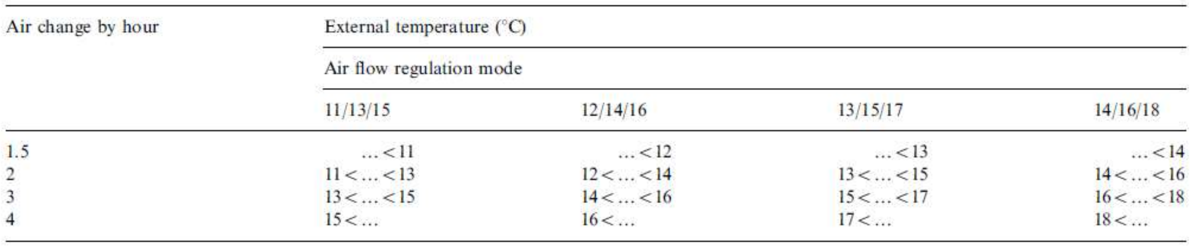
- First mode: on/off based on Tin
  Temperature setpoint for day cooling is between 21℃ and 25℃.
  Day cooling terminates when indoor temperature is below 21℃.

- Second mode: on/off based on Tin & DeltaT
  Temperature setpoint for day cooling is between 21℃ and 25℃.
  Day cooling terminates when indoor temperature is below 21℃.
  When outdoor temperature is higher than the indoors, day cooling is off to avoid heat wave.

- Third mode: Tin & DeltaT
  Temperature setpoint for day cooling is between 21℃ and 25℃.
  Day cooling terminates when indoor temperature is below 21℃.
  The air change rate is modulated according to outdoor temperature. Table 11 described the details of the modulation.

Table 11 Modification of simulated air change rate following external temperature

Source: (Moeseke et al., 2007)



Air change by hour	External temperature (°C)			
	Air flow regulation mode			
	11/13/15	12/14/16	13/15/17	14/16/18
1.5	… < 11	… < 12	… < 13	… < 14
2	11 < … < 13	12 < … < 14	13 < … < 15	14 < … < 16
3	13 < … < 15	14 < … < 16	15 < … < 17	16 < … < 18
4	15 < …	16 < …	17 < …	18 < …

3.1.3 Performance analysis

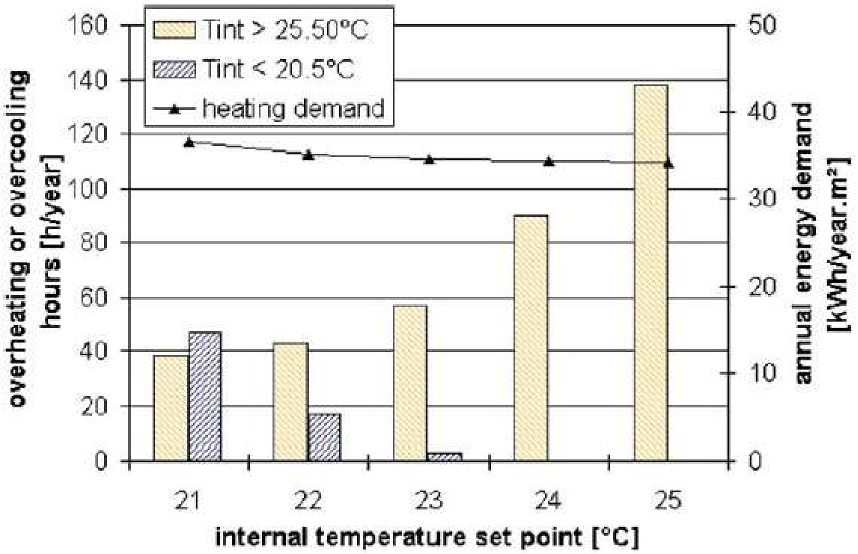
The performance is simulated by the software TRNSYS 16 (used with Trnbuild and Trnsys Studio interface) at a time step of per hour. The control when unoccupied is not considered in this case. The criteria for indoor thermal comfort are as followed.

Overheating is regarded as indoor temperature exceeds 25.5 ℃ when occupied for more than 100 h in a year.

Overcooling is regarded as indoor temperature below 20.5 ℃ when occupied.

Figure 19 Influence of internal temperature set point on overheating or overcooling hours and annual energy demand for an office module with day cooling: First mode for a whole typical year

Source: (Moeseke et al., 2007)



From Figure 19, it can be concluded that rising in setpoint increases overheating hours, decreases overcooling hours and reduces heating demand. In addition, this mode receives 14 days of heat wave in one month.

As for comfort, day cooling has a great contribution in reducing annual overheating hours and heat wave, compared to the one without day cooling, which is 831 overheating hours and a month with 20 days heat wave. From heating demand point of view, it only consumes 10% of the reference group, which is 34.21kWh/m2 per year.

From Figure 20, it can be concluded that heating demand for the first and second mode is similar, which means the additional measure is not helpful.

Figure 20 Influence of internal temperature set point on overheating or overcooling for an office module with day cooling: First & Second mode for a whole typical year

Source: (Moeseke et al., 2007)

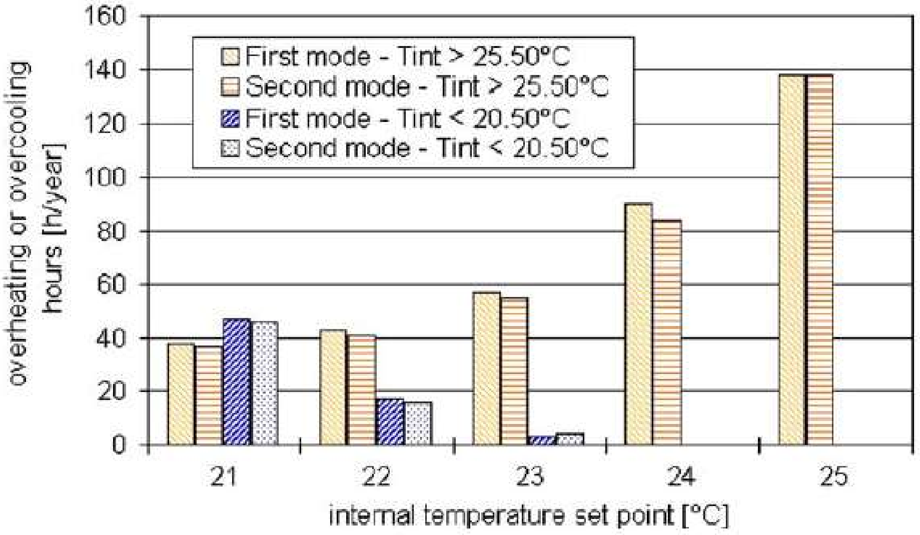
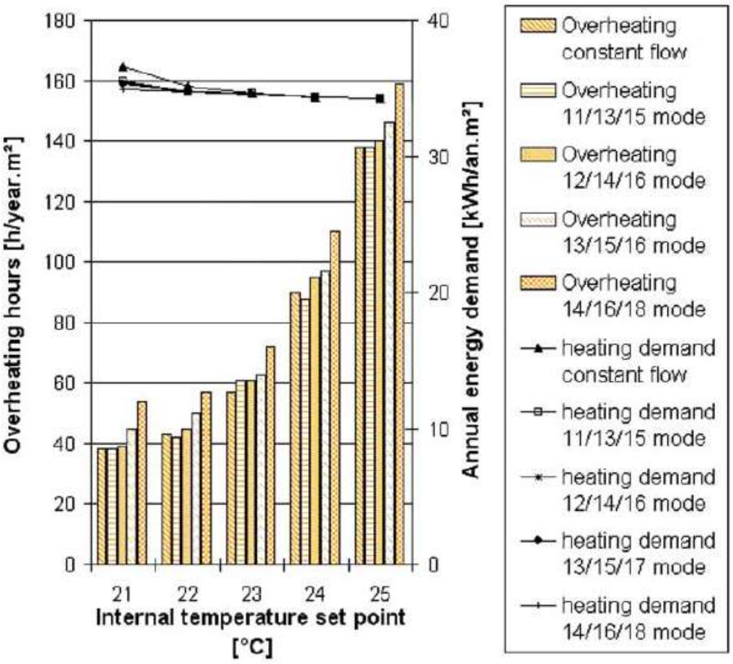


Figure 21 Influence of internal temperature set point on overheating or overcooling hours and annual energy demand for an office module with day cooling: Third mode

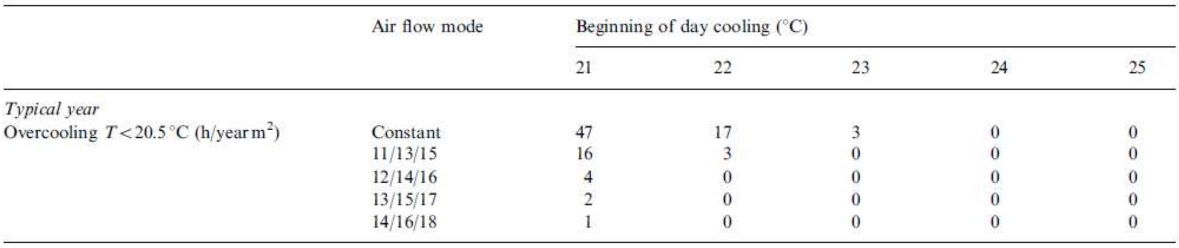
Source: (Moeseke et al., 2007)



As for the third mode, compared with the first control mode, adding Air change rate modulation can reduce the heating demand saving to 3-5% but it becomes less and less effective when the temperature setpoint increases. Figure 21 and Table 12 shows that 14/16/18 mode has the greatest flow reduction but increases in overheating hours by about 42%. Considering comfort and energy together, 11/13/15 mode seems to be a reasonable choice with a low temperature setpoint.

Table 12 Overcooling hours for a typical year according to different controls in third modes

Source: (Moeseke et al., 2007)



	Air flow mode	Beginning of day cooling (°C)				
		21	22	23	24	25
Typical year						
Overcooling $T < 20.5\,°C$ (h/year m^2)	Constant	47	17	3	0	0
	11/13/15	16	3	0	0	0
	12/14/16	4	0	0	0	0
	13/15/17	2	0	0	0	0
	14/16/18	1	0	0	0	0

For natural ventilation in day cooling, limiting the flow rate when external temperature drops is found to be efficient to save energy. All these results and conclusions are based on the Belgian weather. In spring and summer, heating is still active but sometimes cooling is needed, the day cooling control strategy need to be taken into account of the local weather so that it will not end with excessive cooling.

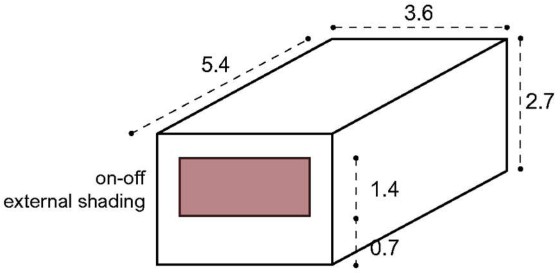
3.2 Case study – Night cooling and Shading

This case uses the control strategies of on-off external shading and night cooling by single-sided natural ventilation for a south-oriented office room in Belgium.

3.2.1 Base case

Figure 22 The basic settings of the modelled office

Room thermal mass:	365 kg for 1m2 gross floor
External wall:	U = 0.33 W/m2K
South WWR:	40%
Glazing:	
U-value	2.95W/m2K
Solar factor	0.11
Frame:	
U-value	6.48W/m2K
Frame/glazing ratio	0.3
Internal gain:	35W/m2
Infiltration rate:	0.2 ach
Air change rate:	6ach
Heating setpoint:	20.5℃ in occupied hours; 15℃ at night; turned off from May to September.
The occupied time:	8 am to 6 pm/everyday with a reduction factor: 0.5 (8 am to 9 am, 12 am to 2 pm, 5 pm to 6 pm).



Geometry and dimension of the modelled office

The base case is similar to the case study in Section 4.1, which is also retrieved from Moeseke et al. (2007). However, the glazing properties and the air change rate are different, which were highlighted in red in Figure 22. External air is preheated to 13℃ when outside temperature is lower than 13℃

3.2.2 Control strategy

- Night cooling

  The night cooling will be active when the indoor temperature is larger than 23℃ at 12pm. It will stop at 5am or when the indoor temperature reaches 19℃.

  Indoor temperature of 19℃ will rise around 5 am and by the time the occupants arrive (8am), the indoor temperature should be reached around 20℃because of the thermal mass of walls, floor and ceiling.

- Shading
  There are 3 control modes for annual control.

  - First mode: on-off based on solar radiation (SR)
    SR on vertical direction of the facade exceeds setpoint, the blinds are closed.
    SR on vertical direction of the facade is below setpoint, the blinds are opened.

    A setpoint value greater than 500W would not be reasonable to low occurrence (lower than 500h a year) in Belgian climate. Setpoints varies between 0 and 500W with a 50W step.

  - Second mode: on-off based on indoor temperature (Tin)
    Indoor temperature exceeds determined temperature, the blinds are closed.
    Indoor temperature is below 21 ℃, the blinds are opened.
    The threshold of 21 ℃ manages a dead zone between shading and heating setpoints of 0.5 ℃.

  - Third mode: on-off based on SR & Tin
    Blinds are closed when both conditions are fulfilled and opened when one of the above opening conditions is fulfilled.

3.2.3 Performance analysis

Figure 23 Overheating (dashed lines) and closed mode hours (full lines) in an office module for various irradiations and temperature set points.

Source: (Moeseke et al., 2007)

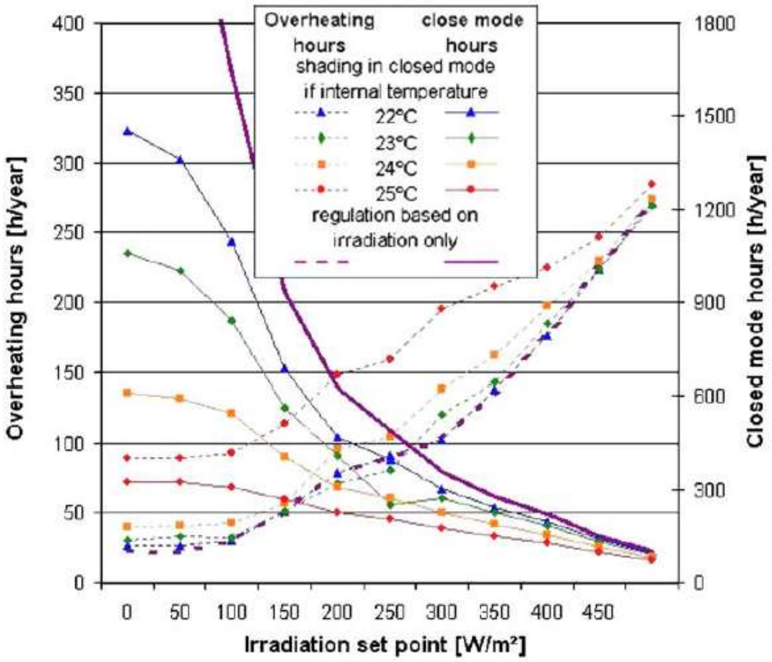
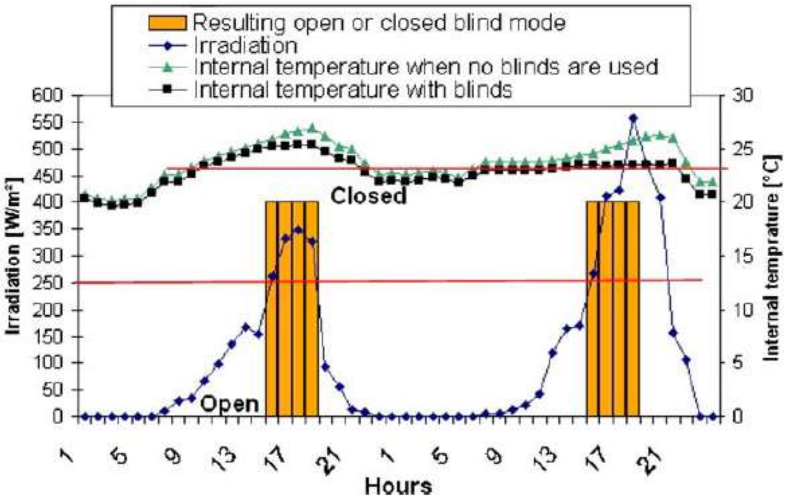


Figure 23 demonstrates strategies based on both indoor temperature and solar irradiation set points are shown to be more efficient than strategies based on solar irradiation or indoor temperature alone.

25℃ is a common cooling setpoint for BMS. Shadings should be closed before reaching the setpoint of BMS to avoid overheating. To be more specific, a setpoint of 23℃ or 24 ℃ may be chosen for shading to be closed. SR of 200 W/m2 to 300W/m2 can be chosen to avoid overheating and active closed mode for the smallest active hours. In this case, the setpoints combination of 23 ℃ for Tin and 250W/m2 for SR seems quite efficient. Figure 24 indicates the use of blinds has a significant contribution to maintaining thermal comfort even with rough control.

Figure 24 Internal temperature profile and blinds closing for the 20th of July of the typical year, set points fixed to 23 ℃ and 250W/m2

Source: (Moeseke et al., 2007)



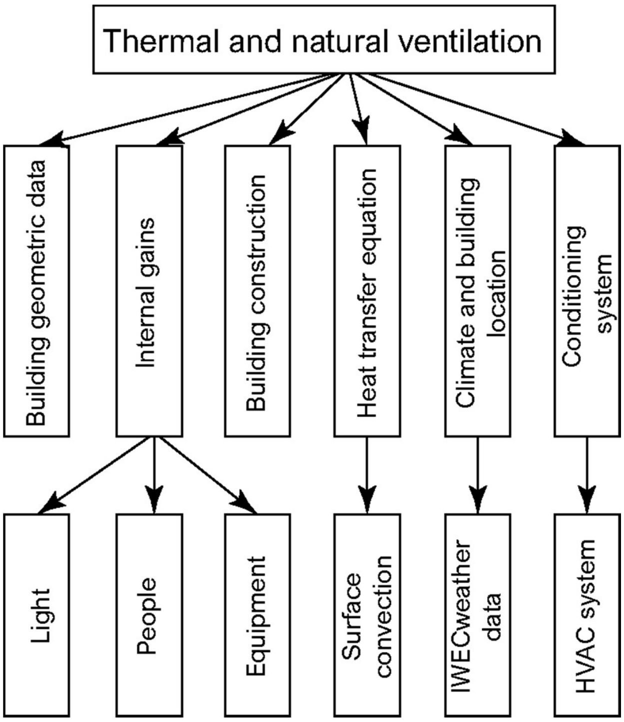
In this case, night cooling and shading combo are effective on thermal comfort. Considering sharing the same stimulus, which is the indoor temperature, they both contributed to the cooling saving and thermal comfort. In addition, thermal condition in other three seasons and lighting performance are not analyzed, which means overcooling or overheating may exist due to the conflict between night cooling ventilation and shading control. Also, the use of shading does not eliminate all sources of overheating, introducing natural ventilation when occupied may also help to alleviate the heat.

Design preparations

4.1 Software

EnergyPlus is for simulating building energy performance such as heating, cooling, lighting and ventilation, which is funded by the U.S. Department of Energy's Building Technologies Office and developed by the National Renewable Energy Laboratory. It is capable of modelling modular systems and plant integrated with heat balance-based zone simulation, multizone air flow, thermal comfort, and photovoltaic systems. It allows users to define simulation time steps so that in certain cases it does not need to sacrifice simulation speed for precision (EnergyPlus Development Team, 2010). Figure 25 shows the settings of EnergyPlus that related to this project.

Figure 25. Settings of EnergyPlus that related to this project



DesignBuilder is a user-friendly modelling interface that uses the EnergyPlus dynamic simulation engine to generate environmental data such as energy consumption, carbon emissions, comfort conditions, daylight illuminance, temperature distribution and HVAC component sizes (DesignBuilder, 2019).

4.2 Modelling

To be parallel with FLDP, the base model used the same dimension of 3.6mX5mX4.2m, with four adiabatic blocks surrounded to eliminated the indoor influence (Figure 26).

Figure 26. DB model information

Parameters for simulation

• Location	Delft, Netherlands
• Orientation	East
• Overhang	0.75m
• Wall	
East	U=1.1 W/m2K
West, south, north	adiabatic
• Roof	adiabatic
• Floor	U=0.25 W/m2K
• Crack	poor

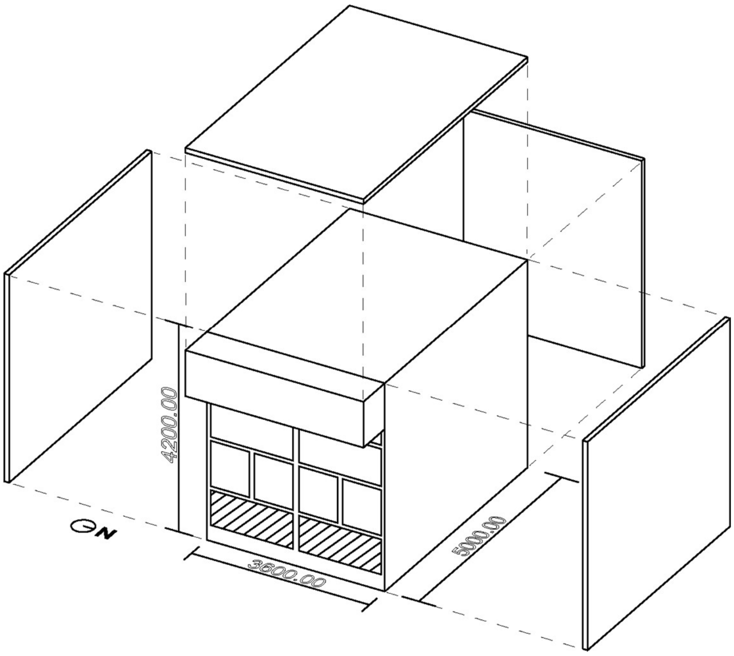
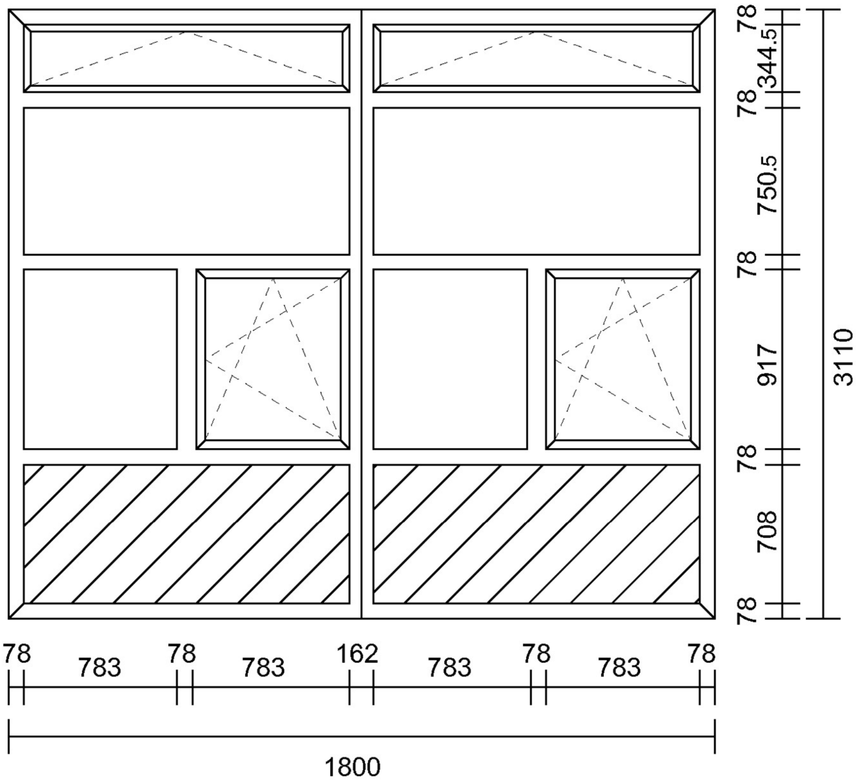


Figure 27. Facade layout and properties

New construction
U_g=0.7 W/m^{2}K
g=0.53
Lt=0.698
U_f=1.1W/m^{2}K
U_s=0.8W/m2K

Old construction
U_g=5.42 W/m^{2}K
g=0.81
Lt=0.88
U_f=1.1W/m^{2}K
U_s=0.8W/m2K



The proposed facade panel layout (Appendix 2) followed the settings in FLDP, which consisted of triple-glazing and aluminium frame. The old construction consists of the existing glazing, a new frame and a new sandwich panel. The inputs are in Figure 27.

As for the shading, the internal shading would not be modelled since it only could be controlled manually. The external shadings were slatted blinds. The properties are shown in Table 13.

Table 13. Slat properties

Slat orientation	Horizontal
Slat thickness	0.001 m
Slat conductivity	0.900 W/m·K
Slat solar transmittance	0.000
Slat solar reflectance,front side	0.200
Slat solar reflectance, back side	0.200
Slat visible transmittance	0.000
Slat visible reflectance, front side	0.200
Slat visible reflectance, back side	0.200
Slat hemispherical transmittance	0.000
Slat hemispherical emissivity, front side	0.900
Slat hemispherical emissivity, back side	0.900

4.3 General settings

As overheating existed in not only summer, but also spring and autumn of Netherlands, the potential of free cooling by the low-temperature outdoor air could be utilized in the control. (Figure 28). The simulation periods were divided into 4 periods (Table 14 and Figure 29) based on outdoor temperature (Tex), among which spring and autumn shared the same control. As it was shown in Figure 30, the occupied time was from 8:00 to 18:00 in weekdays. It was assumed that there were two occupants and two computers. The artificial lighting control was active when indoor illuminance was less than 500lux during occupied time.

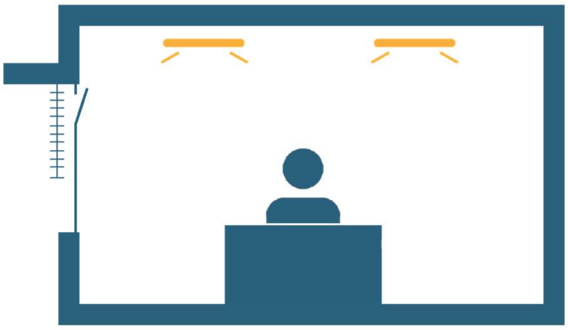


Figure 28. Impression of the room

Simulation weather	
• Spring	Apr 1st - May 31th
• Summer	Jun 1st - Aug 31th
• Autumn	Sep 1st - Oct 31th
• Winter	Nov 1st - Mar 31th
• Weather file	NLD_AMSTERDAM_IWEC

Table 14. Simulation periods distribution

Figure 29. Simulation periods distribution

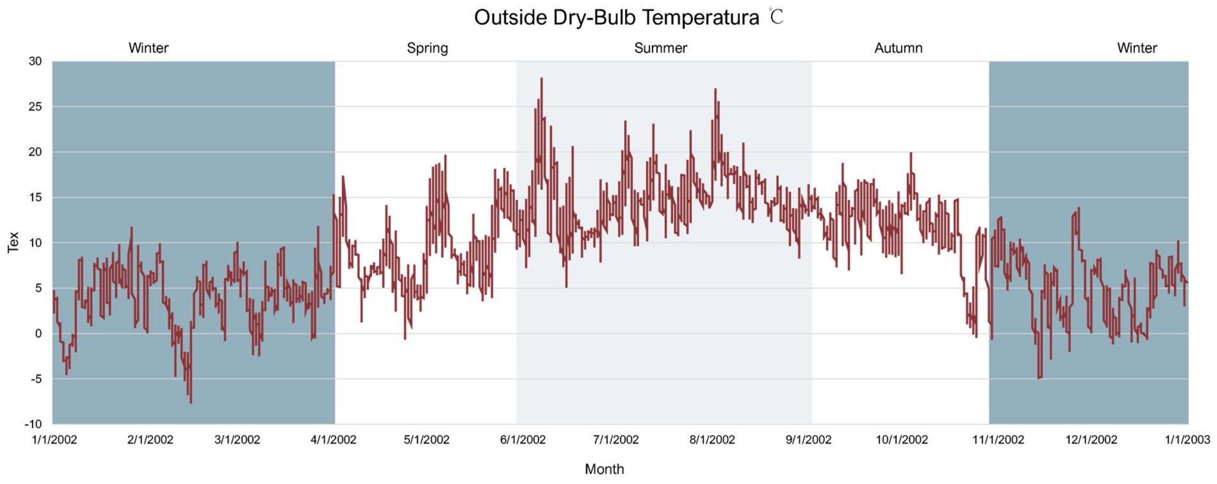
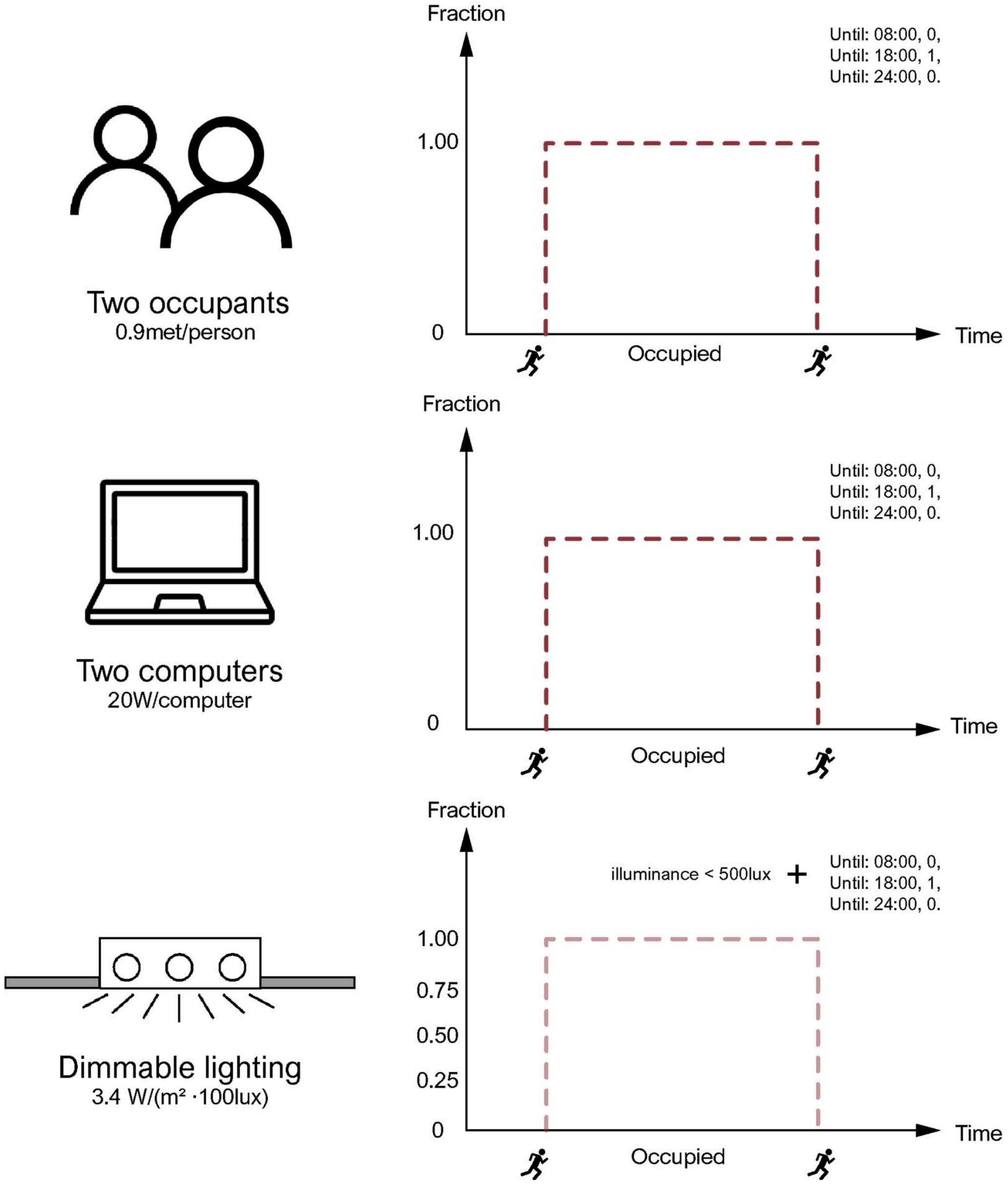


Figure 30. General setting & Schedule in DB



4.4 Reference groups

The ‘OfficeVitae’ had the monitoring data of CEG from November to April. Since it was not complete and could not be used for comparison directly, the reference groups have to be set up in DB for evaluating the effectiveness of the control strategy. The simulations kept the average indoor air temperature similar to the average value of OfficeVitae and inputted a fixed air flow rate for natural ventilation calculated from the average CO2 concentration value (Table 15). Winter simulation used the data from November to March when occupied and the other three seasons used the data of April.

Reference group 1, which used an infiltration of 0.35ach, U-value of 5.42W/m^2 • K and g-value of 0.81, was for the comparison to the existing facade with control. Reference group 2, which used an infiltration of 0.15ach, Ug-value of 0.7W/m^2 • K and g-value of 0.53, was for the comparison to new construction with control. The properties such as the wall and sandwich panel insulations would remain the same. For system settings, the dimmable light would have been activated if the indoor illuminance was lower than 500lux. Neither shading nor night-cooling (natural ventilation at night) was active during four seasons and heating was not active in summer.

The results were shown in Table 16. The ‘heating consumption in reality’ was retrieved from ‘TU Delft Energy Monitor’. The heating energy consumptions of group 1 were similar to the reality’s mainly because it used the average values throughout the monitoring period and the accuracy of the construction input. The discomfort results could not be compared with the reality since how people operated the system setting and how the hourly weather data like were quite different from the real condition. However, it was sufficient enough to be used as references for the control strategy in the following chapter. Changing the facade properties (from old construction to new construction) received a reduction of 74.5hrs in total discomfort and a reduction of 49kWh (46%) in annual heating.

Table 15. The input reference from OfficeVitae

Month	Average Tin [℃]	Average CO2 [ppm]	Air flow rate (converted) [ach]
Nov-Mar	20.4	733	1.47
Apr	22.3	619	2.23

Table 16. Simulation results of the reference groups

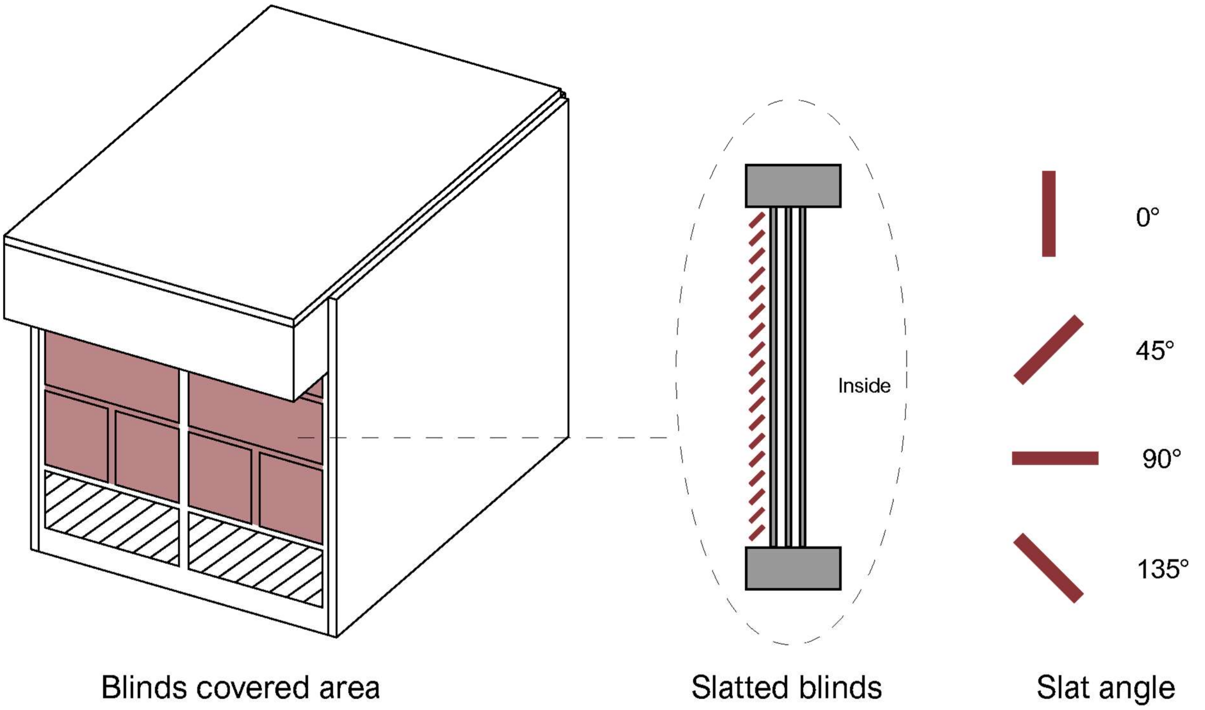
Group	Season	Over cooling [hrs]	Over heating [hrs]	Discomfor [hrs]	Lighting [kWh]	Heating [kWh]	Heating [kWh/m2]	Heating (Reality) [kWh/m2]
Reference group 1	Spring	7	20	27	13.06	297.73	16.54	16.38
	Summer	106.5	113	219.5	18.06	0.00	0.00	1.80
	Autumn	12	0	13	22.39	284.64	15.81	10.51
	Winter	1	0	0	120.81	1365.20	75.84	78.91
Reference group 2	Spring	0	12.5	12.5	13.91	174.05	9.67	-
	Summer	43.5	127.5	171	18.38	0.00	0.00	-
	Autumn	0	0	0	25.89	160.03	8.89	-
	Winter	1.5	0	1.5	135.73	719.05	39.95	-

4.5 Design variables & criteria

4.5.1 Shading variables

The external shading was activated when the operation schedule approved and the setpoint in the control type was fulfilled. The slat angle could be controlled by different parameters in different periods. Visual comfort would be fulfilled by internal shading which was manually controlled according to occupants adaptive behaviour.

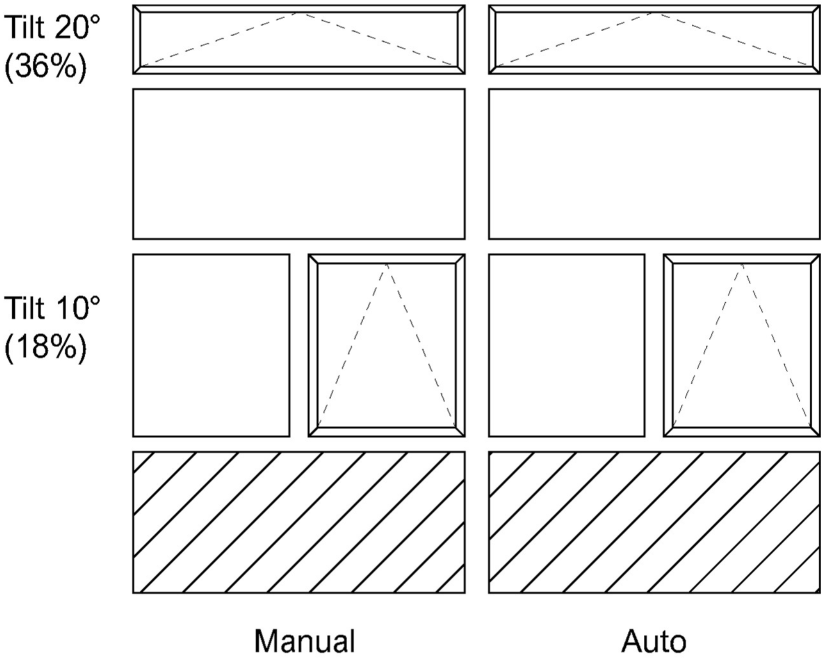
Figure 31. Shading control illustration



4.5.2 Operable window variables

The window control was set up after the shading control was defined, which meant before adding window ventilation, lighting, shading and heating were already implemented. In the 'Scheduled natural ventilation' in DB, the ventilation rates are predefined using a maximum air change rate modified by operation schedules, which may not be achieved only by operable windows. So in this project, 'Calculated natural ventilation' method was chosen, in which the ventilation rates are calculated using wind and buoyancy-driven pressure, opening sizes and operation, crack sizes.

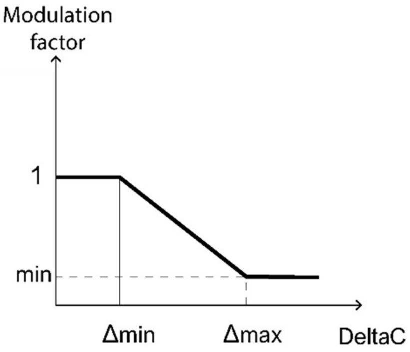
Figure 32. Operable windows



The east facade consisted of two panels, one with auto control and one with manual control. Within one panel, it was assumed that the maximum tilt angles of the top window and the bottom window were 20° (open factor 36%) and 10° (open factor 18%) respectively. Since the control focused on the tilt openings, it was assumed that wind and rain would not obstruct the operation.

The control parameters were Tin setpoint and operation schedule for activating the natural ventilation, Tin and Tex difference (DeltaC) and modulation factor for reducing opening area (Figure 33). In conclusion, the final open factor depended on time fraction, modulation factor and the opening factor of the window.

Figure 33. DeltaC and modulation factor relation



Final open factor = Time fraction X Modulation factor X Opening factor

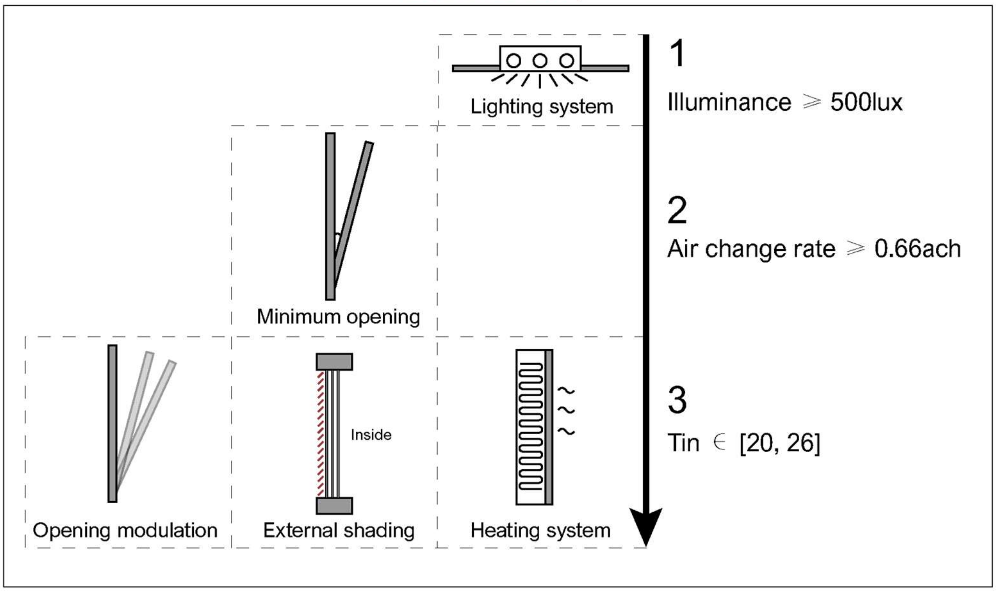
4.5.3 Criteria

The indoor illuminance should not be less then 500lux. The minimum air change rate was 0.66ach for two occupants, this value was calculated based on the CO2 concentration and Dutch standard (25 m3/h per person). The overheating was regarded as the condition below 20℃ and the overcooling was regarded as the condition above 26℃. The precise comfort range would be from 19.98℃ to 26.02℃ since 0.02℃ is the smallest temperature difference that people could recognize.

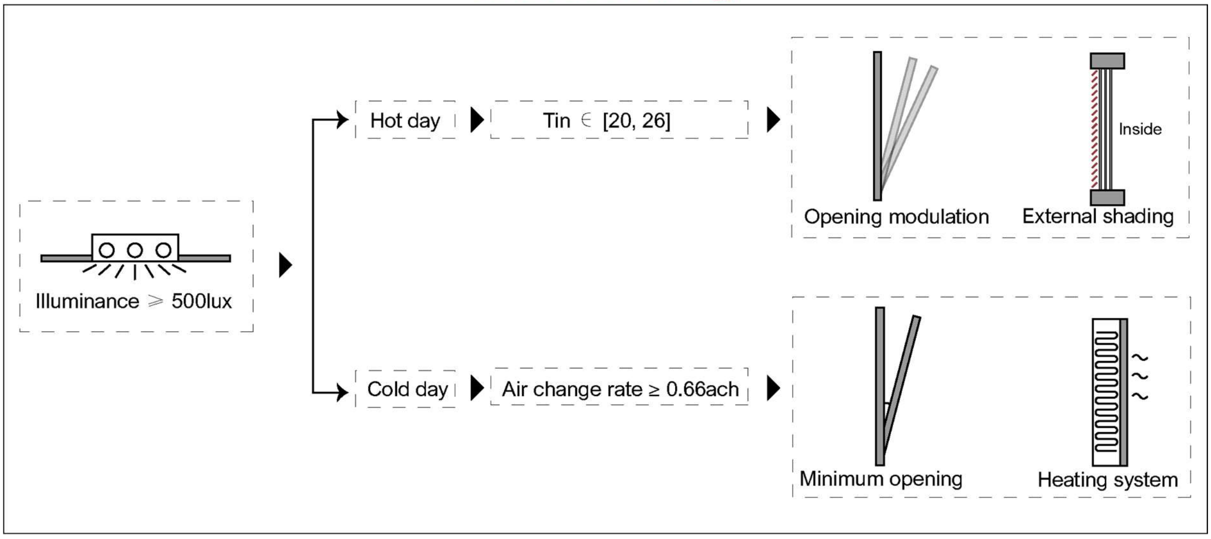
The control focused on thermal comfort and automation and then evaluated the energy consumption for heating and lighting. The control strategy was set up step by step. The optimization sequence began with the Blank group, lighting system was activated at the beginning because it affected the internal heat gains. Later in the Shading group and Nat vent group, the control mainly focused on thermal comfort without compromising the need for minimum fresh air. The operation required least operation of the manual panel and the two controls should be work in symbiosis. The general control strategy was based on the climate condition and the control hierarchy.

Figure 34. Control hierarchy, general control strategy & optimization sequence

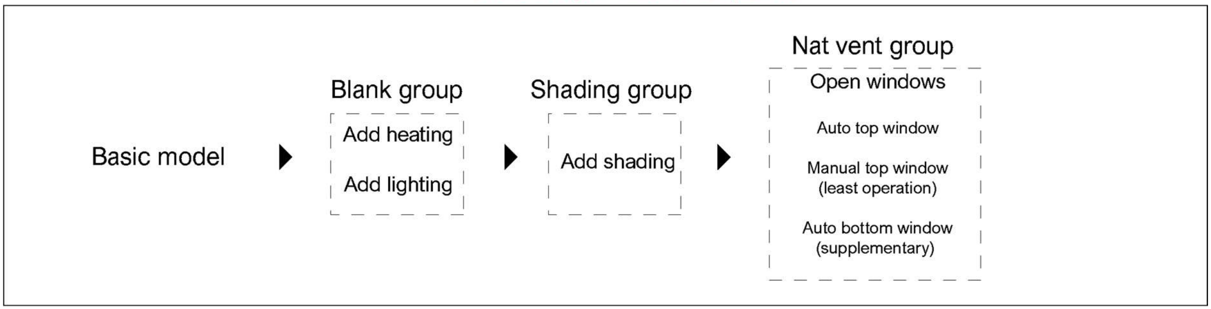
Control hierarchy



General control strategy



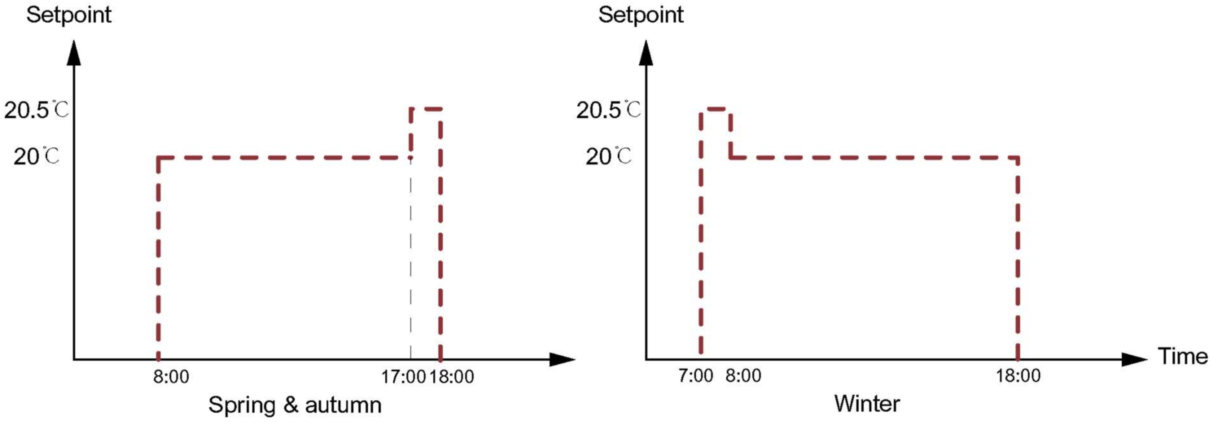
Control optimization sequence



Control of the new construction

The Tin data for evaluation was the results during occupied time. On weekends the control system would be off to reserve energy and to prevent damages from the outdoor climate under no supervision. The hearing schedule was in Figure 35.

Figure 35. Heating schedule for new construction



5.1 Summer

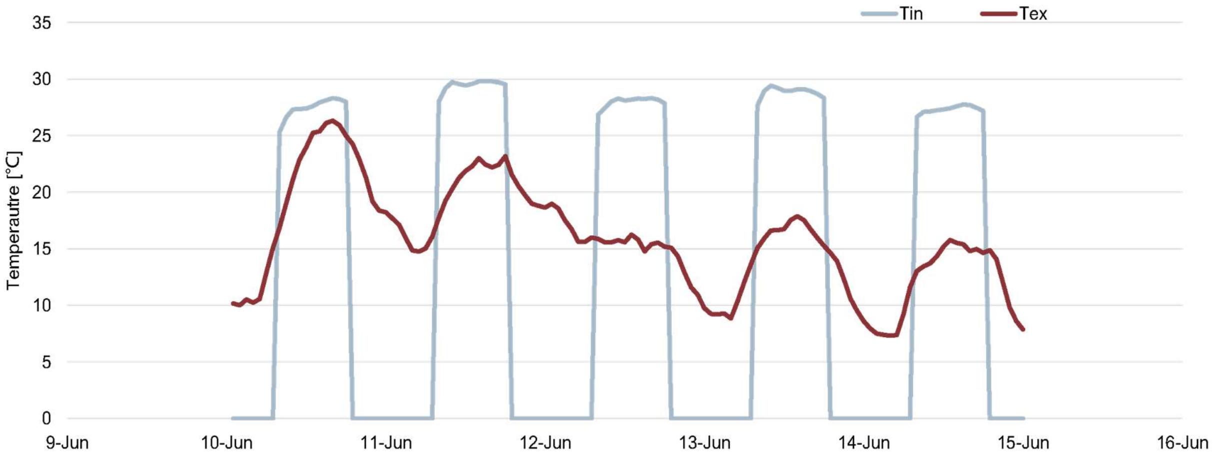
The summer in Netherlands was moderate, with Tex ranged from 4℃ to 28℃. Since there was no air conditioning and heating in summer, the goal for summer would be reducing the sum of the overcooling and overheating hours to the lowest value.

5.1.1 Shading control

The goal of summer shading control was reducing overheating without increasing overcooling. Lighting energy demand should be taken into consideration for the final choice.

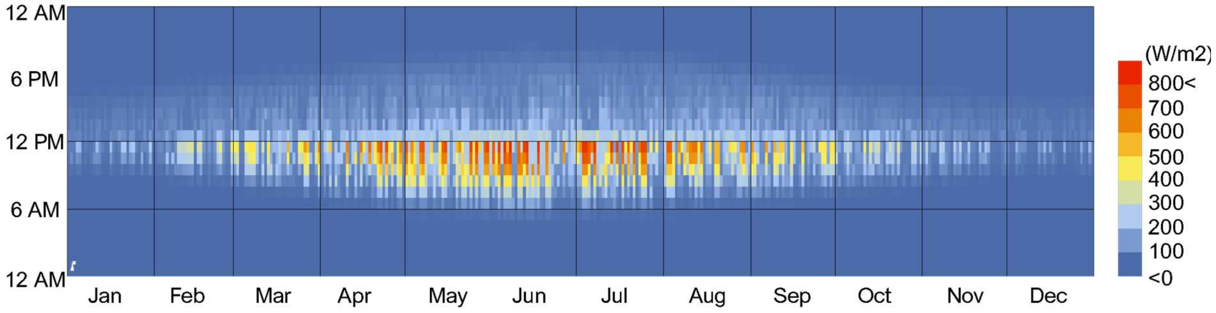
As it is shown in Figure 36, during occupied, the outdoor temperatures on June 10th were much lower than those on June 10th, while the indoor temperatures (Tin) were similar. Therefore, it was not reasonable to use outdoor temperature for shading control in this context. The setpoints for Tin were from 24℃ to 27℃, with a step of 0.5℃.

Figure 36. Indoor and outdoor temperature in summer typical week (Blank group)



From the research on control strategies of shading, the minimum direct plus diffuse solar radiation(SR) setpoint was 200W/m2, Figure 37 shows the annual distribution of SR fell on the glazing area. The setpoints for DB simulations were from 150W/m2 to 500W/m2, with a step of 50W/m2.

Figure 37. Annual distribution of SR fell on the glazing area



- Step 1 Mode selection for blinds
  The blinds only can be active from 8:00 to 18:00 on weekdays, which is regarded as the occupied time. In this step, the slat angle control is set to block beam solar (the further explanation was in Step 2). The blinds have two position, which is at a downward position when it's on and at an upward position when it’s off.

  - Blind control mode

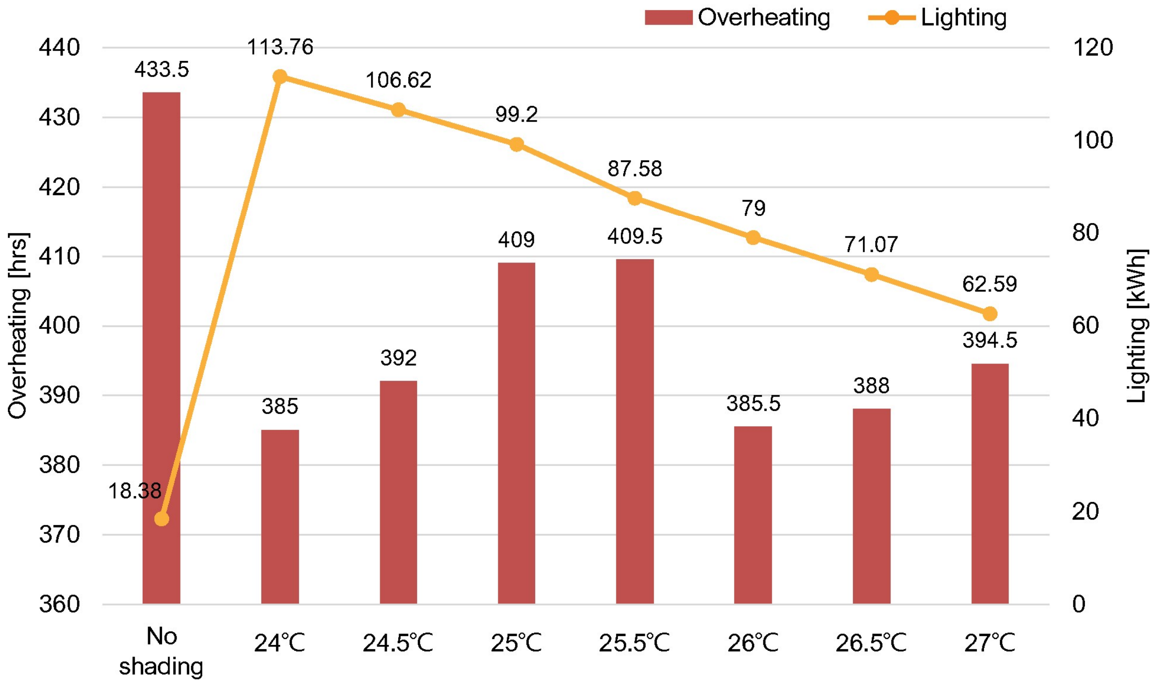
    Mode Tin: Indoor air temperature
    Blinds are on if Tin exceeds its setpoint.

    Mode HSR: Horizontal solar irradiance
    Blinds are on if total HSR exceeds its setpoint.

Mode SR: Solar radiation
Blinds are on if beam plus diffuse SR fall on the window exceeds its setpoint.

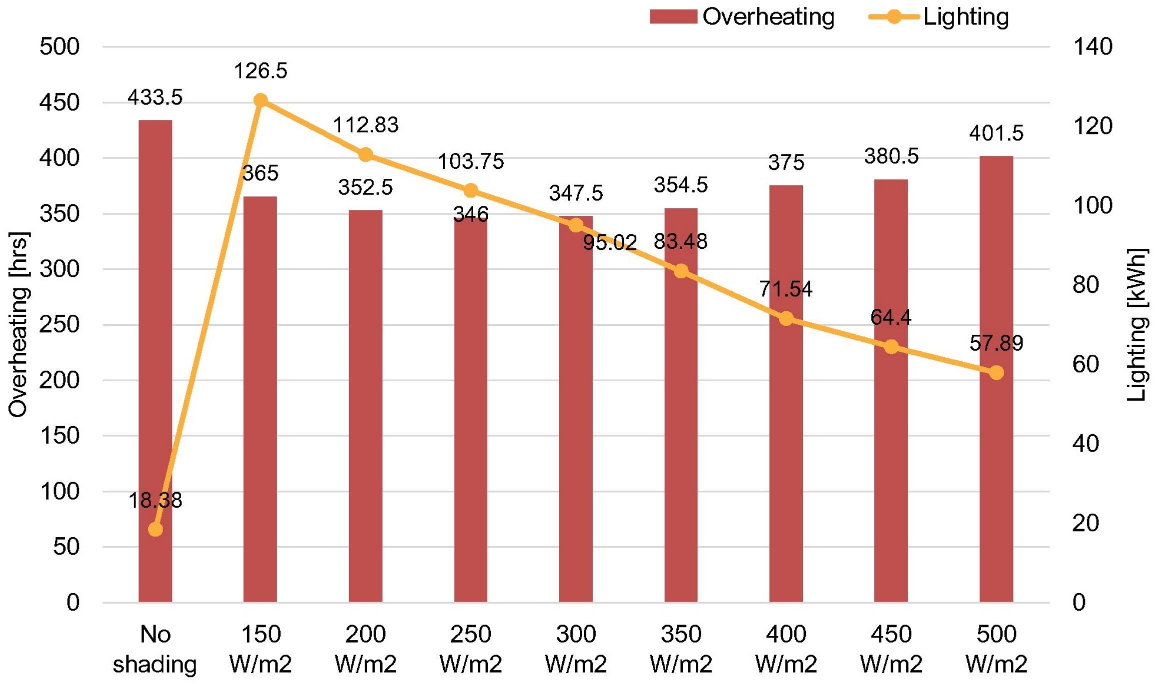
- Results and conclusion

Figure 38. Overheating hours and lighting demand of Mode Tin (Total: 715hrs)



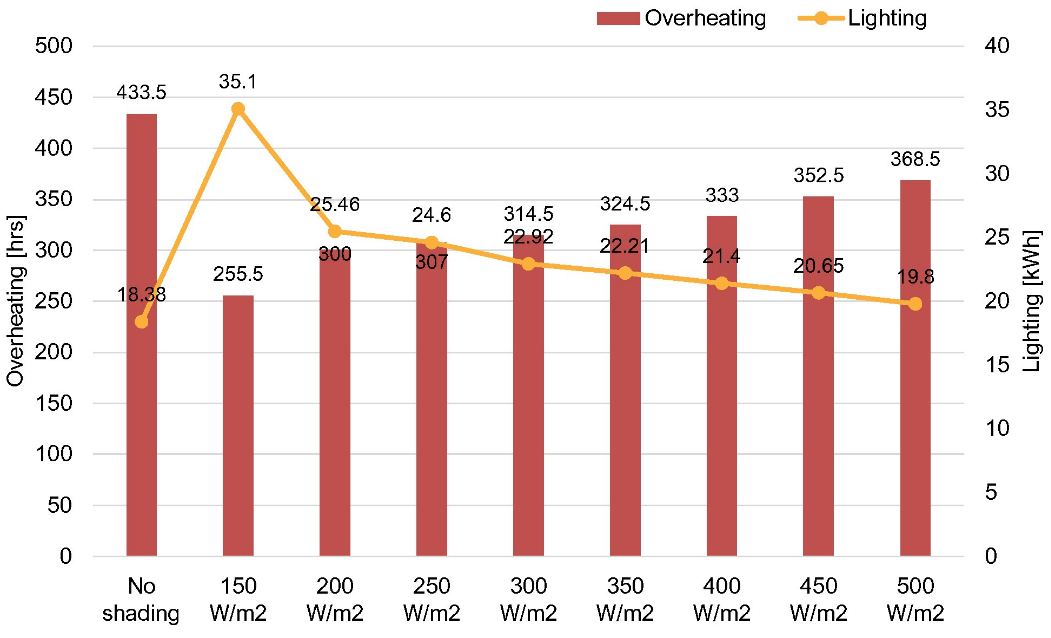
In results of Mode Tin (Figure 38), the overheating hours followed a pattern of increasing from 24℃ to 25.5℃, dropping from 25.5℃ to 26℃ and increasing again from 26℃ to 27℃. This was because when the blinds were active, the infiltration flow was affected and followed the opposite of the pattern of overheating hours.

Figure 39. Overheating hours and lighting demand of Mode HSR (Total: 715hrs)



As for Mode HSR (Figure 39), the overheating hours followed a pattern of decreasing from 150W/m2 to 250W/m2 and increasing from 250W/m2 to 500W/m2. When HSR was from 150W/m2 to 200W/m2, the shading was active for a long time (which can be seen from the lighting energy demand) that it impeded the cool air going into the space. When HSR was from 200W/m2 to 500 W/m2, the blinds were active less so that too much heat entered from the glazing.

Figure 40 . Overheating hours and lighting demand of Mode SR (Total: 715hrs)



For Mode 3, it can be concluded that SR has a great impact on reducing solar heat gain. When the setpoint increased, the overheating hours increased. The setpoint of 150W/m2 had the best performance if only considering Tin.

Compared with the first two modes, Mode SR used less lighting energy and had the greatest reduction in overheating hours. Combining with lighting consumption, a setpoint of 200W/m2 would be the best choice of Step1.

- Step 2 Mode selection for slat angle
  - Slat angle

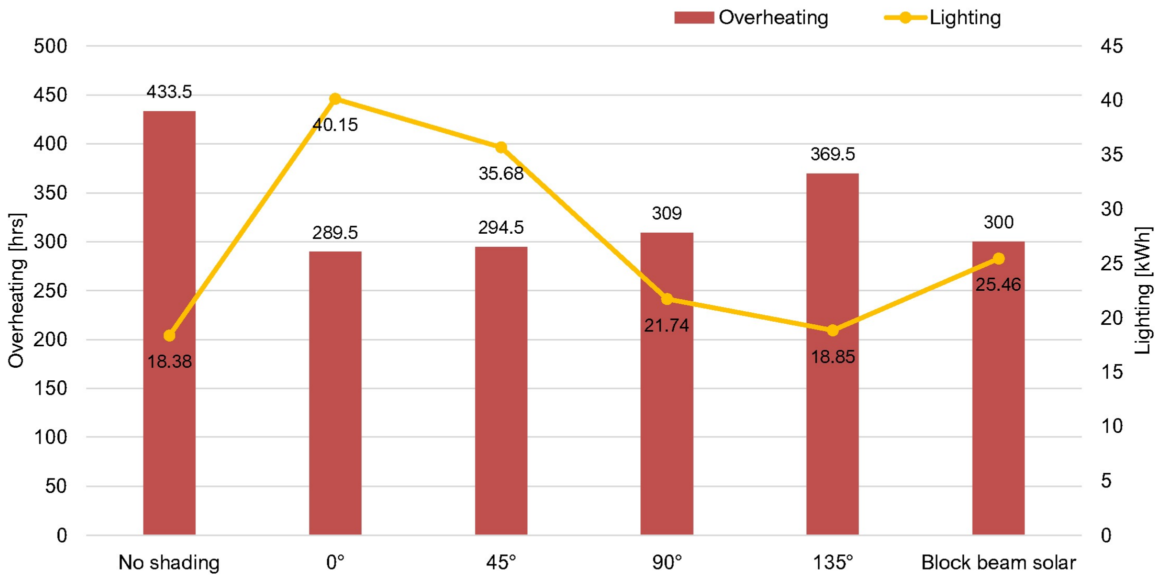
    In this step, the blinds are on when SR exceeding 200W/m2. The slats are set either at a fixed angle or block beam solar when the blind is on. The setpoints were 45° , 90° , 135° and block beam solar. Block beam solar means the slats are orientated to be perpendicular to the direction of the sun rays to block as much solar radiation as possible when the blind is on.

  - Results and conclusion

Table 17. Overheating hours and lighting demand with SR setpoint of 200W/m2

Slat angle	No shading	0°	45°	90°	135°	Block beam solar
Overheating [hrs]	433.5	289.5	294.5	309	369.5	300
Lighting [kWh]	18.38	40.15	35.68	21.74	18.85	25.46

Figure 41. Overheating hours and lighting demand with SR setpoint of 200W/m2 (Total: 715hrs)



From the results in Table 17 and Figure 41, slat angles controlled to block beam solar had a moderate towards reducing overheating and consuming lighting energy. In conclusion, using Mode SR (200W/m2) for blinds and block beam solar for slat angle was the choice of summer shading control, which had a reduction of 133.5hrs in overheating hours and an addition of 7.08kWh in lighting energy demand, comparing with the Blank group.

5.1.2 Operable window control

The goal for summer operable window control would be further reducing total discomfort hour to the lowest value. The detailed simulation results were in Appendix 3.

- Step1. Two top window

A pretest showed that only operating the auto top window was not enough to reach satisfying cooling effect in summer. Therefore the first step was to see the effect of using two top windows. The manual top window should be at a fixed position without any setpoint during the whole summer to avoid frequent manual operation. As for the auto top window, first the operation was 24 hours on weekdays with an open factor of 36% (which was the maximum) and a Tin setpoint of 20℃ (the most critical operation temperature that caused overcooling). Then DeltaC and different Tin setpoints were used to refine the two window control. Tin setpoint ranged from 20℃ to 21.5℃ with a step of 0.5℃.

Figure 42 Discomfort hours of summer ventilation without modulation

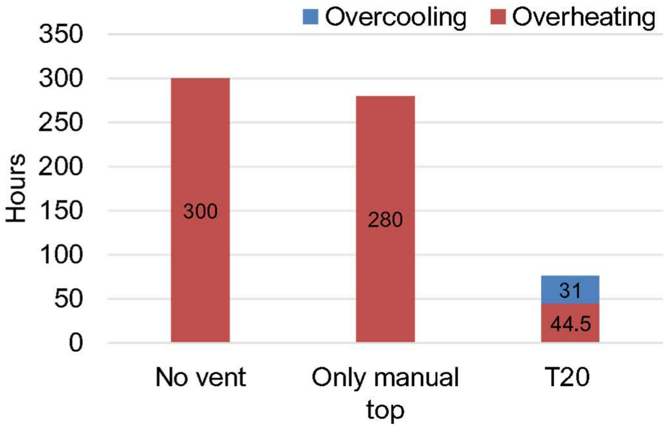


Figure 43. Discomfort hours of summer ventilation with DeltaC modulation

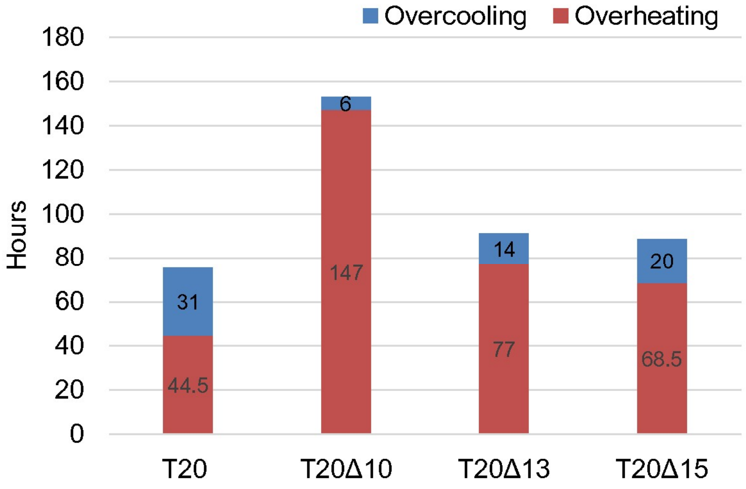
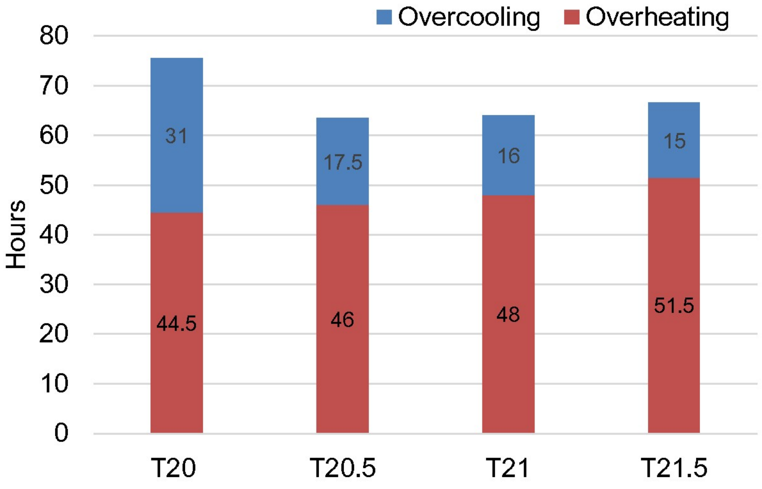


Figure 44. Discomfort hours of summer ventilation with Tin modulation



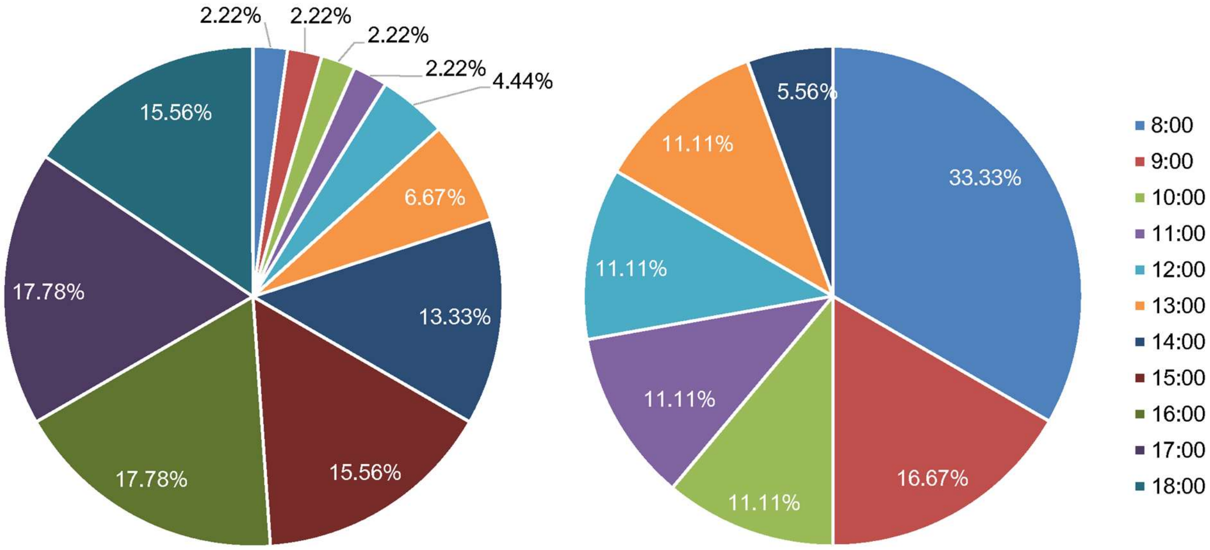
The simulations showed that an open factor of 27% was the maximum value for the manual top window to operating 24 hours without causing overcooling. From Figure 42, only using the manual top window could reduce 20 hours of overheating. Combining the auto top window could reduce 224.5 hours of overheating while increase 31 hours of overcooling. Figure 43 shows the results of adding DeltaC modulation for the auto top window without changing Tin setpoint. DeltaC reduced overcooling and increased much more in overheating, which meant it did not help in reducing total discomfort hours. Figure 44 shows the results of changing Tin setpoint for the auto top window. This measure also reduced overcooling and increased overheating, but it lowered the total discomfort hours.

As a conclusion in this step, the control would be the manual top window kept opening 27% and the auto top window opened 36% when reaching Tin setpoint of 20.5℃, which had the best performance of 63.5 hours in discomfort.

- Step 2. Auto bottom window for supplement

In this step, the auto bottom window was used for further reducing overheating hours. As the auto windows were activated by the same Tin setpoint and adding bottom window would change the operation for the auto top window by affecting Tin, four proposals were introduced in this step. The schedules in proposal 2 and 3 (P2& P3) were based on the discomfort hour distribution of the control option in Step 1 (Figure 45), in which overcooling mostly happened in 8:00 to 13:00 while overheating mostly happened in 14:00 to 18:00.

Figure 45. Discomfort hour distribution of the control option in Step 1



Auto top 36%(24/7)+Manual top 27%(24/7)
T20.5 Overheating time distribution

Auto top 36%(24/7)+Manual top 27%(24/7)
T20.5 Overcooling time distribution

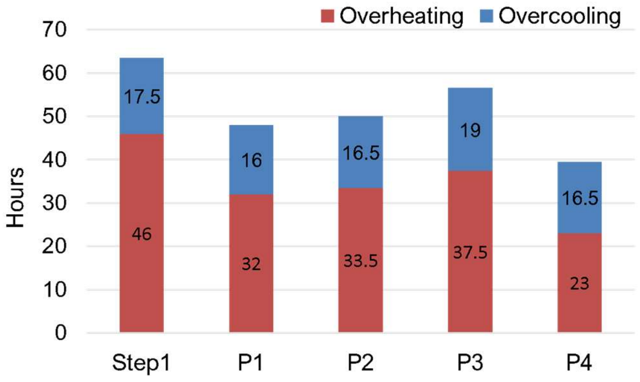
P1 was to use the auto bottom window from 8:00 to 18:00 and share the same DeltaC with auto top window while the manual top window remained the same. The best option for this proposal was using a Tin setpoint of 21.5℃ and a shared DeltaC of 22℃.

P2 was to use the auto bottom window from 13:00 to 18:00 (began at 13:00 instead of 14:00 to pre-cool the space) with DeltaC modulation and shared the same Tin setpoint with auto top window. The manual top window would be always opened 27% and the auto top window would be opened 36% if reaching Tin setpoint during 24 hours in weekdays. The best option for this proposal was using a Tin setpoint of 21℃ and a DeltaC of 14℃.

P3 was similar to P2, the manual top window remained the same. The difference was the two auto windows would share the same DeltaC to modulate the opening together since using different DeltaCs would break the balance and cause frequent operation of the windows. The best option for this proposal was using a Tin setpoint of 20.5℃ and a shared DeltaC of 20℃.

P4 was to use the auto bottom window that shares the same DeltaC and schedule (24/7) with auto top window while the manual top window remained the same. The best option for this proposal was using a Tin setpoint of 21.5℃ without DeltaC.

Figure 46. Discomfort hours for different proposals



Proposal	Detail
Step1	T20.5
P1	T21.5_t36%(24/7)_b18%(8:00-18:00)_Δ22
P2	T21_t36%(24/7)_b18%Δ14(13:00-18:00)
P3	T20.5_t36%(24/7)_b18%(13:00-18:00)_Δ20
P4	T21.5_t36%(24/7)_b18%(24/7)

Comparing these three proposals with the option in Step 1 (Figure 46), P4 would be the final choice for summer control, which had the least discomfort hours of 39.5.

5.2 Winter

Tex in winter was almost always under 15℃. The control goal for winter was to use the least heating energy.

5.2.1 Shading control

In this season, the need for heating was dominant, so SR will not be used for controlling shading since it would reduce the solar gain. The goal of this part was reducing overcooling and heating energy demand.

The blinds only can be active from 18:00 to 8:00 on weekdays. During occupied time, the blinds will not be active so as to gain solar heat and light. When the value is below the setpoint, blinds are active, the slat angle would be 0° , which is regarded as parallel to the glazing and has the best thermal insulation. As Tin should be maintained above 20℃ as possible to reduce heating energy, the Tin at night (Night Tin) setpoints were 20℃, 20.5℃ and 21℃.

Table 17. Discomfort hours and energy demand in winter (Total: 1177hrs)

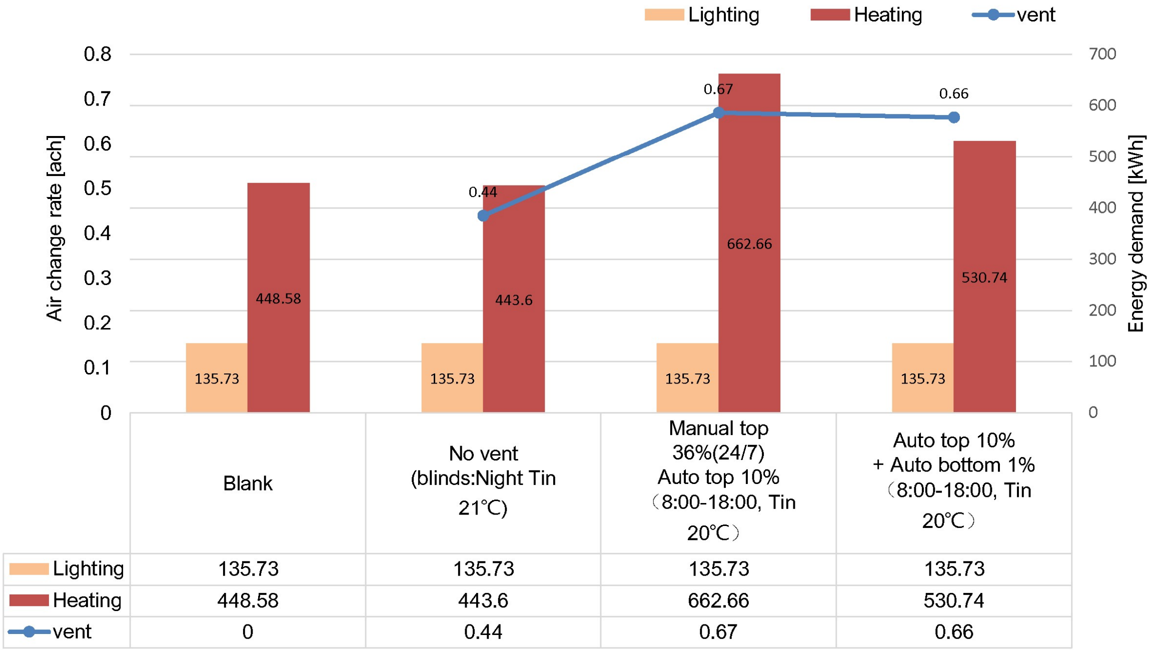
	Night Tin [℃]	Overheating [hrs]	Overcooling [hrs]	Lighting [kWh]	Heating [kWh]
Winter without heating	Blank	0	1167	135.73	-
	Night Tin 20℃	0	1166	135.73	-
	Night Tin 20.5℃	0	1166	135.73	-
	Night Tin 21℃	0	1166	135.73	-
	on 18:00-8:00	0	1169	135.73	-
Winter with heating	Blank	0	0	135.73	448.58
	Night Tin 20℃	0	0	135.73	443.87
	Night Tin 20.5℃	0	0	135.73	443.76
	Night Tin 21℃	0	0	135.73	443.6
	on 18:00-8:00	0	0	135.73	445.71

From Table 17, activating the shading when unoccupied reduced the heat gain in the morning, so it caused more heating energy. Although using Night Tin as stimulus just reduce one hour of overcooling, it contributed to the reduction of heating demand in the early morning without obstructing the heating entering the glazing. Therefore, for winter, the blinds would use Night Tin of 21℃ as setpoint.

5.2.2 Operable window control

To meet the control goal of winter, the natural ventilation through operable windows was to meet the minimum fresh air requirement (0.66ach for two people). With the heating system to maintain Tin at 20℃, using two top windows can reach no discomfort hour, but resulting in large heating consumption, which was 662.66kWh. This was because the manual top window brought too much cold air and increased heat loss. The final window control would be opening the auto bottom window at 1% and top auto window at 36% when occupied, whose heating consumption was 530.74kWh (Figure 47).

Figure 47. Ventilation and energy demand in winter (Total: 1177hrs)



	Blank	No vent (blinds:Night Tin 21℃)	Manual top 36%(24/7) Auto top 10%（8:00-18:00, Tin 20℃）	Auto top 10% + Auto bottom 1%（8:00-18:00, Tin 20℃）
Lighting	135.73	135.73	135.73	135.73
Heating	448.58	443.6	662.66	530.74
vent	0	0.44	0.67	0.66

5.3 Spring & Autumn

There were overheating and overcooling in spring and autumn, the overcooling could be eliminated by the heating system. The overheating could be eliminated when implementing natural ventilation. As spring had a more fluctuant temperature pattern, spring was chosen for the simulation and autumn used the same control as spring’s.

5.3.1 Shading control

The goal of this part was to reduce heating consumption. Table 18 was the results of the shading simulation using the same logic of winter.

Table 18. Discomfort hours and energy demand in spring (Total:495hrs) & autumn (Total:484hrs)

	Night Tin [℃]	Overheating [hrs]	Overcooling [hrs]	Lighting [kWh]	Heating [kWh]
Spring without heating	Blank	84	189	13.91	-
	Night Tin 20℃	84	188	13.91	-
	Night Tin 20.5℃	84	188	13.91	-
	Night Tin 21℃	84	188	13.91	-
	on 18:00-8:00	65.5	199	13.91	-
Spring with heating	Blank	84	0	13.91	26.95
	Night Tin 20℃	84	0	13.91	26.44
	Night Tin 20.5℃	84	0	13.91	26.41
	Night Tin 21℃	84	0	13.91	26.4
	on 18:00-8:00	69	0	13.91	29.64
Autumn without heating	Blank	0	158.5	25.89	-
Autumn with heating	Blank	0	0	25.89	27.27

The results of spring had a similar pattern as winter's, but the control was not contributed obviously in the reduction of heating energy. In conclusion, the shading control would not be active in spring and autumn.

5.3.2 Operable window control

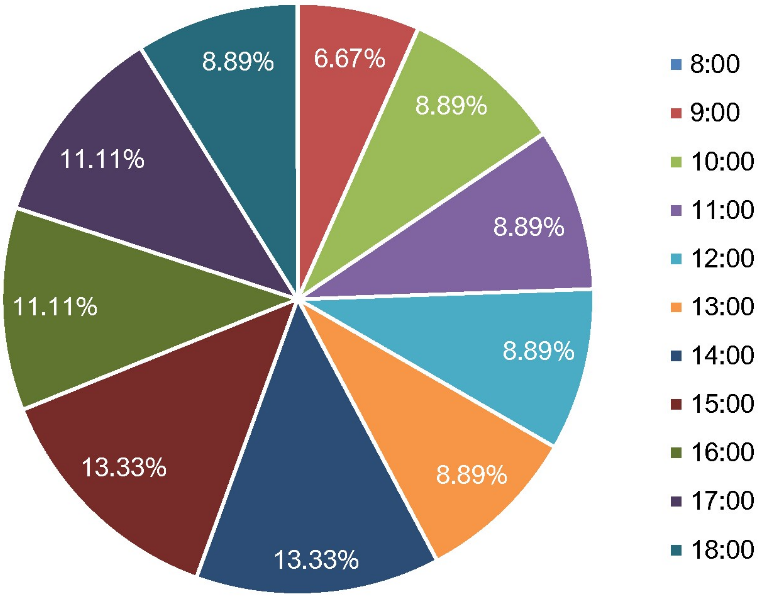
The control goal was to reach minimum overheating and ensure the fresh air need in the cold day.

- Step1 Two top window

  The auto top window was opened 36% when occupied and the manual top window was opened 12% during the whole spring to meet the requirement of minimum fresh air as well as to avoid consuming too much heating energy (The results were shown in Table 19).

- Step2 Auto bottom window for supplement

Figure 48. Overheating hour distribution of the control option in Step 1



In this step, the auto bottom window was used for further reducing overheating hours. Based on the discomfort hour distribution of the control option in Step 1 (Figure 48), in which 45 overheating hours which were distributed in 9:00 to 18:00 in May, the schedule for the bottom window was set from 8:00 to 18:00. As the maximum Tin happened was 22.28℃ in April, Tin setpoint should be larger than 22℃ to avoid extra heating consumption.

Figure 49. Performances of different proposals in Spring

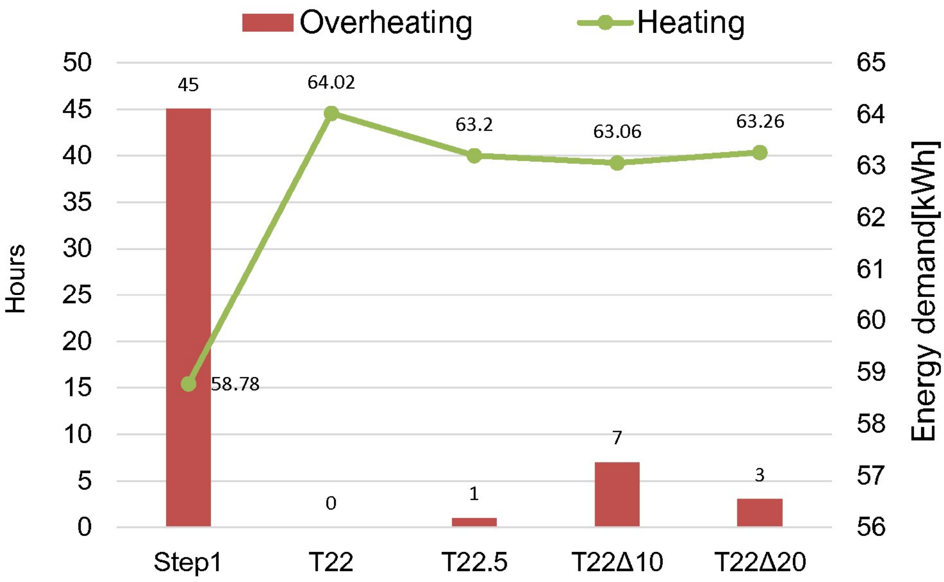


Table 19. Performances of different proposals in spring & autumn verification

Proposal	Detail	Overcooling [hrs]	Overheating [hrs]	Total discomfort [hrs]	Lighting [kWh]	Heating [kWh]
Step1	mt12%_t36%(8:00-18:00)	0	45	45	13.91	58.78
T22	mt12%(24/7)_t36%_b18%T22_(8:00-18:00)	0	0	0	13.91	64.02
T22.5	mt12%(24/7)_t36%_b18%T22.5_(8:00-18:00)	0	1	1	13.91	63.2
T22Δ10	mt12%(24/7)_t36%_b18%Δ10T22_(8:00-18:00)	0	7	7	13.91	63.06
T22Δ20	mt12%(24/7)_t36%_b18%Δ10T22_(8:00-18:00)	0	3	3	13.91	63.26
T22 (Autumn)	mt12%(24/7)_t36%_b18%T22_(8:00-18:00)	0	0	0	25.89	55.1

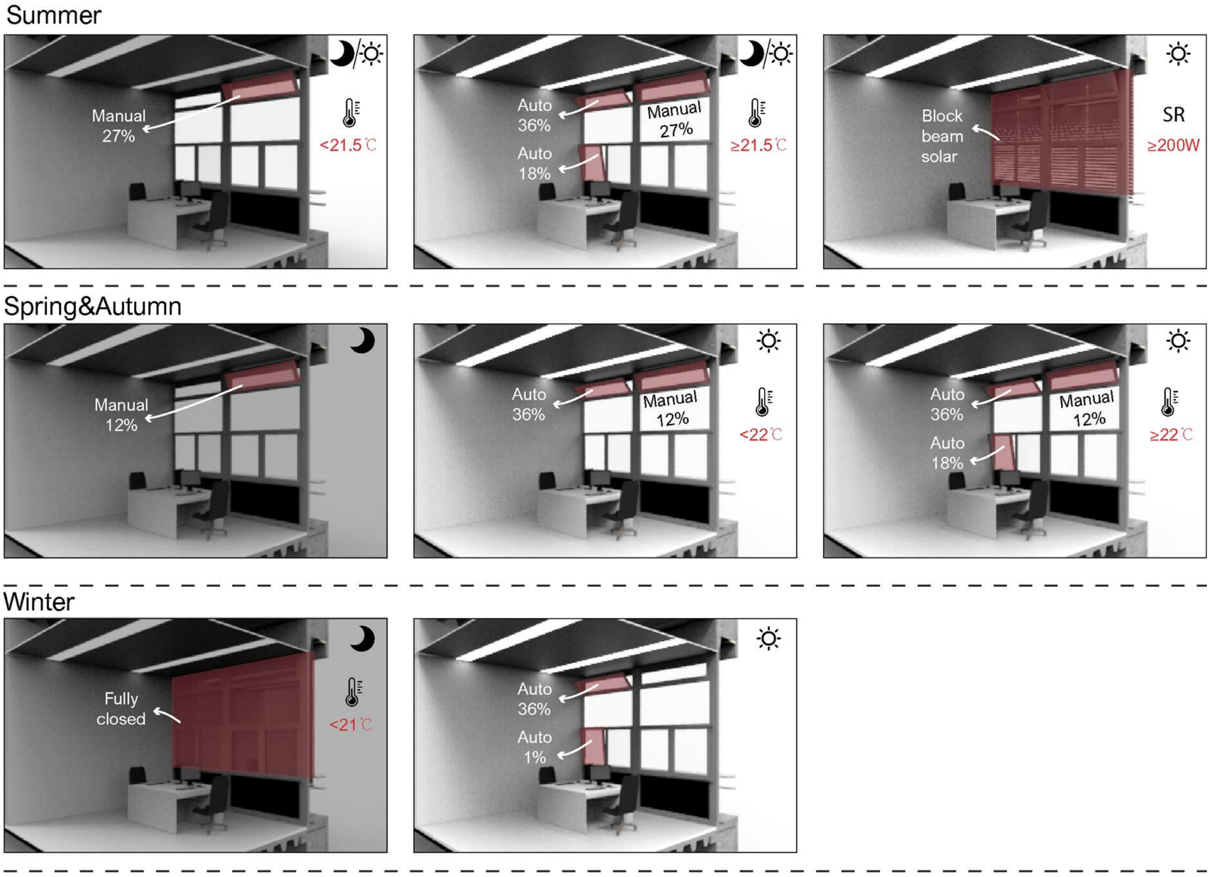
From Figure 49, changing Tin setpoint or DeltaC reduced heating energy but increased overheating. So the best option would be Tin setpoint at 22℃ with no DeltaC, whose total discomfort hour was 0. Implementing it in autumn also resulted in no overheating. Table 24 is a summary of different proposals in spring and the autumn verification.

5.4 Summary

- The control

The control flow chart of new construction was in Appendix 4. Figure 50 was the control scheme of four seasons.

Figure 50. Control scheme of new construction



- Performance

Compared with Reference group 2, the control cut 79% of discomfort hours and 38% of heating demand. To point out, the heating reductions for spring, autumn and winter were 63%, 66%, 26% compared to the one without. For summer, it reduced 77% (131hrs) of discomfort, which was 90% of the total reduction. Table 20 was the summary of the performances with and without control in four seasons.

Figure 51. New construction groups heating energy comparison

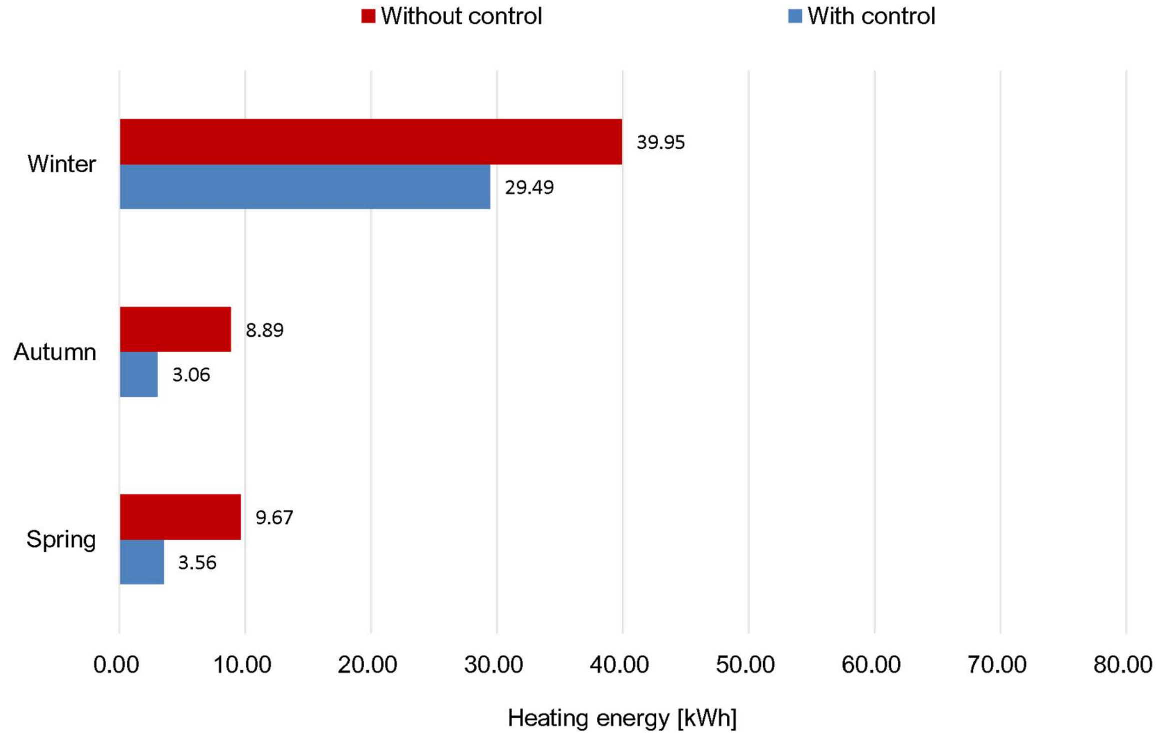


Figure 52. New construction groups comfort comparison(hrs)

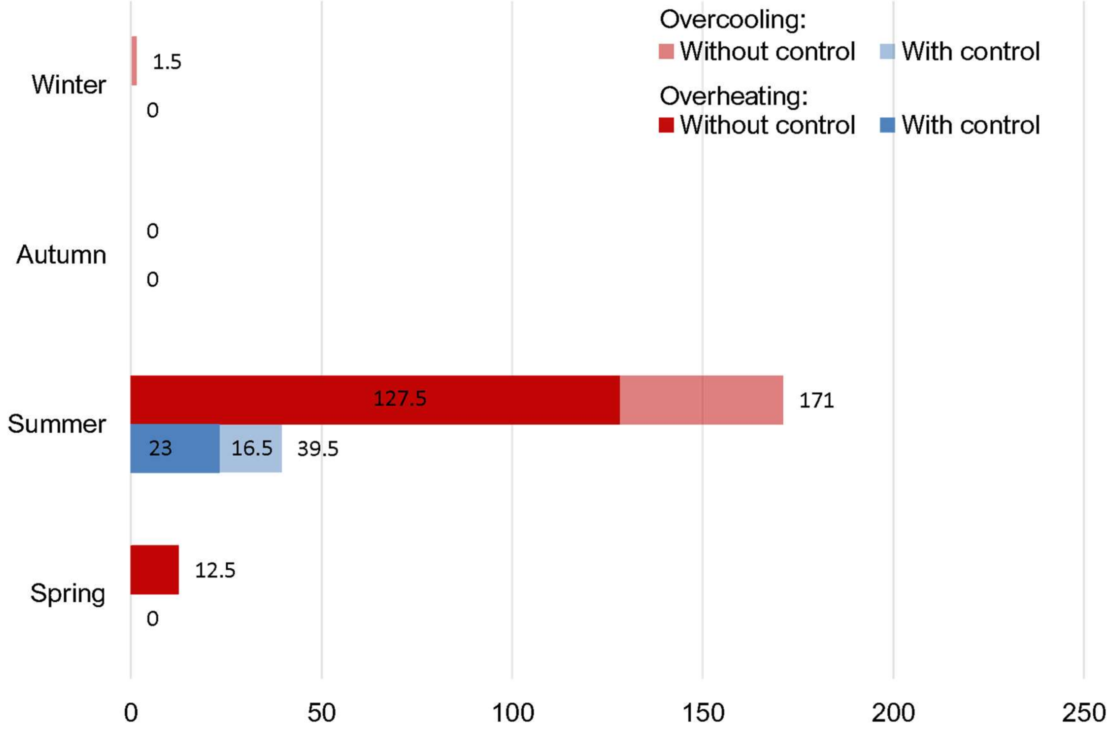


Table 20 Data of the new construction groups

New construction without control (Reference group 2)

Season	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Lighting [kWh]	Heating [kWh]	Heating [kWh/m2]	Heating (Reality) [kWh/m2]
Spring	0	12.5	12.5	13.91	174.05	9.67	-
Summer	43.5	127.5	171	18.38	0.00	0.00	-
Autumn	0	0	0	25.89	160.03	8.89	-
Winter	1.5	0	1.5	135.73	719.05	39.95	-

New construction with control

Season	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Air change rate[ach]	Lighting [kWh]	Heating [kWh]	Heating [kWh/m2]
Spring	0	0	0	1.05	13.91	64.01	3.56
Summer	16.5	23	39.5	1.82	25.46	-	-
Autumn	0	0	0	0.87	25.89	55.1	3.06
Winter	0	0	0	0.66	135.73	530.74	29.49

Control of the old construction

The control of the new construction shows great potential in energy and thermal comfort performance. However, if the control of the old construction could reach the requirement, it may not be necessary to replace the facade materials in the renovation, regarding the CO2 footprint and payback. Therefore, a control for the old construction was developed in this chapter.

6.1 Old construction with ‘New control’

By comparing the performances of new construction with the old one using the same control (the one that the new construction used), the process of designing the new control for the old one could be predefined.

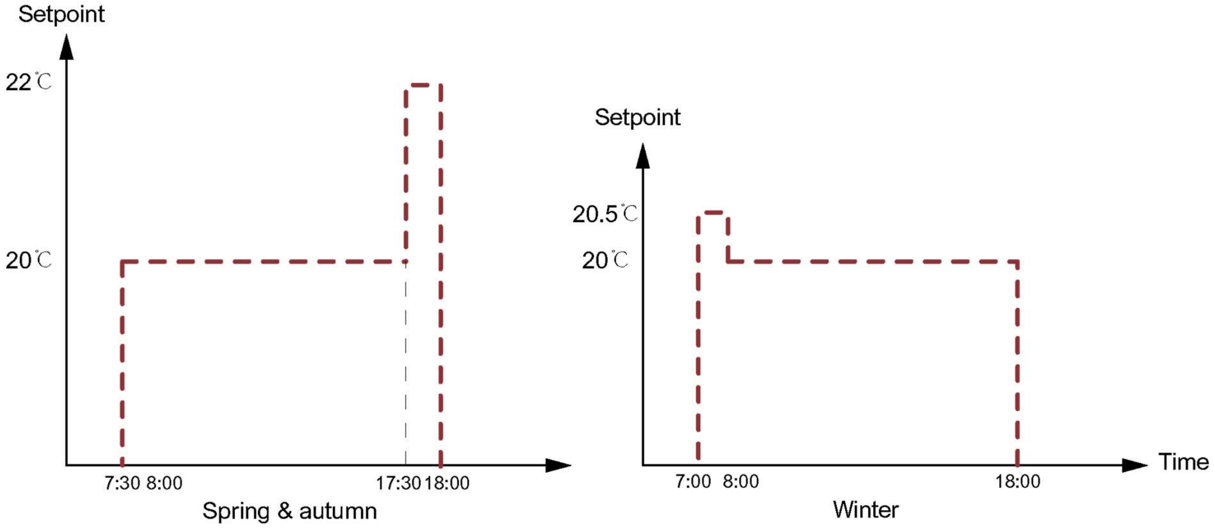
Table 21 Performance of the old construction using the control of new construction

Season	Type	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Air change rate[ach]	Lighting consumption [kWh]	Heating consumption [kWh]
Spring	Blank	19.5	84	103.5	-	13.06	72
	Shading	-	-	-	-	-	-
	Nat Vent	19	19	38	1.1	13.06	114.06
Summer	Blank	22.5	329.5	352	-	18.06	-
	Shading	31.5	159.5	191	-	21.64	-
	Nat Vent	52	53	105	1.74	22.14	-
Autumn	Blank	1	19	20	-	22.39	74.23
	Shading	-	-	-	-	-	-
	Nat Vent	0	19	19	0.86	22.39	106.68
Winter	Blank	0	0	0	-	120.81	899.79
	Shading	0	0	0	-	120.81	813.58
	Nat Vent	0	0	0	0.67	120.81	923.59

The old one has higher U-value & g-value. For the summer blank groups, the old one had overcooling and less overheating. So summer should use Mode SR and slat angle of ‘block beam solar’, and the setpoint should not increase too much overcooling since it would increase more when implementing ventilation. The night shading decreased much more in the heating energy in winter, so winter should use the same control(Night Tin), but whether it would be effective for spring and autumn remained unknown until the simulations.

For ventilation, the design logic was similar to the new construction's. Heating schedule was in Figure 53 (see Section 6.4.1). Other settings such as lighting would remain the same as the control of the new construction.

Figure 53. Heating schedule for old construction



6.2 Summer

6.2.1 Shading control

In Figure 54, when SR setpoint was 650W/m2, the lighting energy was the same as the one without shading control, which meant the shading was only active when the indoor illuminance was over 500lux. However, it was not effective enough for relieving thermal comfort. Overall, the overheating hour decreased and the overcooling hour increased when increasing the SR setpoint value. As adding ventilation would further strengthen this trend. The SR setpoint could not be defined without the estimation of ventilation. Therefore, a ventilation pretest was conducted to help choosing the SR setpoint.

Figure 54. Discomfort hours and lighting demand of different SR setpoints (Total: 715hrs)

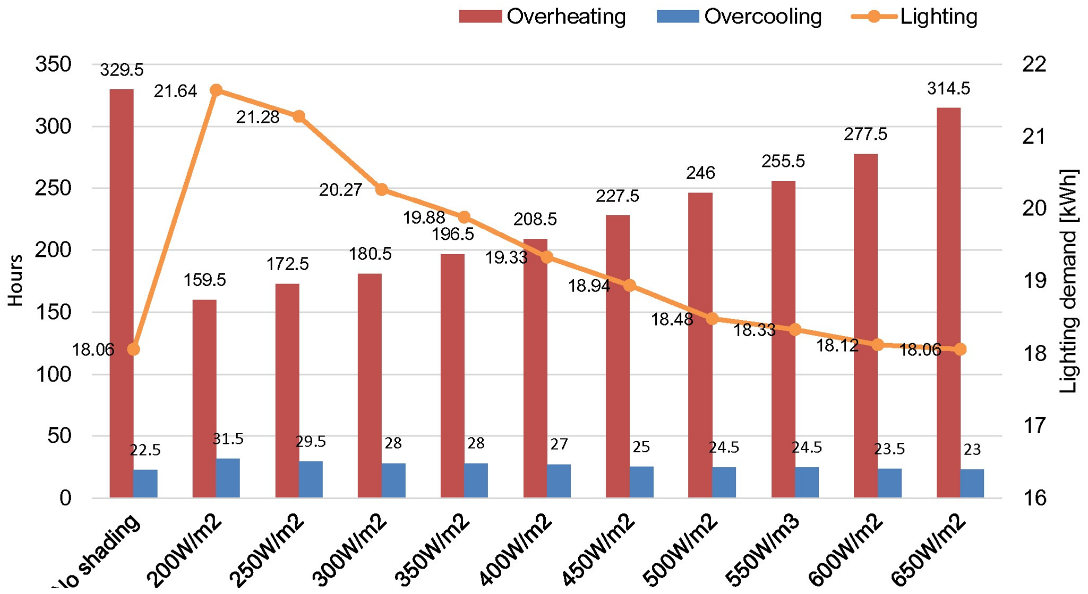


Figure 55. Ventilation pretest of different SR setpoints (1.35ach)

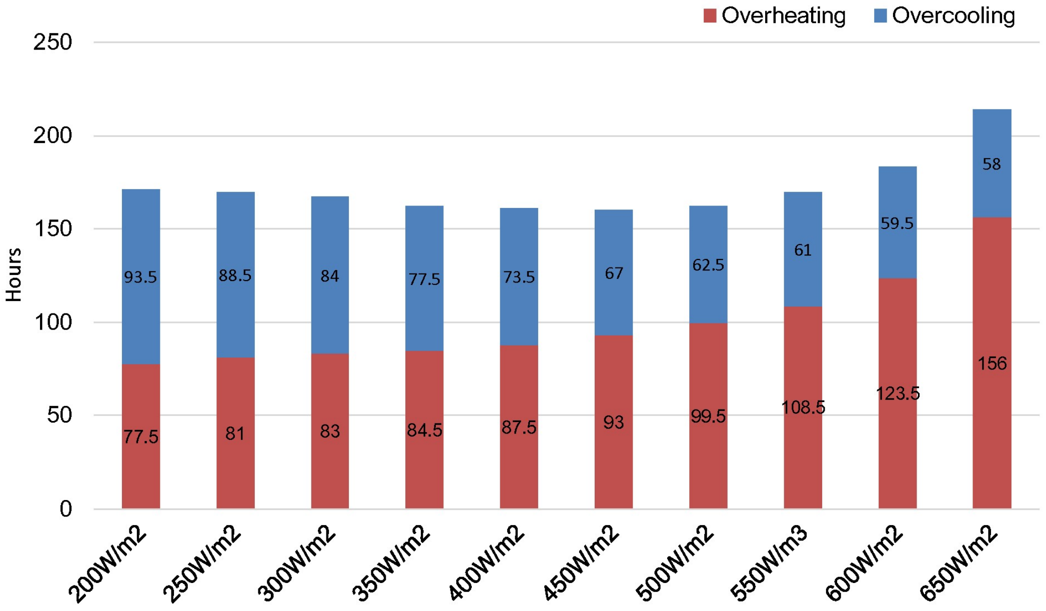
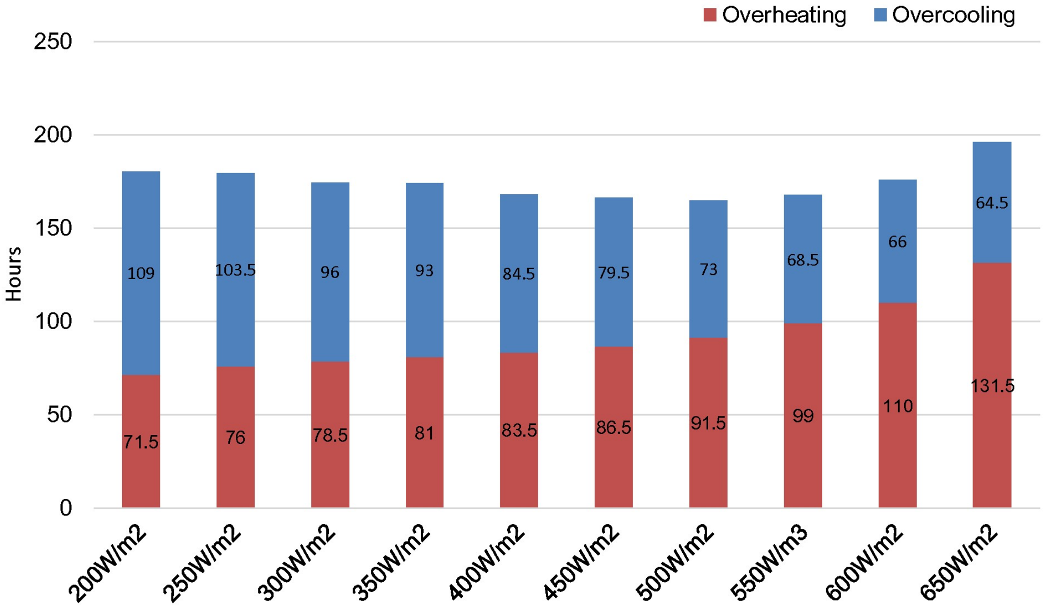


Figure 56. Ventilation pretest of different SR setpoints (1.55ach)



When using a fixed ventilation rate of 1ach and an infiltration of 0.35ach (Figure 55), the discomfort hours first decreased from 200W/m2 to 450W/m2 and then began to increase. When using a fixed ventilation rate of 1.2ach and an infiltration of 0.35ach (Figure 56), the critical setpoint turned to 500W/m2. In other words, the ventilation influenced the shading control selection. For conducting the operable window control, the setpoint of 450W/m2 would be used and the final setpoint for shading would be checked after the window control came out.

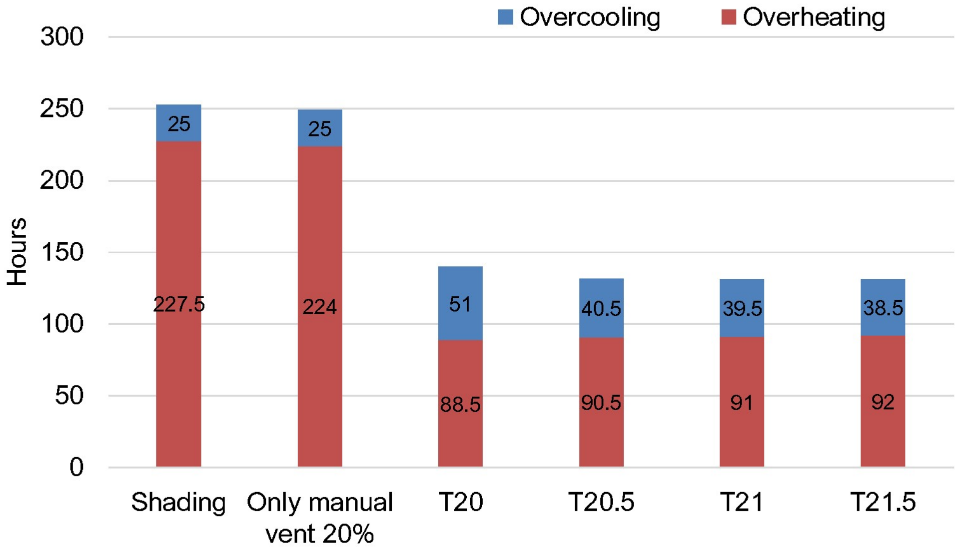
6.2.2 Operable window control

The goal for summer operable window control would be further reducing total discomfort hour to the lowest value. The detailed simulation results were in Appendix 4.

- Step1. Two top window

  Tin setpoint was 20℃ at the beginning since it was the most critical operation temperature that caused overcooling. Then DeltaC and different Tin setpoints were used to refine the two window control. Tin setpoint ranged from 20℃ to 22℃ with a step of 0.5℃.

Figure 57. Discomfort hours of summer ventilation with Tin modulation

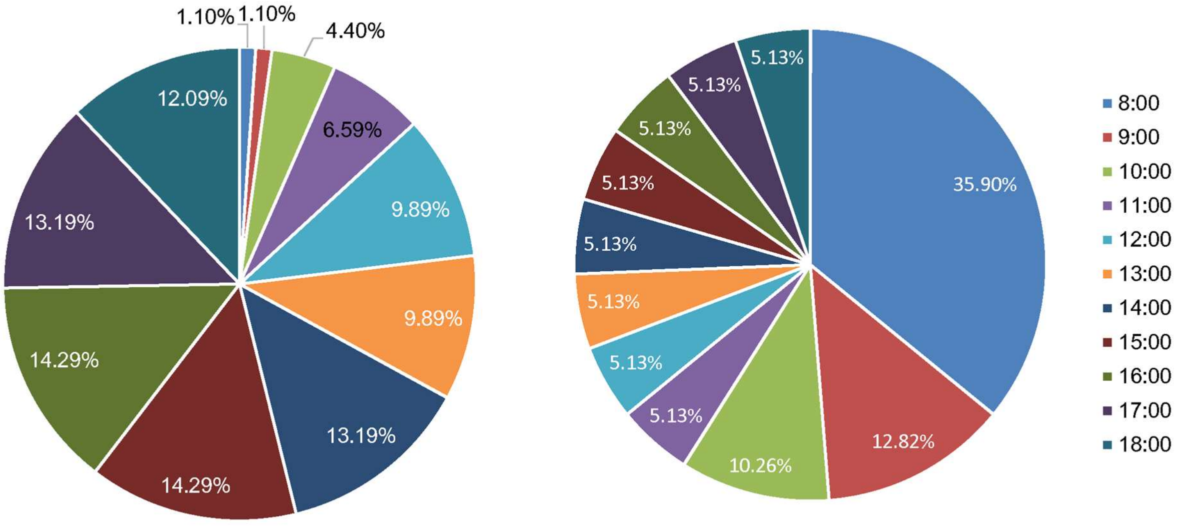


Three windows need to be operated to ensure thermal comfort in summer. The first step was to define the open factor for the manual top window, which was kept opened during the whole summer and should not increase the overcooling hours. An open factor of 20% could satisfy this requirement, resulting in 25hrs overcooling and 224hrs overheating. From Figure 57, only using manual top window could only reduce 3.5 hours of overheating. As from the simulation of new construction control, DeltaC modulation would not be effective for operating two top windows, but Tin modulation would. So the second step would be simulating different Tin for auto top window. As a result, Tin setpoints of 21℃and 21.5℃ both had the least discomfort hours (130.5hrs).

- Step 2. Auto bottom window for supplement

In this step, the auto bottom window was used for further reducing overheating hours. Similar to new construction control, when implementing bottom window, it changed the operation for the auto top window by affecting Tin. So three proposals were introduced in this step, the proposal of operating auto top window when overheated and shared a DeltaC for two auto window was abandoned according to the simulation of new construction control. The schedules in P1 was based on the discomfort hour distribution of the control option in Step 1 (Figure 58), where overcooling mostly happened in 8:00 to 10:00 while overheating mostly happened in 11:00 to 18:00.

Figure 58. Discomfort hour distribution of the control option in Step 1



Auto top 36%(24/7)+Manual top 20%(24/7)
T21 Overheating time distribution

Auto top 36%(24/7)+Manual top 20%(24/7)
T21 Overcooling time distribution

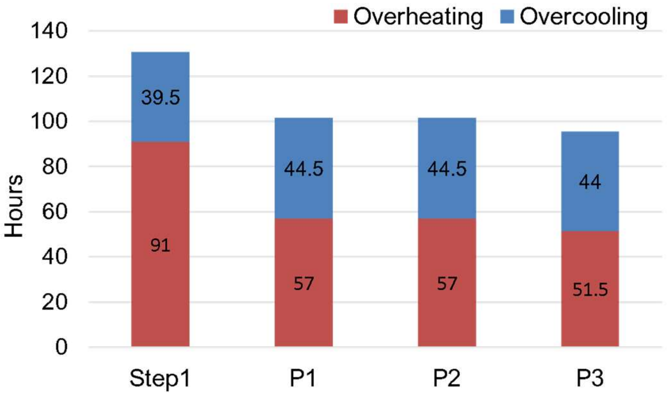
P1 was to use the auto bottom window from 8:00 to 18:00 and share the same DeltaC with auto top window while the manual top window stayed the same.

P2 was to use the auto bottom window from 10:00 to 18:00 with DeltaC modulation and shared the same Tin setpoint with auto top window. The manual top window would be always opened 20% and the auto top window would be opened 36% if reaching Tin setpoint during 24 hours in weekdays.

P3 was to use the auto bottom window that shares the same DeltaC and schedule (24/7) with auto top window while the manual top window remained the same.

The best option for these three proposals were similar, they all used the Tin setpoint of 21.5℃ without DeltaC, the discomfort hours of P1, P2 and P3 by using SR400W/m2 were 106hrs, 106hrs, 100hrs respectively. After applying different SR setpoints, SR of 300W/m2 worked the best for all the proposal. Comparing all proposals with the option in Step 1 (Figure 59), P3 would be the final choice for summer control, which had the least discomfort hours of 95.5.

Figure 59. Discomfort hours for different proposals(SR 300W/m2)



Proposal	Detail
Step1	T21
P1	T21.5_t36%(24/7)_b18%(8:00-18:00)
P2	T21.5_t36%(24/7)_b18%(10:00-18:00)
P3	T21.5_t36%(24/7)_b18%(24/7)

6.3 Winter

6.3.1 Shading control

Same as the control in new construction, the blinds only can be active from 18:00 to 8:00 on weekdays and the slat angle would be 0° . From the former simulation, Tin of 21℃ had the best performance in reducing heating demand. However, keeping closing when unoccupied may be also helpful. The two shading controls results were shown in Table 22. The heating demand reduction of Night Tin of 21℃ was larger, so it would be the choice of this step.

Table 22. Discomfort hours and energy demand in winter (Total: 1177hrs)

	Night Tin [℃]	Overheating [hrs]	Overcooling [hrs]	Lighting [kWh]	Heating [kWh]
Winter without heating	Blank	0	1174.5	120.81	-
	Night Tin 21℃	0	1172.5	120.81	-
	on 18:00-8:00	0	1176.5	120.81	-
Winter with heating	Blank	0	0	120.81	899.79
	Night Tin 21℃	0	0	120.81	813.58
	on 18:00-8:00	0	0	120.81	839.75

6.3.2 Operable window control

In Section 6.1, the simulation of using the same new construction winter control showed that it had an air change rate of 0.67, which was reached the minimum fresh air need. Furthermore, the shading control selection from Section 6.3.1 was identical to the new construction's. Consequently, the control for old construction would be the same as the one for the new construction, which was opening auto bottom window at 1% and top auto window at 36% when occupied. It resulted in 923.59kWh of heating demand.

6.4 Spring & Autumn

6.4.1 Shading control

The goal of this part was to reduce heating consumption. Table 23 was the results of the shading simulation using the same logic of winter. Compared with the new construction, it had similar overheating and much more overcooling due to the worse insulation. Tin was more sensitive towards Tex, when there was a sudden drop in the late afternoon, overcooling happened. Compared with the winter shading control, the blinds did not contribute to reducing heating energy in spring. So for spring and autumn, the shading would not be active.

Table 23. Discomfort hours and energy demand in spring (Total:495hrs) & autumn (Total:484hrs)

	Night Tin [℃]	Overheating [hrs]	Overcooling [hrs]	Lighting [kWh]	Heating [kWh]
Spring without heating	Blank	84	258	13.06	-
	Night Tin 21℃	84	258	13.06	-
Spring with heating	Blank	84	19.5	13.06	72
	Night Tin 21℃	84	19.5	13.06	72
Autumn without heating	Blank	1	229.5	22.39	-
Autumn with heating	Blank	1	19	22.39	74.23

Before adding window control, heating setting had to be modified according to the old construction eliminate the overcooling. As all the overcooling happened at 18:00. and implementing ventilation also would cause overcooling at 8:00, the heating setpoint was 22℃ from 7:30 to 8:00 and from 17:30 to 18:00. From 8:00 to 17:30, the setpoint was 20℃. Table 24 was the result after changing heating setting.

Table 24. Discomfort hours and energy demand in spring & autumn after heating modification

	Night Tin [℃]	Overheating [hrs]	Overcooling [hrs]	Lighting [kWh]	Heating [kWh]
Spring without heating	Blank	84	258	13.06	-
Spring with heating	Blank	84	0	13.06	77.75
Autumn without heating	Blank	1	229.5	22.39	-
Autumn with heating	Blank	1	0	22.39	78.72

6.4.2 Operable window control

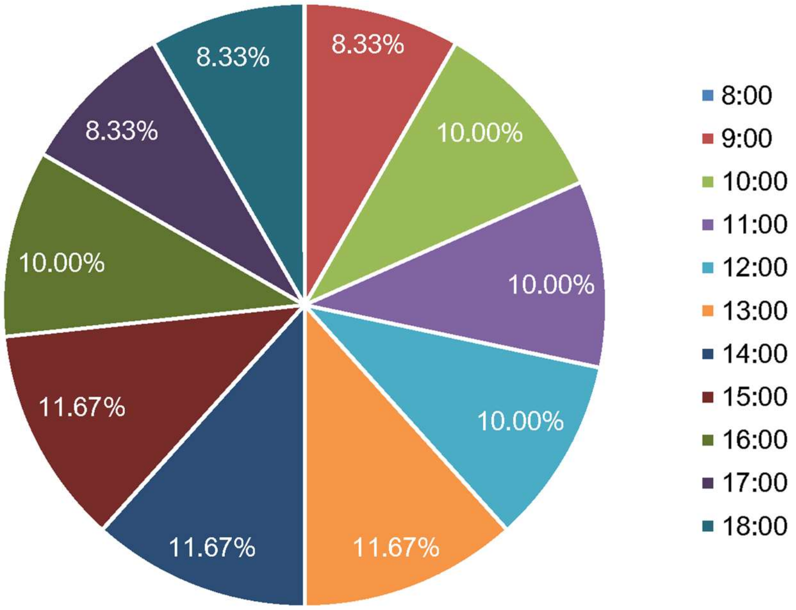
The control goal was to reach minimum overheating and ensure the fresh air need in the cold day.

- Step1 Two top window

  The auto top window was opened 36% when occupied and the manual top window was opened 25% during the whole spring to meet the requirement of minimum fresh air (The results were shown in Table 25).

- Step2 Auto bottom window for supplement

Figure 60. Overheating hour distribution of the control option in Step 1



Auto top 36%(8:00-18:00)+Manual top 25%(24/7)
Overheating time distribution

The schedule for bottom window was set from 8:00 to 18:00, because the 60 overheating hours were distributed in 9:00 to 18:00 in May (Figure 60). As the maximum Tin happened was 22.38℃ in April and the heating setpoint at the end of the day was 22℃, Tin setpoint should be larger than 22℃.

Because in the previous simulation DeltaC modulation increased overheating hours and just decreased little in energy, it would not be taken into consideration. Overheating hours of Tin setpoint at 23℃ was the same as 22℃'s and one hour less than 23.5℃'s. So for spring and autumn control would use Tin setpoint of 23℃.

Figure 61. Performances of different proposals in Spring

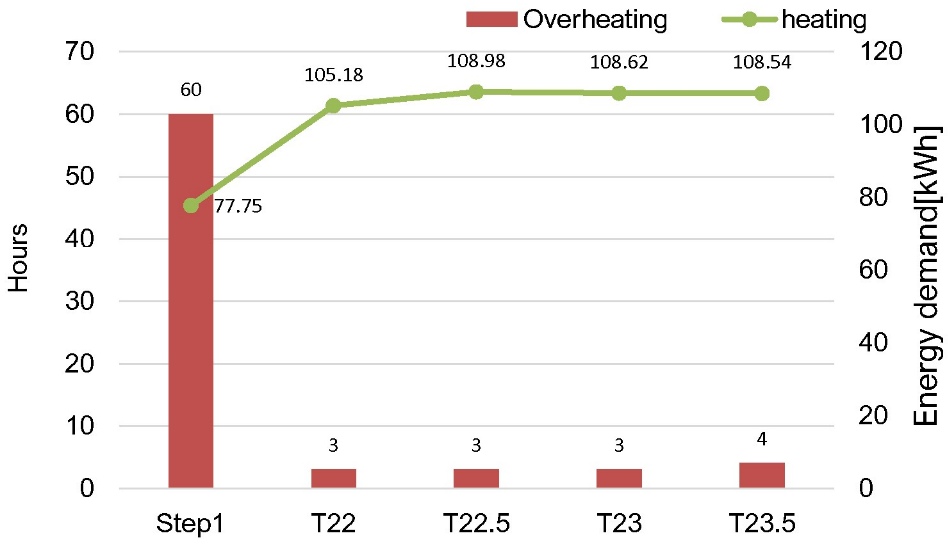


Table 25. Performances of different proposals in spring & autumn verification

Proposal	Detail	Overcooling [hrs]	Overheating [hrs]	Discomfort [hrs]	Lighting [kWh]	Heating [kWh]
Step1	mt25%_t36%(8:00-18:00)	0	60	60	13.06	77.75
T22	mt25%(24/7)_t36%_b18%T22_(8:00-18:00)	0	3	3	13.06	105.18
T22.5	mt25%(24/7)_t36%_b18%T22.5_(8:00-18:00)	0	3	3	13.06	108.98
T23	mt25%(24/7)_t36%_b18%T23_(8:00-18:00)	0	3	3	13.06	108.62
T23.5	mt25%(24/7)_t36%_b18%T23.5_(8:00-18:00)	0	4	4	13.06	108.54
T22 (Autumn)	mt25%(24/7)_t36%_b18%T23_(8:00-18:00)	0	0	0	22.39	102.05

6.5 Summary

- The control

The control flow chart of new construction was in Appendix 6. Figure 62 was the control scheme of four seasons.

Figure 62. Control scheme of new construction

- Performance

Compared with Reference group 1, the control cut 62% of discomfort hours and 42% of heating demand. To point out, the heating reductions for spring, autumn and winter were 63%, 46%, 35%. It removed all the discomfort hours of autumn and winter. As for summer, it reduced 56% (124hrs) of discomfort, which occupied 77% in the total reduction.

Compared with using the control of the new construction for the old one, the heating consumption was the same but the lighting energy was slightly different due to different SR setpoints. In summer, 9.5hrs reduction was due to the control strategy. In spring and autumn, 19hrs reduction was a result of changing heating setting and 35hrs reduction was a result of changing window control. Table 26 was the summary of the performances with and without control in four seasons.

Figure 63. Old construction groups heating energy comparison

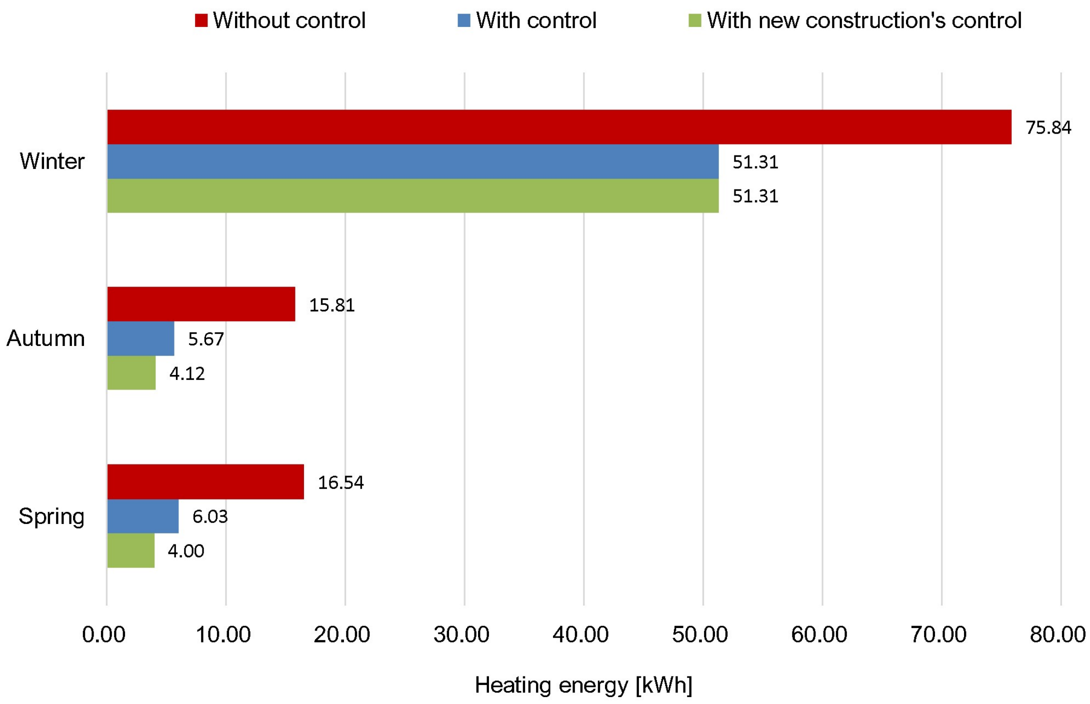


Figure 64. Old construction groups comfort comparison(hrs)

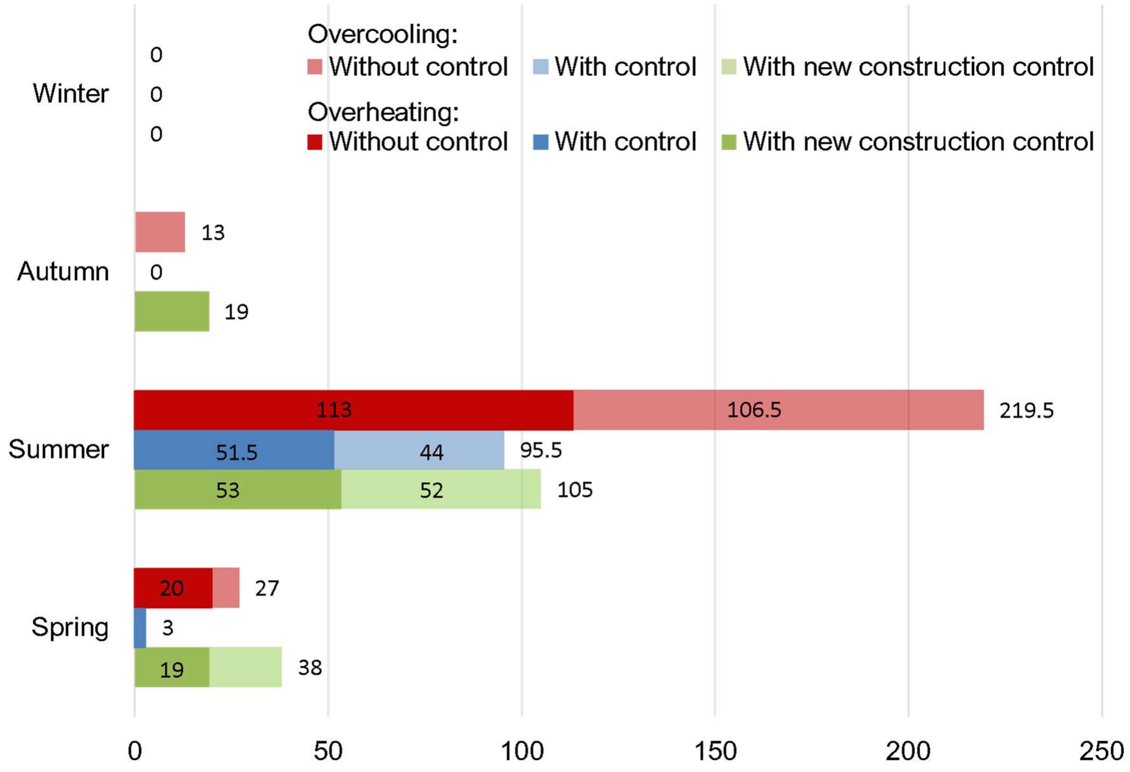


Table 26 Old construction groups data

Old construction without control (Reference group 1)

Season	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Lighting [kWh]	Heating [kWh]	Heating [kWh/m2]	Heating (Reality) [kWh/m2]
Spring	7	20	27	13.06	297.73	16.54	16.38
Summer	106.5	113	219.5	18.06	0.00	0.00	1.80
Autumn	12	0	13	22.39	284.64	15.81	10.51
Winter	1	0	0	120.81	1365.20	75.84	78.91

Old construction with control

Season	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Air change rate[ach]	Lighting [kWh]	Heating [kWh]	Heating [kWh/m2]
Spring	0	3	3	1.17	13.06	108.62	6.03
Summer	44	51.5	95.5	1.81	20.27	-	-
Autumn	0	0	0	0.79	22.39	102.05	5.67
Winter	0	0	0	0.67	120.81	923.59	51.31

Old construction with the control of new construction

Season	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Air change rate[ach]	Lighting [kWh]	Heating [kWh]	Heating [kWh/m2]
Spring	19	19	38	1.1	13.06	114.06	6.34
Summer	52	53	105	1.74	22.14	-	-
Autumn	0	19	19	0.86	22.39	106.68	5.93
Winter	0	0	0	0.67	120.81	923.59	51.31

Final control

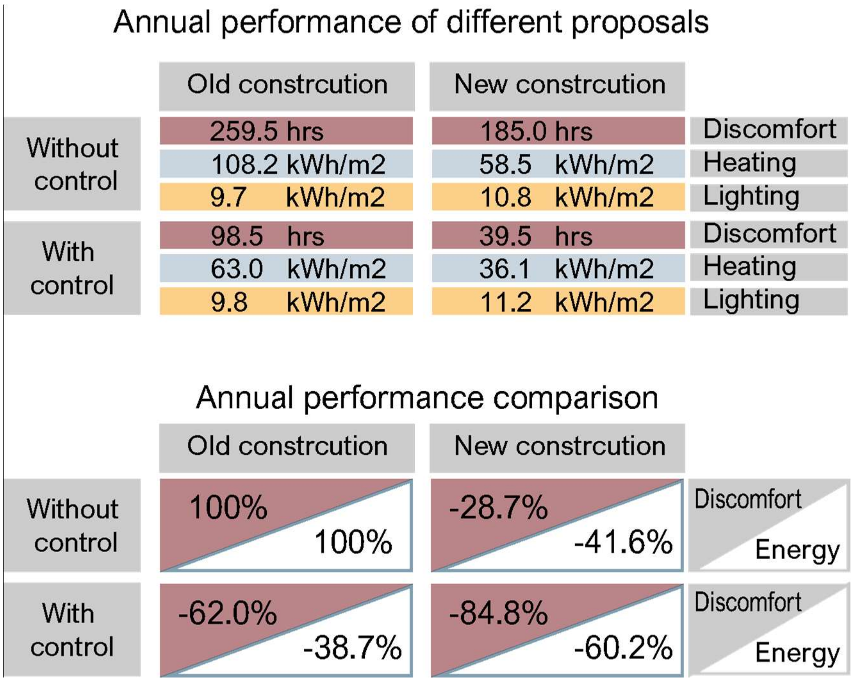
7.1 Selection

In the previous step, five groups were established for selecting the best solution, which were old construction without control and with control, new construction with and without control, old construction with the new construction control (using same control). The data for comparisons were in Appendix 7.

In terms of controlling the facade, the constructions influenced the shading control. For operable window control, the window configuration such as the number of automatic windows and the opening factors were more important.

For summer, the control was a combination of shading and operable window and for the other three seasons, heating also played an important role. The summer discomfort could not be totally removed while those in autumn and winter could. Regardless of the energy demand, the facade construction had a great influence on the performances in spring and summer.

Figure 65. Summary of the proposals



Annual performance of different proposals

	Old constrcution	New constrcution	
Without control	259.5 hrs	185.0 hrs	Discomfort
	108.2 kWh/m2	58.5 kWh/m2	Heating
	9.7 kWh/m2	10.8 kWh/m2	Lighting
With control	98.5 hrs	39.5 hrs	Discomfort
	63.0 kWh/m2	36.1 kWh/m2	Heating
	9.8 kWh/m2	11.2 kWh/m2	Lighting

Annual performance comparison

	Old constrcution	New constrcution	
Without control	100% 100%	-28.7% -41.6%	Discomfort Energy
With control	-62.0% -38.7%	-84.8% -60.2%	Discomfort Energy

Figure 65 showed that with proper control strategy, the facade of the old construction could perform better than the new construction without control, in this case, it only had nearly half discomfort hours of the new construction without control, in addition to 4.5kWh/m2 heating demand. But taken lighting demand into consideration, it still saved 10.42kWh in total energy. Specifically, 75.5hrs reduction in summer discomfort was the profit brought by the shading and window control.

In the aspect of construction, the facade material had moderate influence on indoor comfort and energy consumption. Overall, the control reduced heating demand, discomfort hour with a small increase in lighting demand. In conclusion, setting up proper control had great contributions to the facade performance, especially when the facade construction was not well insulated and when it was in summer.

The control with the new construction had the best performance towards energy and comfort, so it would be the choice of this project.

7.2 Analysis

In this section, the effectiveness of final control, the influence on indoor air quality and visual comfort were estimated. Table 27 showed the results of each step in each seasons.

Table. 27 Results of each step

Season	Type	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Air change rate[ach]	Lighting consumption [kWh]	Heating consumption [kWh]
Spring	Blank	0	84	84	-	13.91	26.95
	Shading	0	84	84	-	13.91	26.95
	Nat Vent	0	0	0	1.05	13.91	64.01
Summer	Blank	0	433.5	433.5	-	18.38	-
	Shading	0	300	300	-	25.46	-
	Nat Vent	16.5	23	39.5	1.82	25.46	-
Autumn	Blank	0	0	0	-	25.89	27.27
	Shading	0	0	0	-	25.89	27.27
	Nat Vent	0	0	0	0.87	25.89	55.1
Winter	Blank	0	0	0	-	135.73	448.58
	Shading	0	0	0	-	135.73	443.6
	Nat Vent	0	0	0	0.66	135.73	530.74

- Shading contribution (Compared to the blank group)

Figure 66. Solar gains of exterior windows

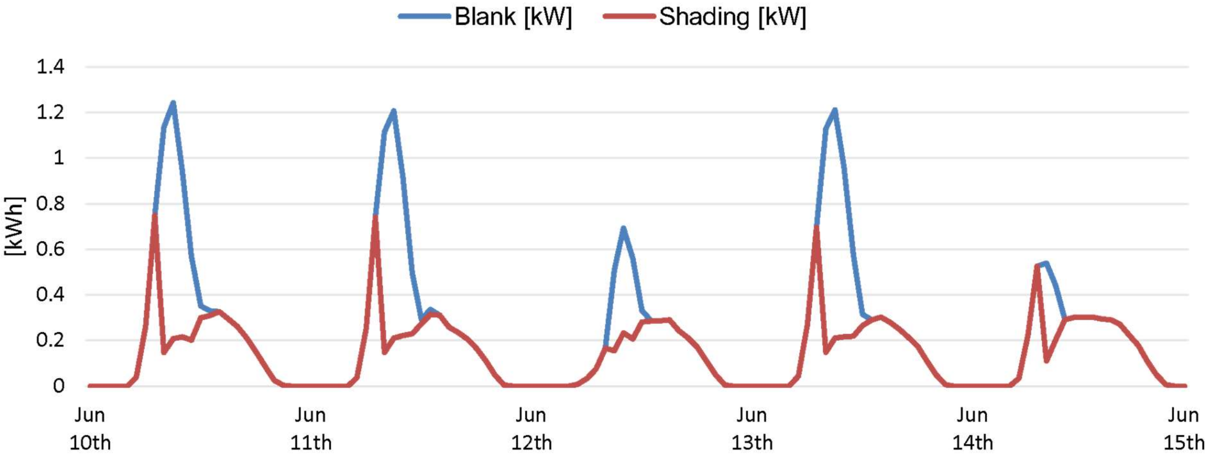


Figure 67. Tin

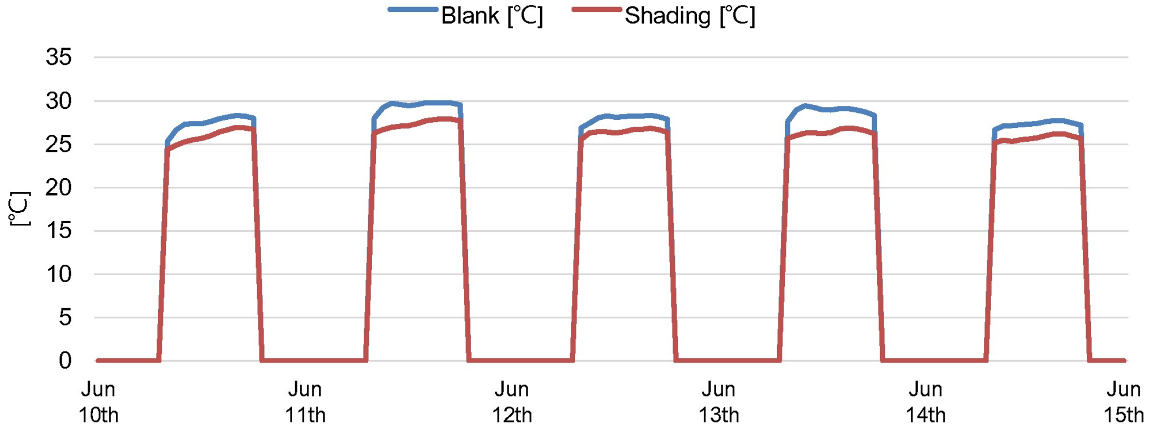


Figure 66 and Figure 67 were the solar gain of windows and Tin in summer typical week when occupied. In summer, the shading reduced 32%(133.5hrs) overheating hours by reducing the amount of solar radiation reaching the glazing. When the shading was retracted, the heat gain by radiation was the same as the one without shading, so the temperature difference between with shading and without remained the same. In winter, the shading was active when Night Tin was below 21℃. It reduced 1.1%(5kWh) of the heating energy. Since the shading was not active in spring and autumn, it did not contribute to their comfort.

- Operable window contribution(Compared to the shading group)

Figure 68. Heat gains of external air

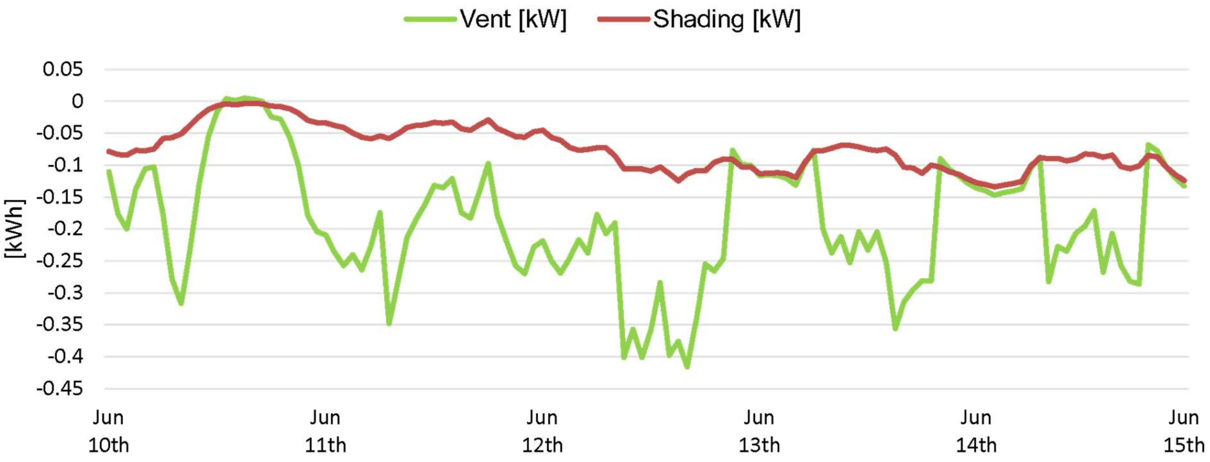
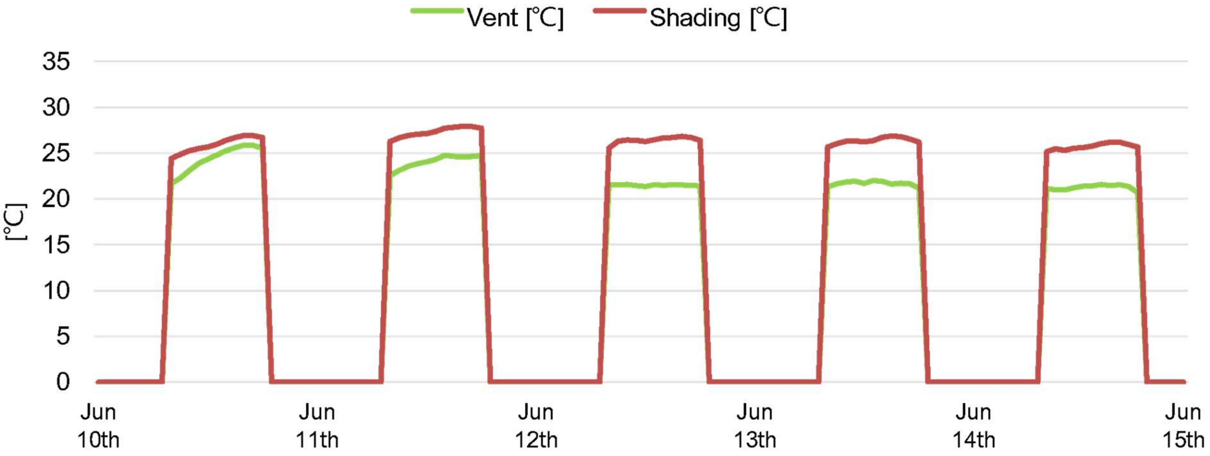


Figure 69. Tin



The cooling effect that windows brought was by convection (Figure 68 & Figure 69). In the cold days, the ventilation increased the heating demand to ensure indoor air quality. Compared with the shading group, in summer, the overheating hours were drop down to 23hrs from 300hrs in the compromise of 16.5hrs addition in overcooling. In autumn, it removed all the overheating hour, which was 84hrs.

- Shading and operable window collaboration

Figure 70. Heat gains of external air

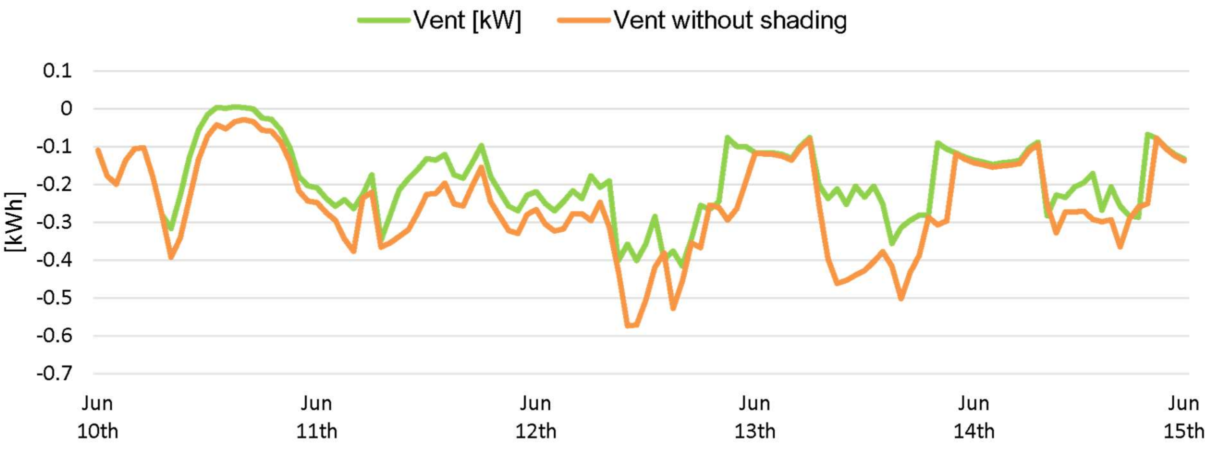
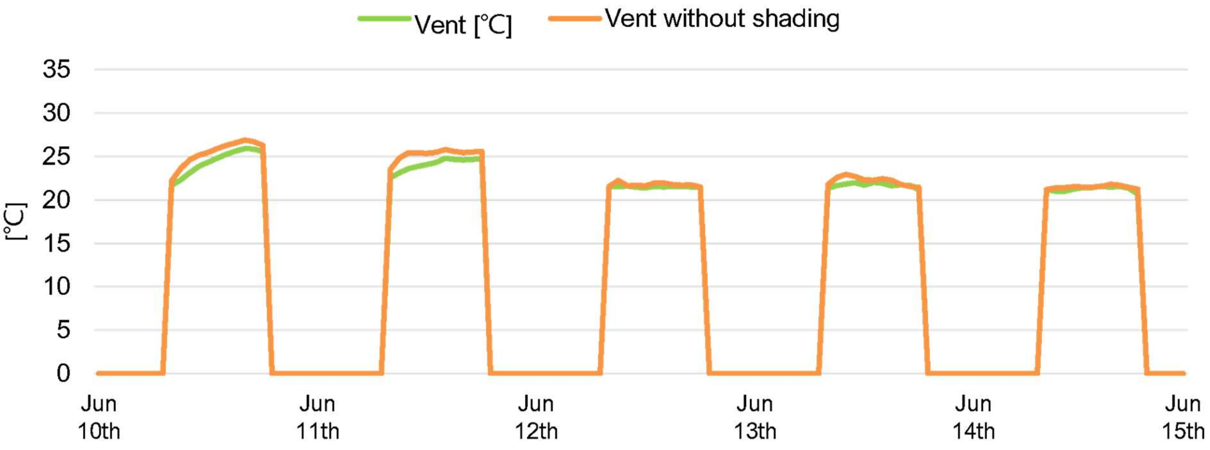


Figure 71. Tin



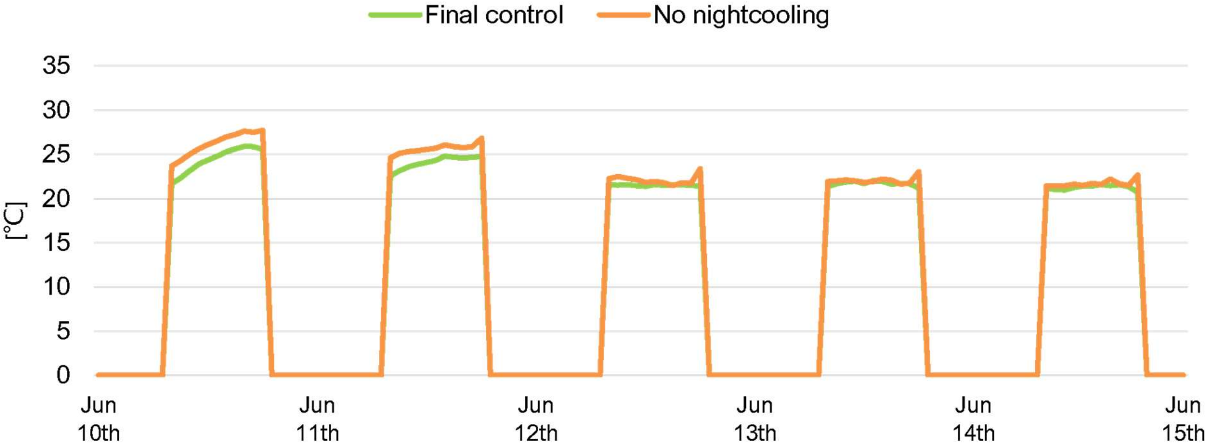
In the hot day, shading and operable working together to reduce the total heat gain of window. However, the shading did obstruct the cool air from coming into the space (Figure 70). But throughout the whole year, the combination of shading and operable window works better than only operating shading or operable window for cooling. For example, in summer, only operating window resulted in 15.5hrs of overcooling and 64hrs of overheating, which in total were 40hrs of discomfort more than the combining control. In winter, when the shading was active during the night, the air change rate also reduced, therefore the shading helped preventing heat loss by increasing insulation and reducing infiltration.

- Night-cooling of the overall control

Table 28 Contributions of nightcooling

	Detail	Overcooling (hrs)	Overheating (hrs)	Total discomfort (hrs)
No nightcooling	T21.5_t36%_b18%_(8:00-18:00)	16.5	42	58.5
Final control	T21.5_t36%(24/7)_b18%(24/7)	16.5	23	39.5

Figure 72 Tin of final control and No nightcooling



As night-cooling was only effective in ventilation in summer in this control. Here would only evaluation how much it contributed to the indoor comfort. Table 28 was a summary of the overall control and the control without night-cooling (The manual window remained opened while all the auto windows were deactivated from 18:00 to 8:00). The results showed that without night-cooling, the overcooling hours was not increased but the overheating hours had a rise of 19hrs throughout the whole summer. Figure 72 was the simulation of the summer typical week. It could be seen that when the day had higher temperatures, the night-cooling effect was more obvious, whose maximal temperature reduction was around 2 ℃. This may because night-cooling was not active when Tin was smaller than 21.5℃.

- Indoor air quality

As shown in Table 29, the air change rate fulfilled the Dutch standard of 25 m3/h per person. The following analysis took the CFD data of the hottest day (Jun 7th), the coldest day (Feb 13th) and the day with largest air change rate (Aug 13th), to see how was the indoor air quality.

Table 29. ACE value

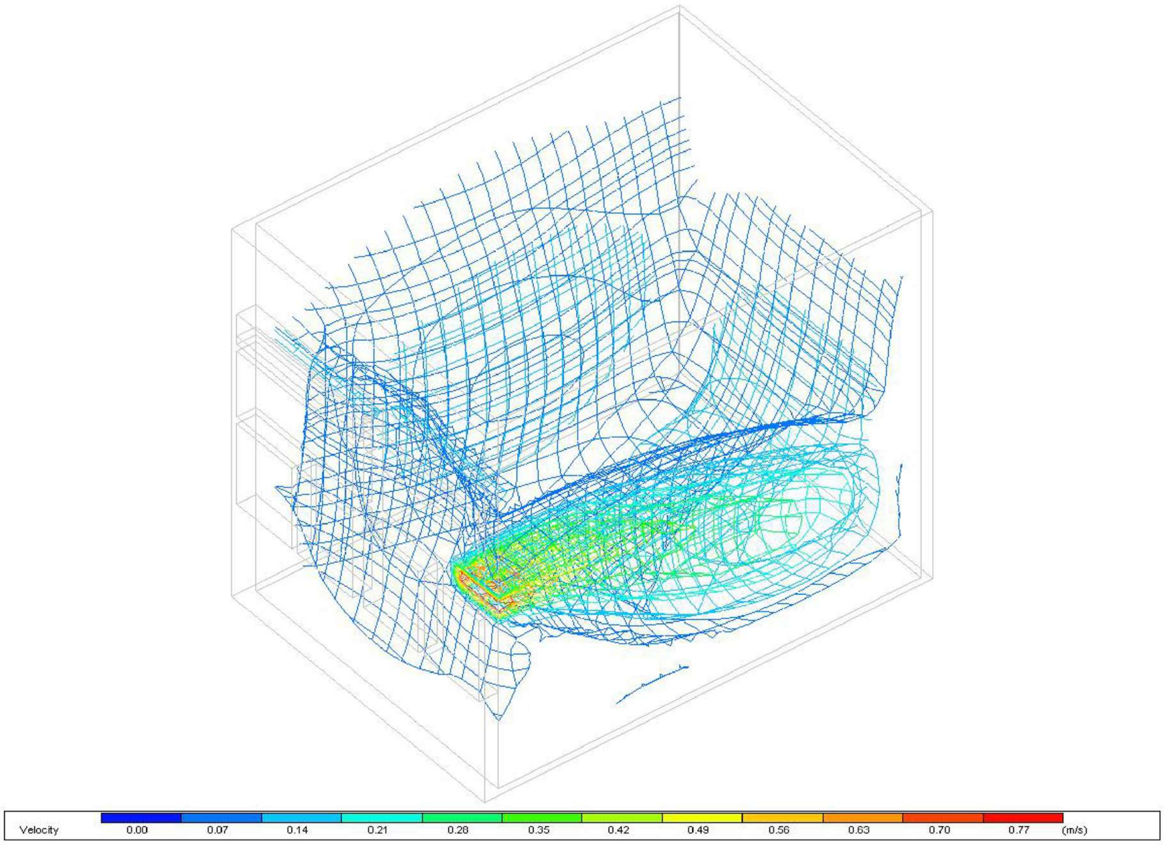
Date	time	ACE
Aug 13th	17:00	0.95
Jun 7th	16:00	0.11
Feb 13th	8:00	0.91

The air change efficiency (ACE) took the breathing zone between 900mm and 1800mm above the floor and 600mm from walls (ASHRAE 62.1, 2007). ACE exceeding the target value should be less than 5%. It could be seen than at the hottest and coldest hour, the ACE did not fulfill the requirement.

From Figure 73 to Figure 75, it could be concluded that normally the air flowed in through the bottom window and flowed out through the top windows. But the patterns of the three hours were different, the same was that the lowest velocity happened in the center of the room. To point out, the high air velocities on Aug 13th and on Feb 13th occurred outside the breathing zone, so they were considered acceptable.

Figure 73. CFD data of Aug 13th

3D view of air velocity distribution at 17p.m., 13th Aug



Airflow distribution on 13th Aug

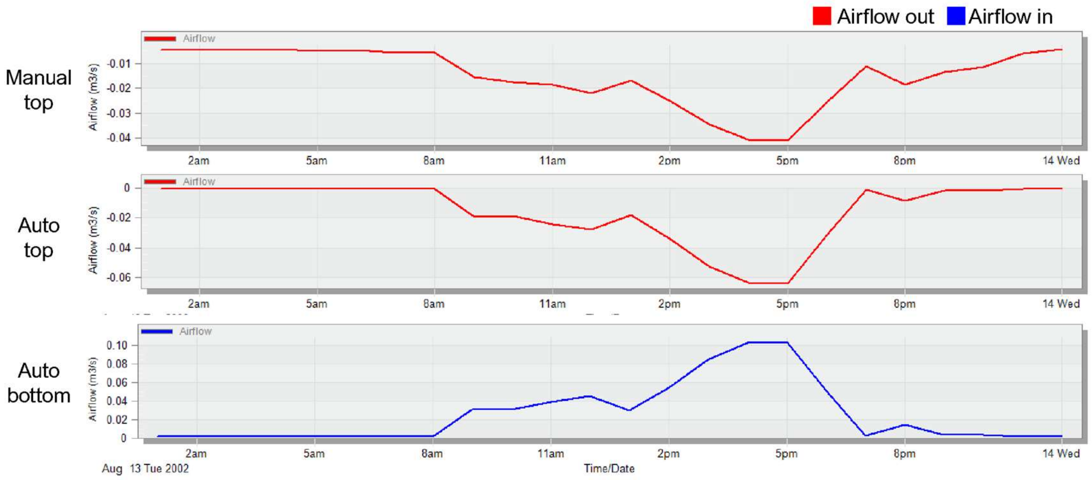
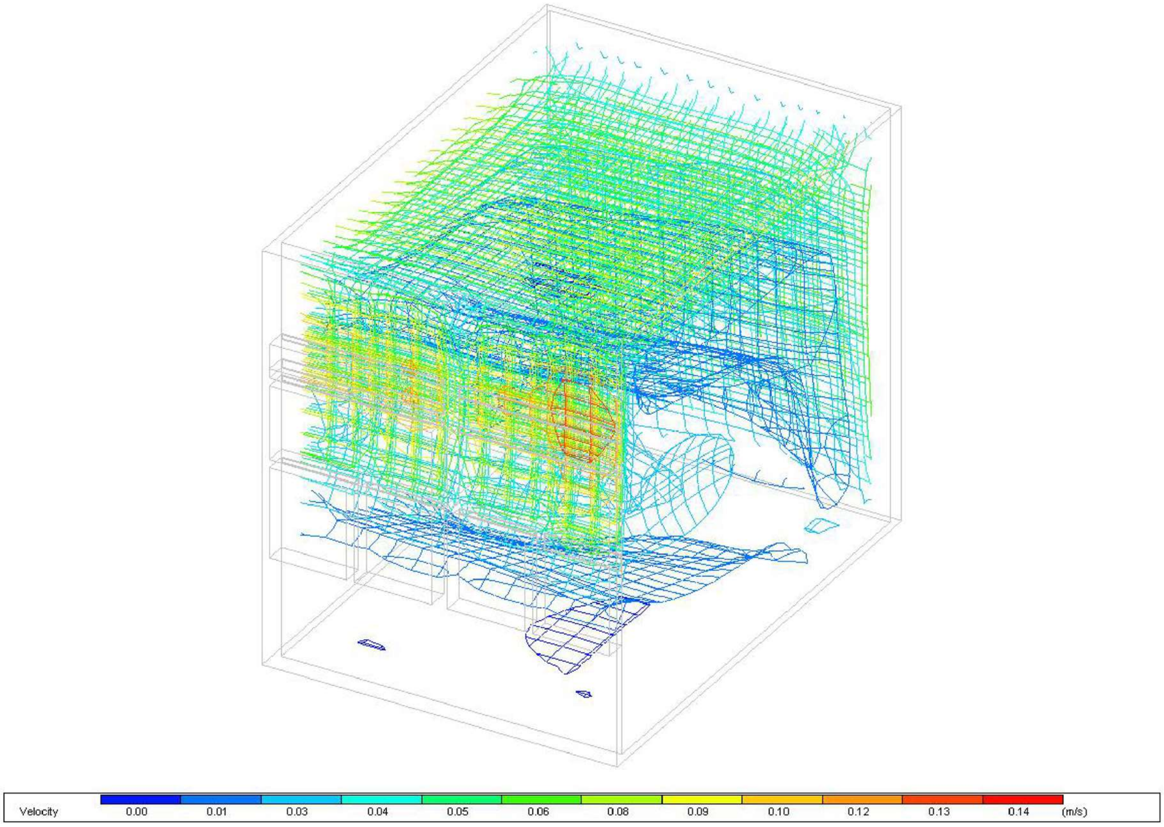


Figure 74. CFD data of Jun 7th

3D view of air velocity distribution at 16p.m., 7th Jun



Airflow distribution on 7th Jun

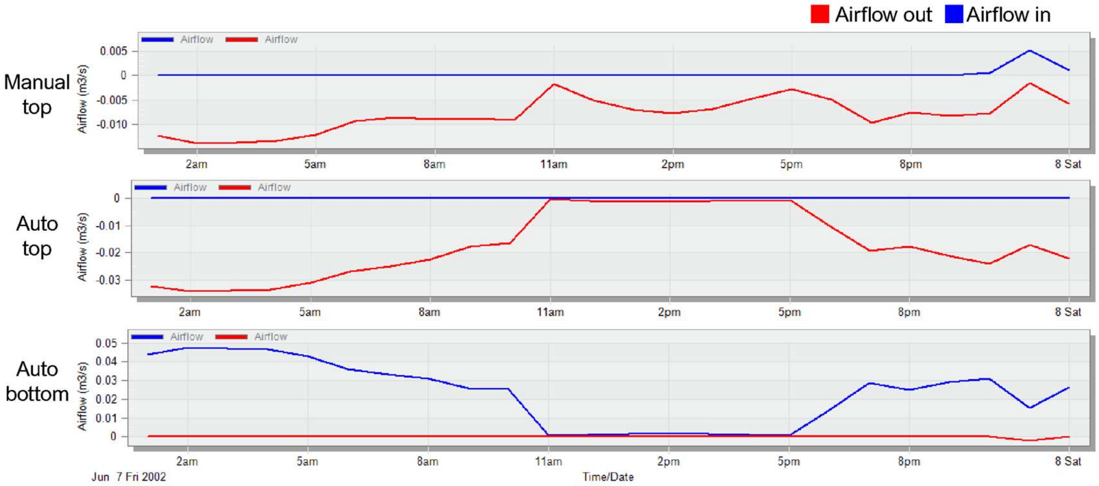
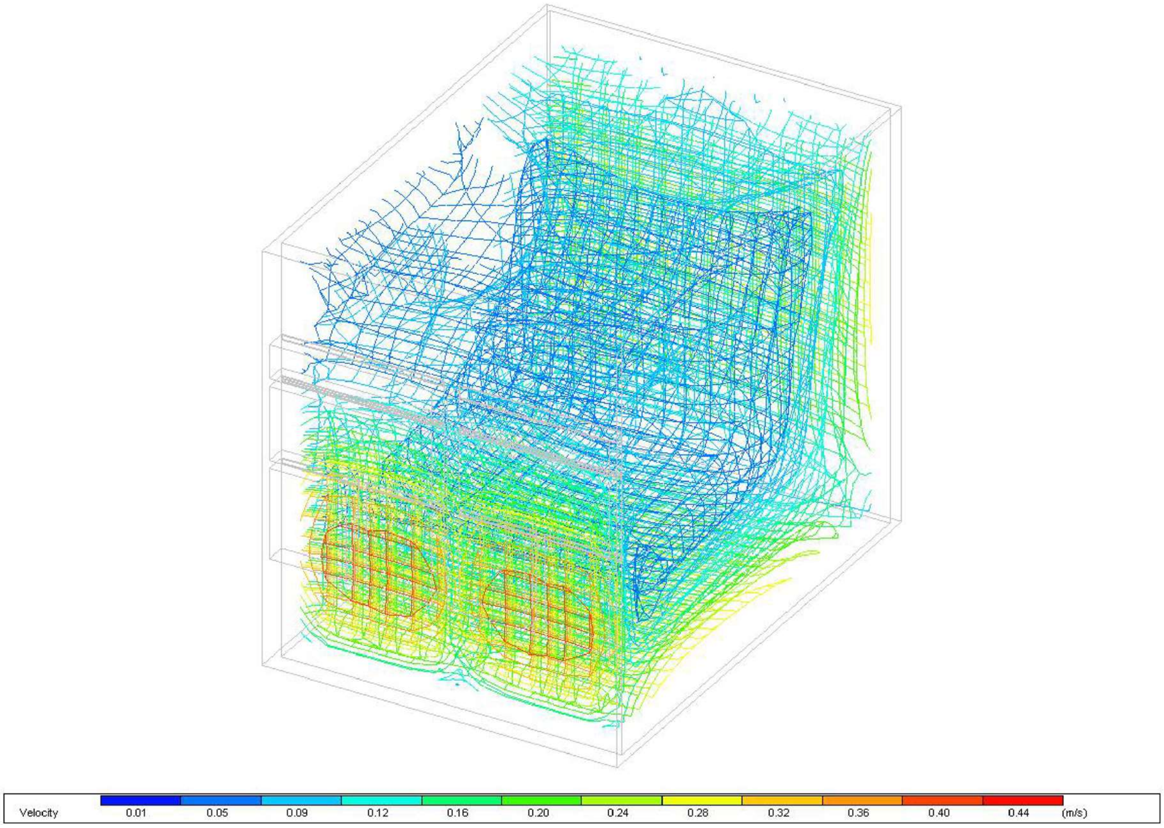
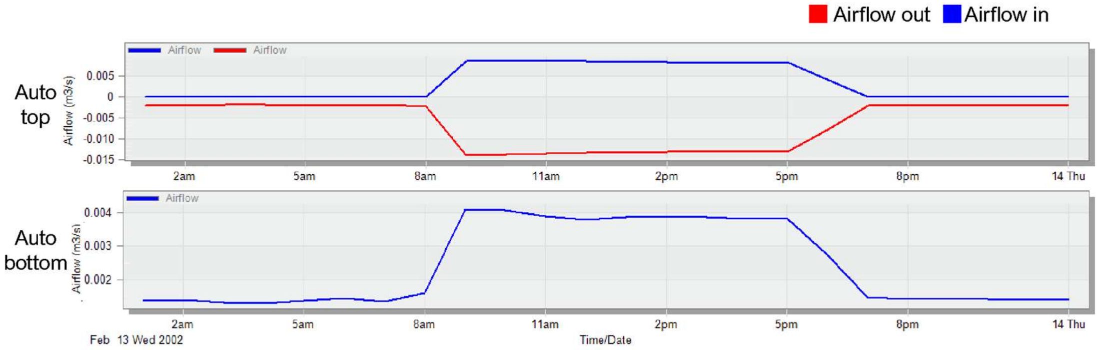


Figure 75. CFD data of Feb 13th

3D view of air velocity distribution at 8a.m.. 13th Feb



Airflow distribution on 13th Feb



- Visual comfort

Since the shading control during occupied time would only be active in summer, here would estimate the visual comfort in summer when using the external shading. The glare was blocked by internal shading by occupant adaptive 87ehavior. The external shading was on when the solar radiation (SR) exceeded 200W/m^2 during occupied time and was off at night to ensure the night cooling effect. The slat angle was adjusted to block beam solar.

From Table 30 the daylighting distributions were the same with and without shading. The under-lit condition did not exist and the over-lit condition only occupied 4.34% of the occupied time. From Table 31， all the time that the shading was on was when the indoor illuminance fell in the range of 500lux to 2000lux, which was regarded as useful but might be too bright at some times.

Table 30. Summer daylighting

	No shading			Shading		
Illuminance[lux]	<100	>2000	[100,2000]	<100	>2000	[100,2000]
hours	0	31	684	0	31	684
percentage of occupied time	0.00	4.34	95.66	0	4.34	95.66

Table 31. Summer indoor comfort and lighting energy

	Overcooling [hrs]	Overheating [hrs]	Hours at [500,2000] [lux]	Shading active [hrs]	lighting [kWh]
No shading	0	433	347	/	18.38
Shading	0	300	211	136	25.46
Note	The shading active time all happened when illuminance fell in the range of 500lux-2000lux				

7.3 Refinement

- Manual control

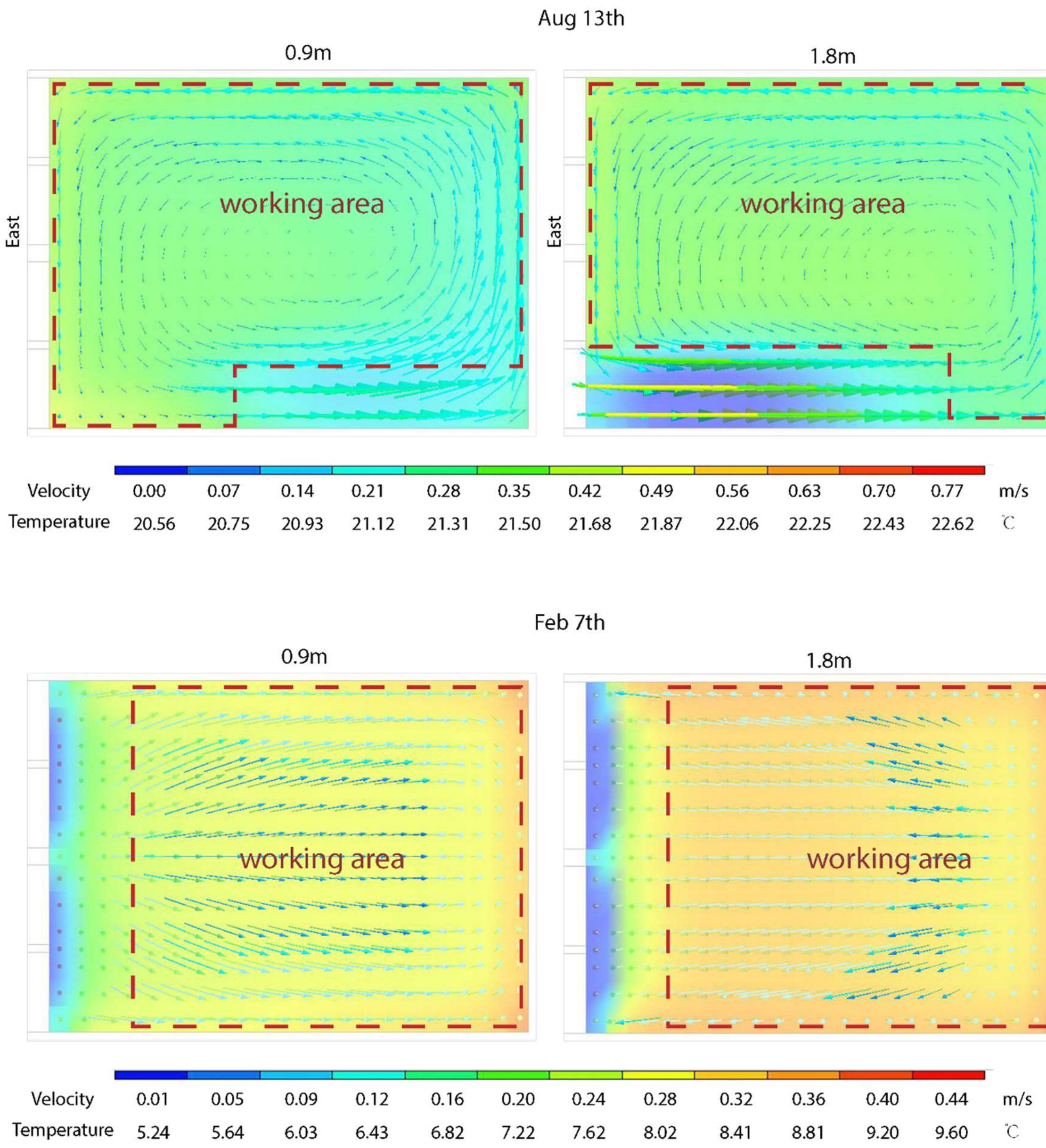
Overall, the occupants have fully control of the internal shading and manual operated windows. Once the manual windows were opened, the auto window would be closed.

- Working area

Choosing an appropriate working space could avoid frequent manual operation and achieve better comfort.

Figure 76 showed that the problem in summer was the high air velocity near the corner and the opening, while the problem in winter the low temperature of the air. Based on these, the suitable working area was outlined in each scheme.

Figure 76 Working area chosen according to air distribution



In Figure 77, the DF analysis result was similar to the illuminance analysis result. The over-lit mostly happened near the window with high frequency. Considering the comfort and the lighting consumption in one year, the working area was selected according to UDI (Figure 78), which had a larger comfortable area.

Combining the working area according to ventilation and daylight analysis, Figure 79 showed the suggestion of the working space.

Figure 77 Analysis of over-lit situation

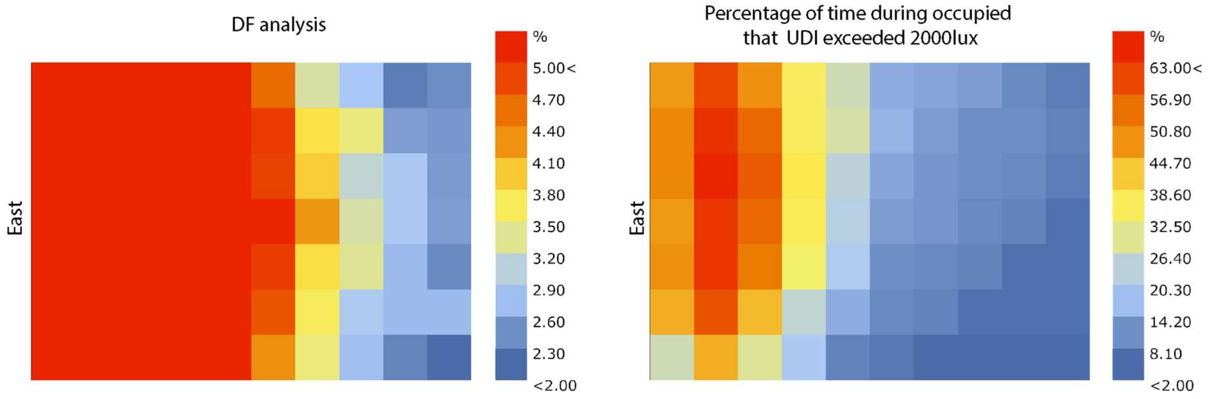


Figure 78 working area chosen according to UDI

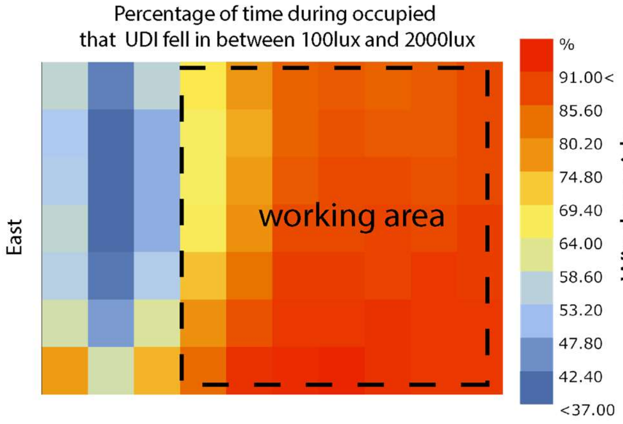
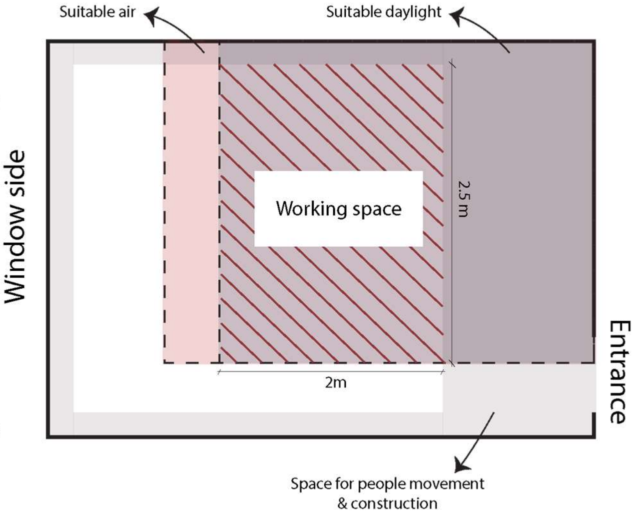


Figure 79 Suggested working space



- Occupancy modes

If the auto control system could adapt to the dynamic occupancy, the energy saving could reach larger without compromising to the comfort.

In this part, three scenarios of the occupant behaviours were set up to check how the heating energy deviated from the final control even with their corresponding control modes, which were set up to reduce the impact of occupant behaviours.

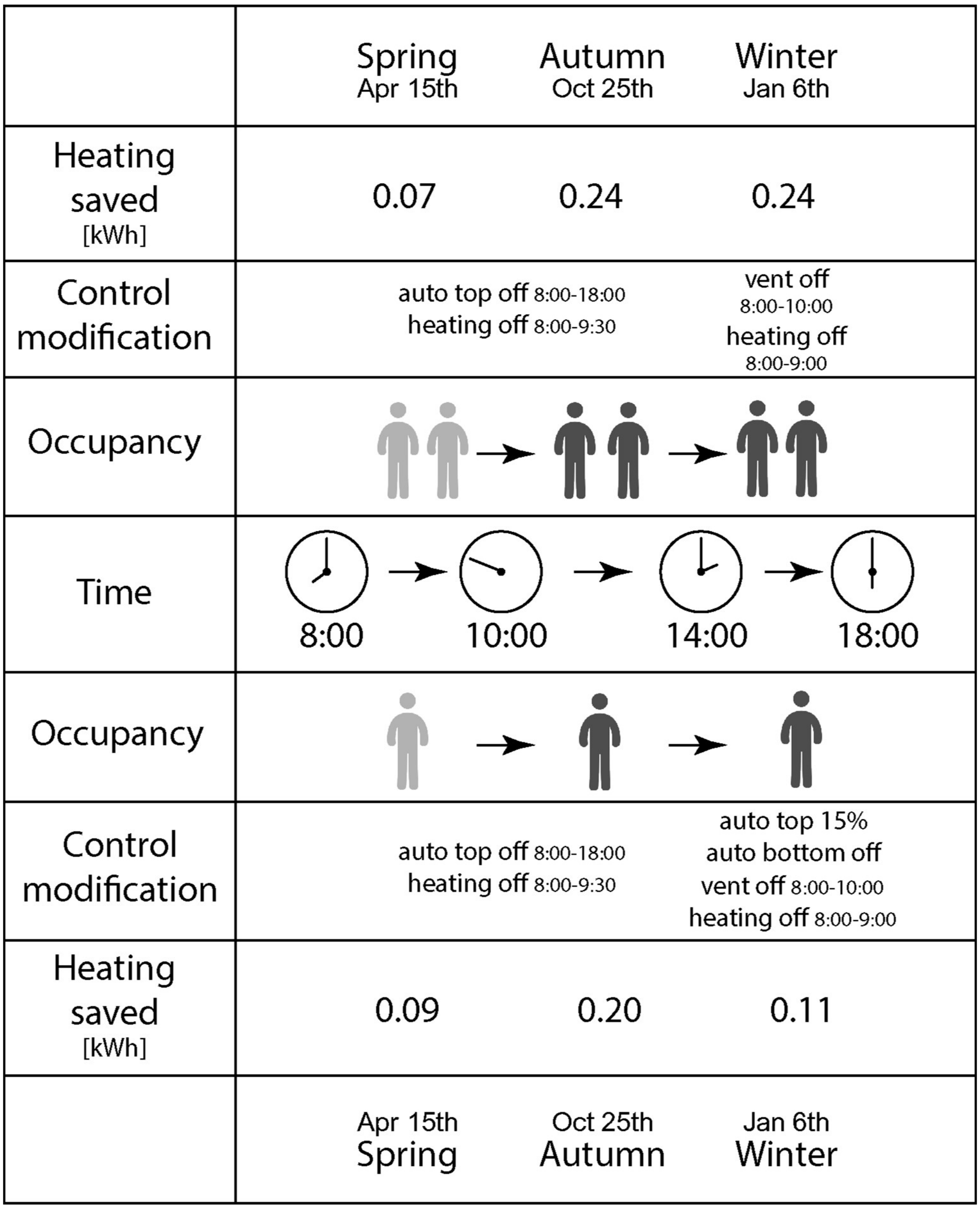
From two occupants to one occupant, the fresh air requirement would drop half, which was 0.33 ach, so the operable windows need to change the control. The reaction of the heating system towards users absent was off, the setpoint did not change but the schedule did. The manual top window should remain the same since its requirement least operation.

In terms of control, in winter, heating could not pause before the occupants left, otherwise it would cause overcooling. The response time for winter heating was 1 hour, so the heating needed to be active one hour before the occupants arrived. Changing from two occupants to one occupant, only auto top window would be active and the opening factor would be 15%. Ventilation could be turned off immediately when the occupants were absent to prevent heat loss.

For spring and autumn control, the response time for heating was 30mins. So the space needs to be heated at least 30mins before occupants arrived. The auto bottom window remained the same because in these two seasons, the cold day temperature did not reach the setpoint of 22℃. It was only used in the hot days to bring more cool air into the space. Changing from two occupants to one occupant, only auto top window was not active since the manual top window already fulfilled the fresh air need. Accordingly, for one occupant, when the occupancy pattern changed, the control did not need to be modified.

Figure 82 to Figure 84 were the heating demand change and the corresponding control of the four scenarios. The heating energy saved was compared with the final control with the same occupancy, because the occupancy activity influenced the heating demand. One day with the maximum heating demand in spring, autumn and winter were selected for data comparison because the occupant behaviours only affected the heating demand. In other aspects, the changes that occupants made in the hot day were aiming to improve their comfort.

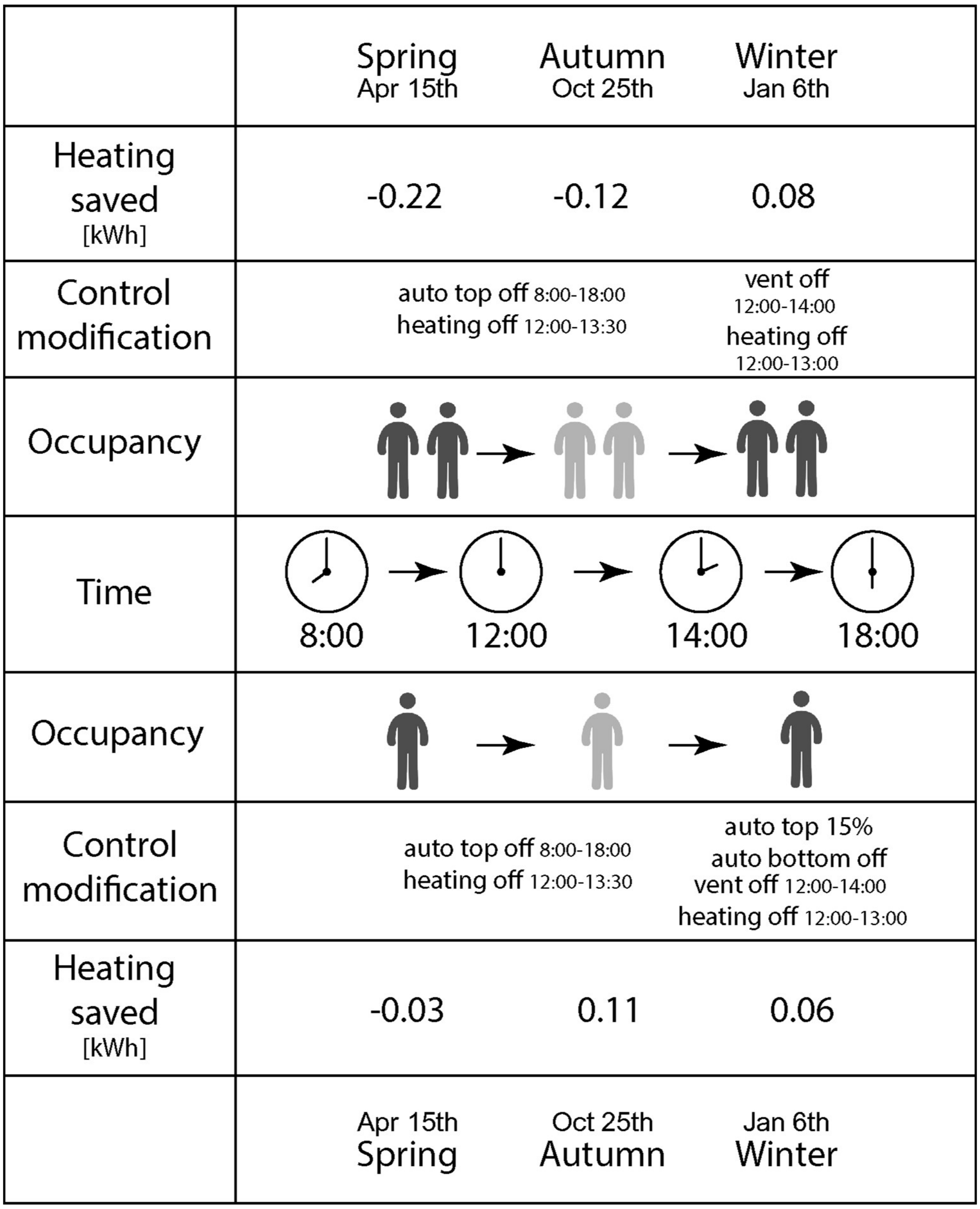
Figure 80. Mode 1 Occupants absent in the early morning



	Spring Apr 15th	Autumn Oct 25th	Winter Jan 6th
Heating saved [kWh]	0.07	0.24	0.24
Control modification	auto top off 8:00-18:00 heating off 8:00-9:30		vent off 8:00-10:00 heating off 8:00-9:00
Occupancy			
Time	8:00 → 10:00 → 14:00 → 18:00		
Occupancy			
Control modification	auto top off 8:00-18:00 heating off 8:00-9:30		auto top 15% auto bottom off vent off 8:00-10:00 heating off 8:00-9:00
Heating saved [kWh]	0.09	0.20	0.11
	Apr 15th Spring	Oct 25th Autumn	Jan 6th Winter

In this mode, the corresponding control helped saving energy either for two occupants or one occupant. The saving performance ranked from high to low was winter, autumn and spring, parallel to the temperature distribution and the heating demand of the seasons. One occupant presented in the space saved more energy than two occupants in spring.

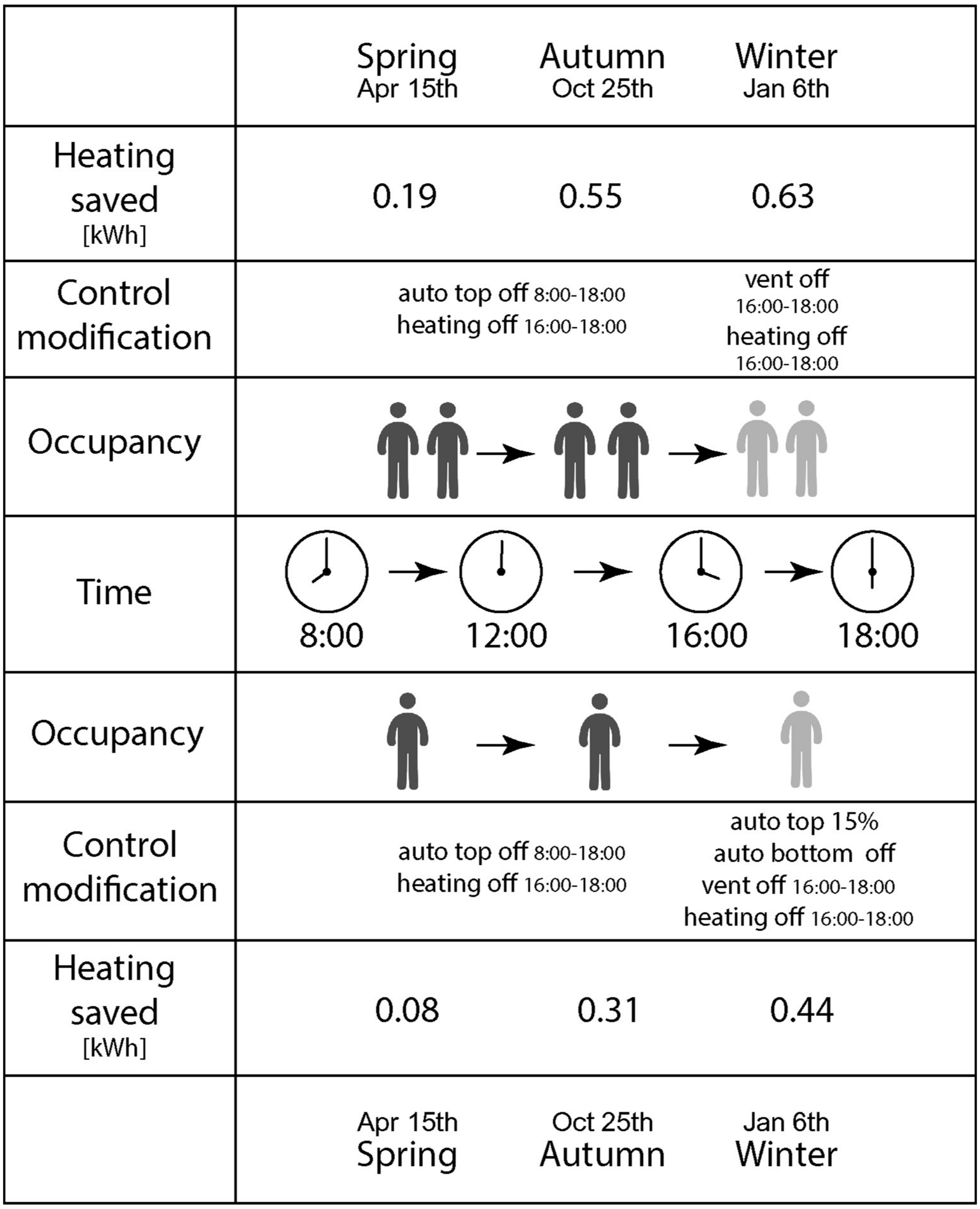
Figure 81. Mode 2 Occupants absent at noon



	Spring Apr 15th	Autumn Oct 25th	Winter Jan 6th
Heating saved [kWh]	-0.22	-0.12	0.08
Control modification	auto top off 8:00-18:00 heating off 12:00-13:30		vent off 12:00-14:00 heating off 12:00-13:00
Occupancy			
Time	8:00 → 12:00	→	14:00 → 18:00
Occupancy			
Control modification	auto top off 8:00-18:00 heating off 12:00-13:30		auto top 15% auto bottom off vent off 12:00-14:00 heating off 12:00-13:00
Heating saved [kWh]	-0.03	0.11	0.06
	Apr 15th Spring	Oct 25th Autumn	Jan 6th Winter

In this mode, the corresponding control helped saving energy only in autumn with one occupant and in winter. In other words, in autumn with two occupants and in spring, this control mode should not be activated.

Figure 82. Mode 3 Occupants absent in the late afternoon



	Spring Apr 15th	Autumn Oct 25th	Winter Jan 6th
Heating saved [kWh]	0.19	0.55	0.63
Control modification	auto top off 8:00-18:00 heating off 16:00-18:00		vent off 16:00-18:00 heating off 16:00-18:00
Occupancy			
Time	8:00 → 12:00 → 16:00 → 18:00		
Occupancy			
Control modification	auto top off 8:00-18:00 heating off 16:00-18:00		auto top 15% auto bottom off vent off 16:00-18:00 heating off 16:00-18:00
Heating saved [kWh]	0.08	0.31	0.44
	Apr 15th Spring	Oct 25th Autumn	Jan 6th Winter

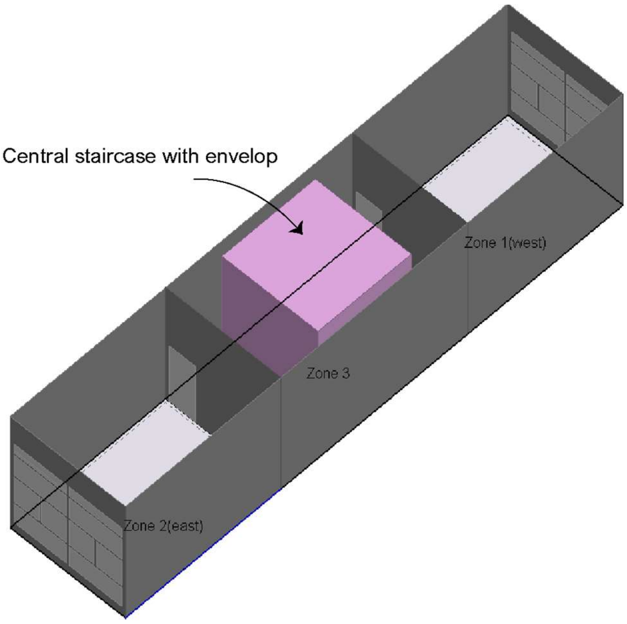
In this mode, the auto windows (winter) and the heating could be turned off immediately after the occupants left. The energy saved was more than the first and second mode. The control mode was effective.

7.4 Deviation

In this section, three scenarios were evaluated, which happened in reality and could make the final control deviated the optimal performance. The deviation from analytical calculation was is Appendix 8.

- Keeping the door opened

Figure 83 Cross ventilation model in DesignBuilder



Keeping the door opened would induce cross ventilation, therefore influence the indoor comfort and energy consumption. Table 32 was the simulation result assuming the office doors on both sides were always opening during occupied hours.

In result, the cross ventilation had a large influence on the air change rate, which in summer could reach 33ach. Compared with the single-sided ventilation, the discomfort increased 68 hrs (172.2%). The energy demand decreased 1.02kWh(2.8%) because of the influence of middle zone lighting.

Table 32. Simulation result of cross ventilation (new construction)

Season	Room	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Air change rate[ach]	Lighting consumption [kWh/m2]	Heating consumption [kWh/m2]
Spring	West	32.5	4.5	37	2.23	0.82	4.01
	East	19.5	10	29.5	1.26	0.75	
Summer	West	50	35	85	5.48	1.10	0
	East	0	45.5	45.5	2.69	1.03	
Autumn	West	34	2.5	36.5	2.47	1.33	2.66
	East	9	0	9	0.93	1.27	
Winter	West	46	2	48	2.04	6.97	18.32
	East	23.5	0	23.5	0.89	7.04	
Total	West	162.5	44	206.5	-	10.21	24.99
	East	52	55.5	107.5	-	10.09	

- Operating internal shading

From the simulation of assuming internal shading active at 16:00-18:00, the operation of internal shading caused more energy then the one without, due to the increased of lighting energy.

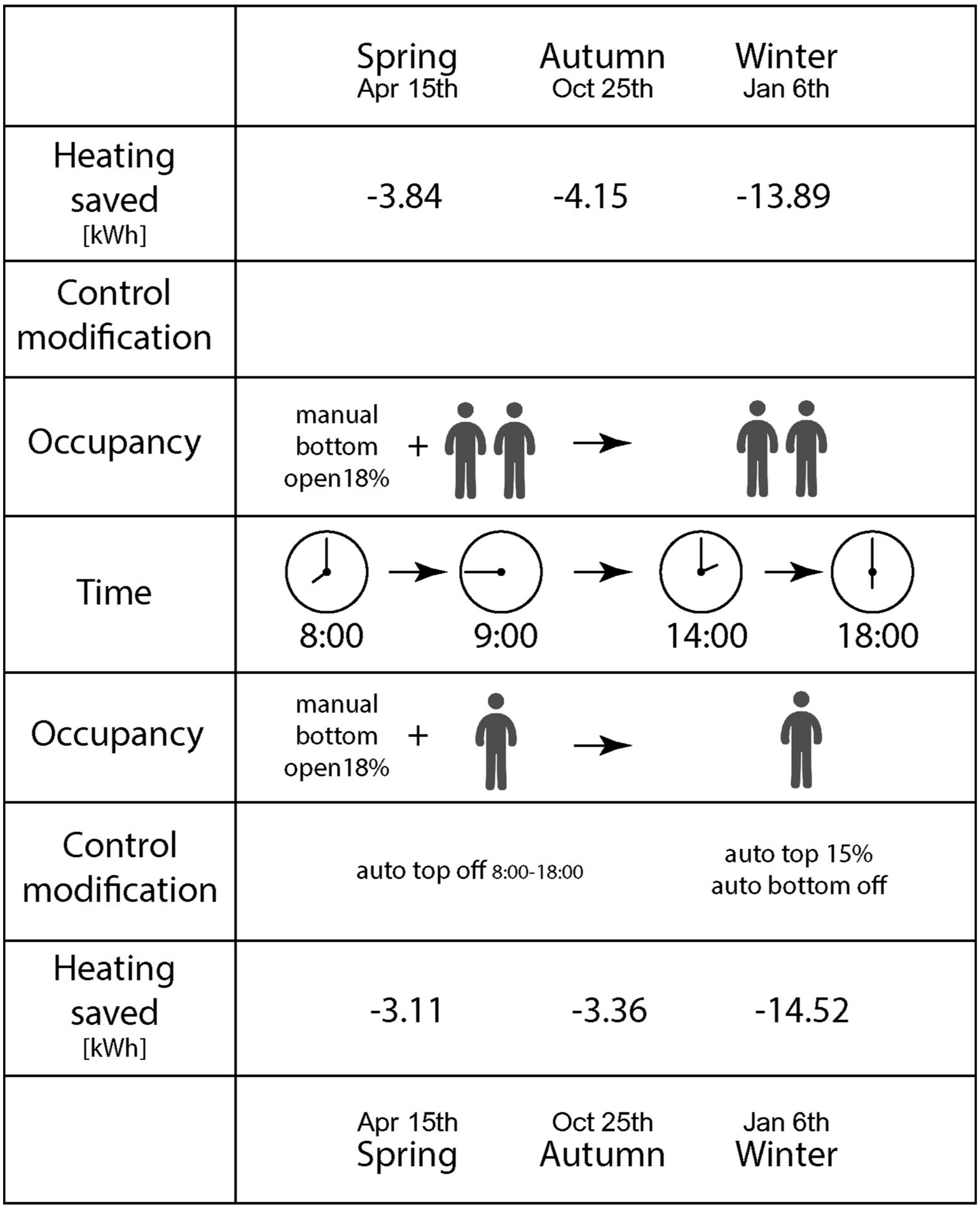
Figure 84 Internal shading active at 16:00-18:00

	Spring Apr 15th	Autumn Oct 25th	Winter Jan 6th	Summer Aug 13th
Air change rate [ach]	0.0026	0.0000	0.0000	0.0088
Lighting saved [kWh]	-0.49	-0.10	-0.01	-0.53
Heating saved [kWh]	0.17	0.10	-0.07	-

- Opening manual window

The occupants may want to open the manual window for more fresh air or remove the smell of the room. In result, opening one manual bottom window for 1 hour after arrival increased the energy demand more than two times as the final control.

Figure 85. Manual bottom window was opened for 1 hour after arrival



	Spring Apr 15th	Autumn Oct 25th	Winter Jan 6th	
Heating saved [kWh]	-3.84	-4.15	-13.89	
Control modification				
Occupancy	manual bottom open18% +	→		
Time	8:00	→ 9:00	→ 14:00	→ 18:00
Occupancy	manual bottom open18% +	→		
Control modification	auto top off 8:00-18:00		auto top 15% auto bottom off	
Heating saved [kWh]	-3.11	-3.36	-14.52	
	Apr 15th Spring	Oct 25th Autumn	Jan 6th Winter	

Conclusion

8.1 Main research question

How can the integrated control of smart facade contribute to the indoor comfort for the east facade of CEG?

Throughout the whole year, the bottom window and the internal shading were manually controlled by the occupants to fulfil the personal preferences. The final control used the new construction. The manual top window was operated with least adjustment.

In summer, the blinds were active and slat angle pointed to the beam solar when solar radiation reached 200W/m2 during 8:00 -18:00. The auto top window was tilt (36%) and the auto bottom window was tilt (18%) when indoor air temperature reached 21.5℃ in all time. The manual top window kept opened 27%.

In winter, the blinds were active and the slat angle was 0° when indoor air temperature reached 21℃ when unoccupied. The auto top window opened 36% and the auto bottom opened 1% during occupied.

In spring and autumn, the shading was not active. The auto top window opened 36% during 8:00-18:00. The auto bottom window open 18% when indoor air temperature reached 22℃ during occupied. The manual top window kept opened 12%.

In conclusion, the final control presented the lowest values of total discomfort occurrence, which was 39.5hrs (16.5 overcooling hours and 23 overheating hours) in summer. The heating energy demand was 36.10kWh/m2 and the lighting demand was 11.17kWh/m2. Compared with the simulation of the existing situation with new construction, it reduced 79%(145.5hrs) of discomfort hours and 66% of heating demand.

8.2 Sub-questions

What are the factors that influence office indoor comfort related to solar shading?

In the research, the amount of daylight, discomfort glare and direct solar radiation were the main issues that solar shading need to resolve in office buildings. They could be evaluated by illuminance, daylight factor, daylight glare index, daylight glare probability and solar radiation. As for control design, the material, geometry, physical properties, slat angle, the control algorithm of the blinds influence the indoor comfort.

Under the context of CEG, solar radiation, indoor air temperature were the direct factors in the aspect of controlling for regulating thermal performance.

How to control solar shading for the sake of indoor comfort?

Solar radiation, illuminance and daylight glare index are commonly used to control the solar shading. The actions include adjusting height, adjusting slat angle, closing and opening. However, the setpoints for activating and modulating the shading are various regarding different building environment, the climate condition and the possible movement of the shading, So as the performance, ranging from 2.5°C to 4.5°C reduction in temperature and 5% to 50% reduction in energy.

In this project, to alleviate overheating and overcooling, indoor air temperature, horizontal solar irradiance and solar radiation were tested for activating the blinds. Direct radiation and fixed schedule were tested for slat angle adjustment. If only considering reducing heat gains, using solar radiation as stimuli would be the best, then horizontal solar irradiance and indoor air temperature. A slat angle fixed at 0° was the best for reducing heat loss and heat gains. So for summer, solar radiation should be used for shading control. For other three seasons, attracting more heat during the day and preventing heat loss during the night were the most important, so indoor air temperature should be the stimuli and the slat angle should be fixed at 0° .

What are the factors that influence office indoor comfort related to operable windows?

The purpose of operating windows is ventilation, for this context, the ventilation would be single-sided ventilation induced by buoyancy and wind. Accordingly, air flow rate, air change rate, air velocity, temperature and CO2 are the factor that related to it. In terms of control design, building geometry, window configuration, location and climate condition are significant, which could be further broken into temperature difference of indoor and outdoor, effective area, wind direction and wind velocity.

As for CEG facade, the temperature difference of indoor and outdoor, effective area were the direct factors influencing the control for the sake of regulating thermal performance.

How to control operable windows for the sake of indoor comfort?

The stimulus for controlling operable windows are temperature, humidity, pressure difference, wind speed, airflow rate and CO2 concentration. With a predefined context, the values for the stimulus could be converted into each other. The actions include adjusting opening size, closing and opening. The energy saving ranges from 12% to 20% and the temperature reducing by operating windows ranges from 1.2℃ to 3℃.

In this project, indoor air temperature, temperature difference of indoor and outdoor (DeltaC) and schedule were used for the control. The control should first fulfil the air quality and then use for thermal improvement. The control was similar to those in the literature, in which it was used to limit the CO2 levels in the cold day and cool the space in the hot day.

How can the shading and operable window control be integrated to reach the most effective for CEG?

If choosing the best solution for shading and operable window separately and combining them together, or avoiding operating these two functions at the same time, it will not reach the most effective. Choosing the most effective stimulus in the independent control was helpful, since the response time for changing indoor air quality for the shading was slow and for the operable window was fast.

Generally, the shading control contributed to thermal comfort by reducing solar radiation in the hot days and reducing convection at the cold day night. The operable window contributed to thermal comfort by increasing convection. So when controlling these two together, the reaction of the temperature was complex. The integrated control was designed and analyzed step by step for selecting proper stimulus and avoiding unnecessary iterations. The final control was simple, which did not require gradually control but on/off control. In other words, complex control was not effective when integrating shading and operable windows. To reach the most effective, the integrated control needs to remain simple, avoid manual control and be adjusted based on occupancy.

What is the energy impact of the design solution?

When designing the control, the energy demand was taken into consideration, the heating system worked paralleled with the control. The effectiveness of the control not only appeared in the thermal comfort, but also in energy consumption. In addition, the occupancy mode helped saving energy and the manual control increased energy demand.

Limitation & Recommendation

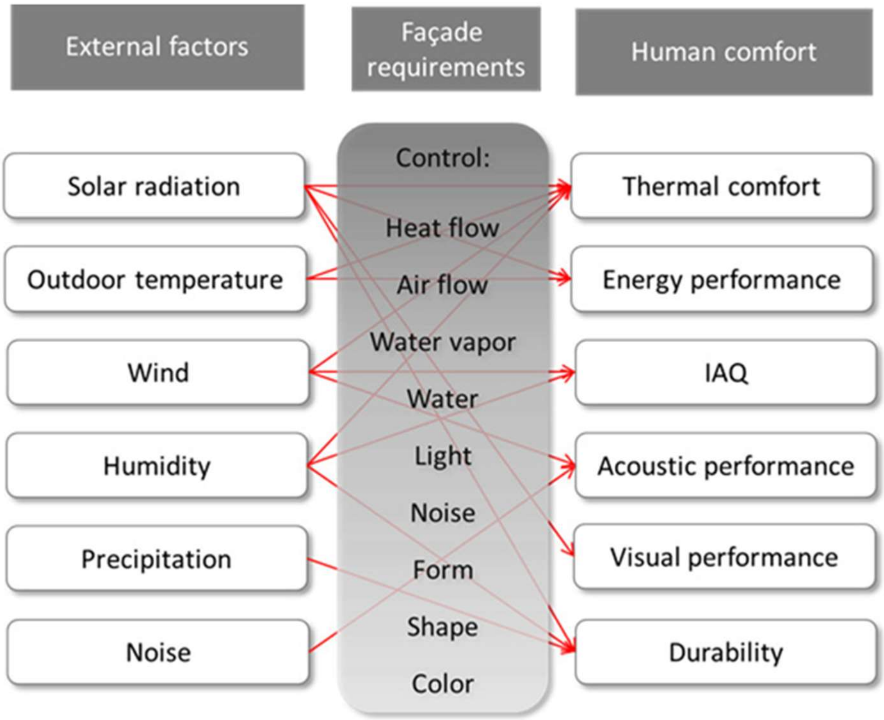
When designing the control strategies, certain assumptions had been made for the simulations and for the concentration on exploring different controls when the CEG facade was put into use.

They were:

- The new construction material properties and available control variables were already defined before designing the control strategies.
- The room only had single-sided ventilation.
- The ventilation rate of 0.66ach and the internal shading could fulfil the occupants' need for air quality and visual comfort.
- The tilt and turn opening method of the window, as well as the operation of the shadings would not be affected by the wind and rain.

Figure 86. The factors that connect the outdoor environment, SF and human indoor comfort

Source: (Loonen et al., 2015)



The project focused on the thermal contribution of the integrated control of shading and operable windows and the evaluation focused on the performance during the operating period. However, human comfort is affected by multiple factors (Figure 86) and the sustainability of the SF depends on the assessment on its whole life span. Therefore, several ideas are listed here for future exploration.

The performance is sensitive to climatic conditions and human preference. Also the simulation may not fully represent the reality. Therefore, On-site measurement of the cross ventilation influence, allowing the control strategy for commissioning and adjusting the control based on the future climatic conditions was recommended.

Different occupants may use the room throughout the life of the facade and they have personal preferences towards comfort and control. The challenges of the control were the complexity of capturing transient and holistic occupant response and its integration in the early-design stages. Incorporating machine learning and adjusting autonomy in smart control might be a good solution.

How the SF control helps the building approaching sustainability need its assessment from the production to the end of life. Economical cost, CO2 footprints, maintenance, life cycle assessments were recommended for the CEG and further market penetration.

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Appendix

Appendix 1 Reference list of Table 5

In this appendix, [1]-[16] are retrieved from Correia et al. 's study named 'Influence of shading control patterns on the energy assessment of office spaces' (Correia et al., 2012). [17]-[29] are retrieved from Rodrigo Mogárrio Freitas Leal's study named 'Energy and luminous performance simulation for venetian blinds control strategies' (Rodrigo Mogárrio Freitas Leal, 2016). In addition, [4] & [5] are both appeared in two studies.

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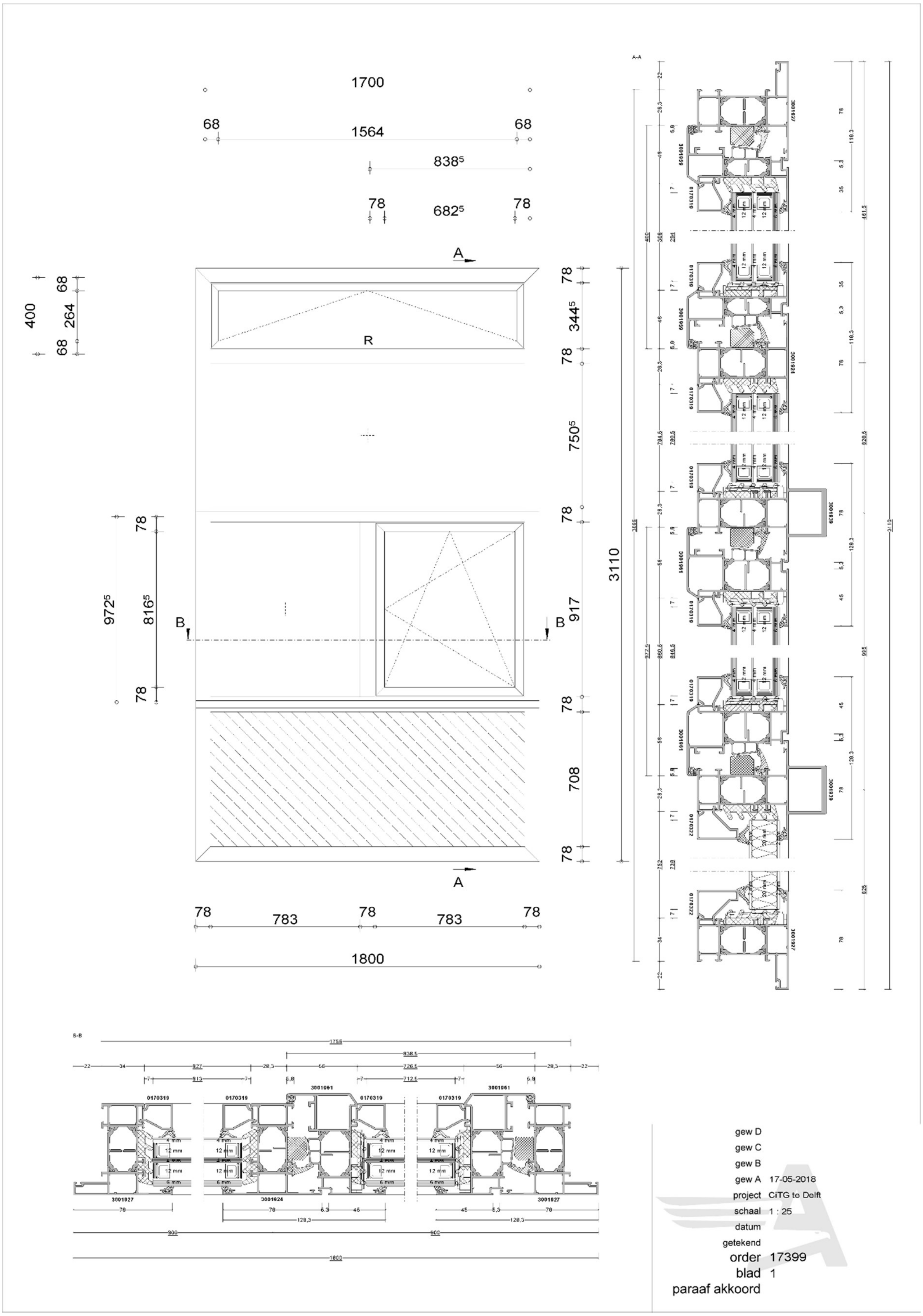
Appendix 2 The proposed facade panel layout



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Appendix 3 Summer operable window control simulation detail (New construction)

Step 1 Two top windows			
	Overheating [hrs]	Overcooling [hrs]	Lighting [kWh]
T20	31	44.5	75.5
T20Δ10	6	147	153
T20Δ13	14	77	91
T20Δ15	20	68.5	88.5
T20.5	17.5	46	63.5
T21	16	48	64
T21.5	15	51.5	66.5

Step 2. Proposal 1 with SR 200W/m2 (Add bottom auto 18%, 8:0-18:00, shared DeltaC with auto top)				
	Overcooling [hrs]	Overheating [hrs]	Discomfort [hrs]	lighting (kWh)
T20.5_two top	17.5	46	63.5	25.46
b18%	41	26	67	25.46
Δ14	19.5	39	58.5	25.46
Δ16	22.5	33.5	56	25.46
Δ18	24.5	32	56.5	25.46
Δ20	25.5	31	56.5	25.46
T21_two top	16	48	64	25.46
b18%	24.5	27.5	52	25.46
Δ12	16	41	57	25.46
Δ14	16.5	34.5	51	25.46
Δ16	17.5	33	50.5	25.46
Δ18	17	32.5	49.5	25.46
Δ20	20	31.5	51.5	25.46
T21.5_two top	15	51.5	66.5	25.46
b18%	17.5	31	48.5	25.46
Δ20	16	33	49	25.46
Δ22	16	32	48	25.46
Δ24	16	32	48	25.46

Step 2. Proposal 2 with SR 200W/m2 (Add bottom auto 18% with DeltaC, 13:0-18:00)				
	Overcooling [hrs]	Overheating [hrs]	Discomfort [hrs]	lighting (kWh)
T20.5_two top	17.5	46	63.5	25.46
b18%	24	31.5	55.5	25.46
Δ10	19.5	33	52.5	25.46
Δ12	19	33	52	25.46
Δ14	19.5	33	52.5	25.46
T21_two top	16	48	64	25.46
b18%	19	32	51	25.46
Δ12	16.5	34	50.5	25.46
Δ14	16.5	33.5	50	25.46
Δ16	16.5	33.5	50	25.46
T21.5_two top	15	51.5	66.5	25.46
b18%	16.5	34	50.5	25.46
Δ12	15.5	35.5	51	25.46
Δ14	15.5	35	50.5	25.46
Δ16	16	35	51	25.46

Step 2. Proposal 3 with SR 200W/m2
(Add bottom auto 18%, 13:0-18:00, shared DeltaC with auto top)

	Overcooling [hrs]	Overheating [hrs]	Discomfort [hrs]	lighting (kWh)
T20.5_two top	17.5	46	63.5	25.46
b18%	24	31.5	55.5	25.46
Δ10	6.5	85.5	92	25.46
Δ20	19	37.5	56.5	25.46

Step 2. Proposal 4 with SR 200W/m2
(Add bottom auto 18%，24/7 8:0-18:00, shared DeltaC with auto top)

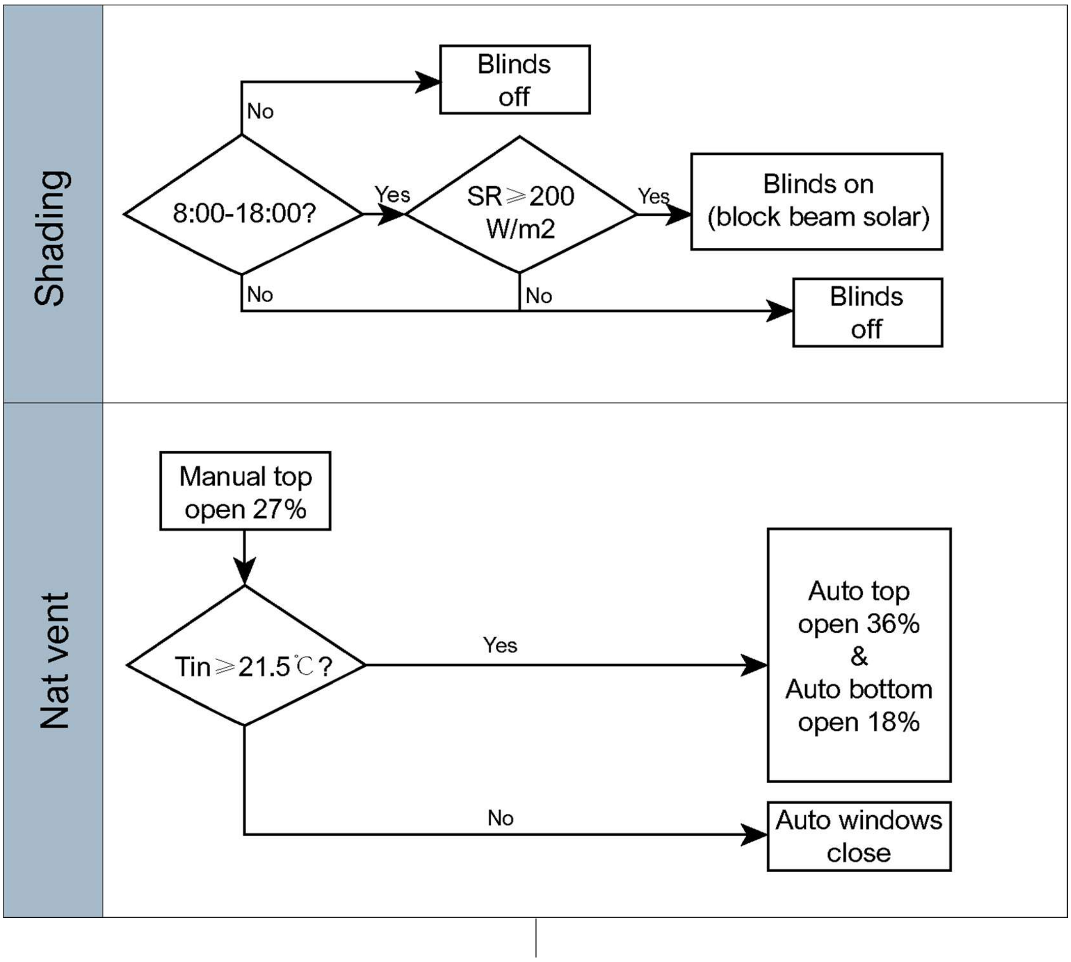
	Overcooling [hrs]	Overheating [hrs]	Discomfort [hrs]	lighting (kWh)
T20.5_two top	17.5	46	63.5	25.46
b18%	45.5	18	63.5	25.46
Δ26	33	19.5	52.5	25.46
Δ28	31.5	19.5	51	25.46
Δ30	33.5	19	52.5	25.46
T21_two top	16	48	64	25.46
b18%	26	19.5	45.5	25.46
Δ18	18.5	22.5	41	25.46
Δ20	18	22	40	25.46
Δ22	21	21.5	42.5	25.46
T21.5_two top	15	51.5	66.5	25.46
b18%	16.5	23	39.5	25.46
Δ18	16.5	26	42.5	25.46
Δ20	16.5	25	41.5	25.46

Proposal selection

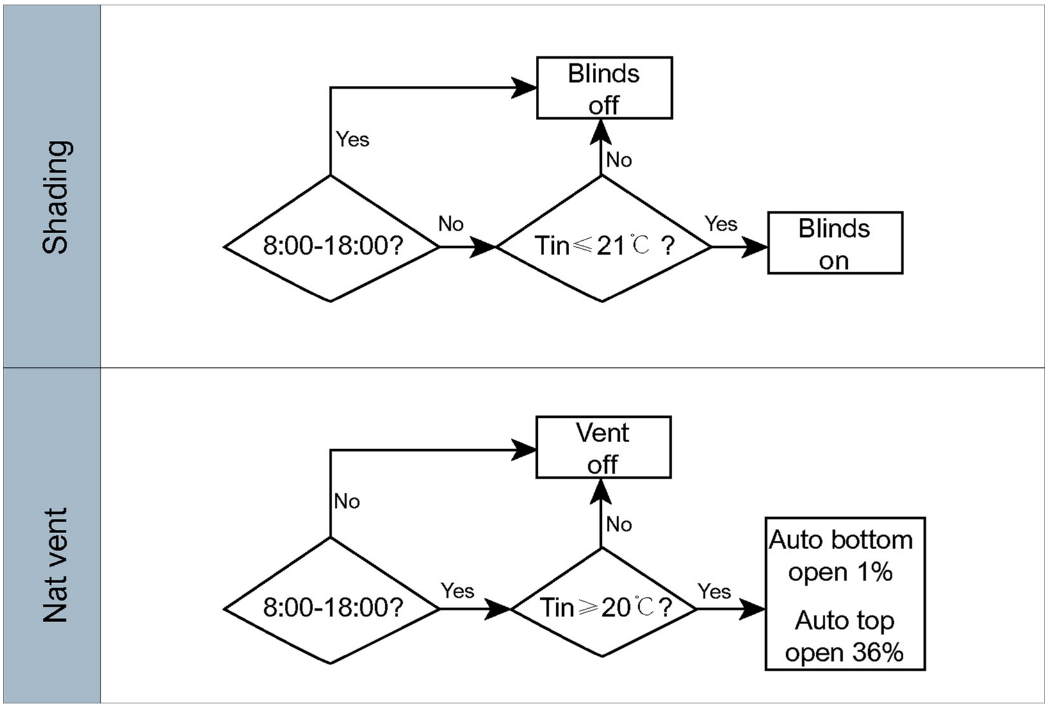
Proposal	Detail	Overcooling [hrs]	Overheating [hrs]	Discomfort [hrs]	Vent (ach)	lighting (kWh)
Step1	T20.5	17.5	46	63.5		
P1	T21.5_t36%(24/7)_b18%(8:00-18:00)_Δ22	16	32	48		
P2	T21_t36%(24/7)_b18%Δ14(13:00-18:00)	16.5	33.5	50		
P3	T20.5_t36%(24/7)_b18%(13:00-18:00)_Δ20	19	37.5	56.5		
P4	T21.5_t36%(24/7)_b18%(24/7)	16.5	23	39.5	1.82	25.46

Appendix 4 New construction control flow chart

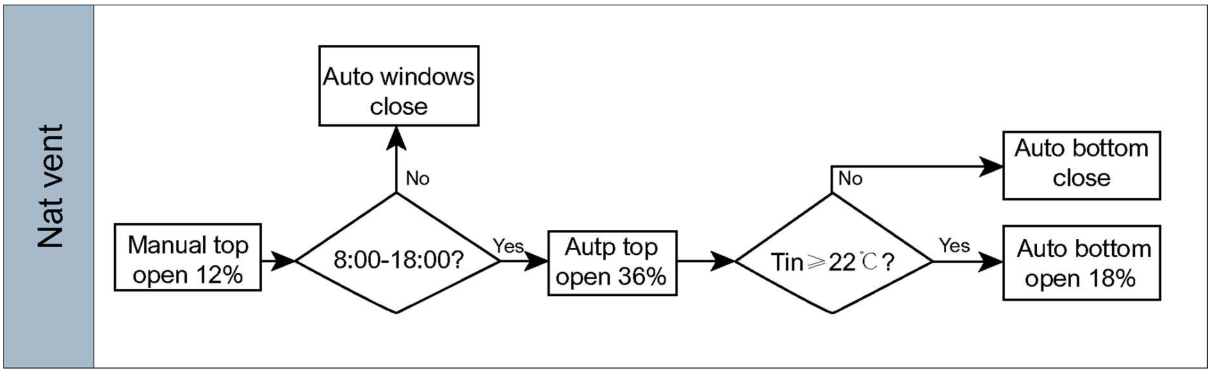
Summer control scheme



Winter control scheme



Spring & autumn control scheme



Appendix 5 Summer operable window control simulation detail (Old construction)

Step 1 Two top windows

	Overheating [hrs]	Overcooling [hrs]	Lighting [kWh]	Note
No shading	329.5	22.5	18.06	
Shading	227.5	25	18.94	
Only manual vent 20%	224	25	18.94	
T20	88.5	51	18.94	Add auto top 36%(24/7)
T20.5	90.5	40.5	18.94	
T21	91	39.5	18.94	
T21.5	92	38.5	18.94	

Step 2. Proposal 1 with SR 450W/m2
(Add bottom auto 18%, 8:0-18:00, shared DeltaC with auto top)

	Overcooling [hrs]	Overheating [hrs]	Discomfort [hrs]	lighting (kWh)
T20.5_two top	40.5	90.5	131	18.94
b18%	52.5	60.5	113	18.94
Δ18	50.5	68	118.5	18.94
Δ20	49.5	66.5	116	18.94
Δ22	51	65.5	116.5	18.94
Δ24	48	65	113	18.94
Δ26	49.5	65	114.5	18.94
T21_two top	39.5	91	130.5	18.94
b18%	45	63.5	108.5	18.94
Δ18	42	69.5	111.5	18.94
Δ20	42.5	67.5	110	18.94
Δ22	43.5	66.5	110	18.94
Δ24	43.5	65.5	109	18.94
Δ26	43.5	65.5	109	18.94
T21.5	38.5	92	130.5	18.94
b18%	42	64	106	18.94
Δ16	40.5	74	114.5	18.94
Δ20	40.5	68	108.5	18.94
Δ22	40.5	67.5	108	18.94
Δ24	40.5	66	106.5	18.94
Δ26	40.5	66	106.5	18.94
(T21b18%)_SR correction test				
450W/m2	42	64	106	18.94
400W/m2	40.5	62.5	103	19.33
350W/m2	43	59	102	19.88
300W/m3	44.5	57	101.5	20.27
250W/m3	47	55.5	102.5	21.28

Step 2. Proposal 2 with SR 450W/m2 (Add bottom auto 18% with DeltaC, 10:0-18:00				
	Overcooling [hrs]	Overheating [hrs]	Discomfort [hrs]	lighting (kWh)
T20.5_two top	40.5	90.5	131	18.94
b18%	50	64.5	114.5	18.94
Δ20	47.5	67	114.5	18.94
T21_two top	39.5	91	130.5	18.94
b18%	44	64.5	108.5	18.94
Δ20	42	68	110	18.94
T21.5_two top	38.5	92	130.5	18.94
b18%	41	65	106	18.94
Δ16	40.5	70	110.5	18.94
Δ22	40.5	68.5	109	18.94
Δ26	40.5	68	108.5	18.94
(T21b18%)_SR correction test				
450W/m2	41	65	106	18.94
400W/m2	40.5	62.5	103	19.33
350W/m2	43	59	102	19.88
300W/m3	44.5	57	101.5	20.27
250W/m3	47	55.5	102.5	21.28

Step 2. Proposal 3 with SR 450W/m2 (Add bottom auto 18%， 24/7 8:0-18:00, shared DeltaC with auto top)				
	Overcooling [hrs]	Overheating [hrs]	Discomfort [hrs]	lighting (kWh)
T20.5_two top	40.5	90.5	131	18.94
b18%	55	56	111	18.94
T21_two top	39.5	91	130.5	18.94
b18%	46	57	103	18.94
T21.5	38.5	92	130.5	18.94
b18%	41.5	58.5	100	18.94
(T21b18%)_SR correction test				
450W/m2	41.5	58.5	100	18.94
400W/m2	42	55.5	97.5	19.33
350W/m2	43	53.5	96.5	19.88
300W/m3	44	51.5	95.5	20.27
250W/m3	48	49	97	21.28

Proposal selection						
Proposal	Detail	Overcooling [hrs]	Overheating [hrs]	Discomfort [hrs]	Vent (ach)	lighting (kWh)
Step1	T21	39.5	91	130.5		
P1	T21.5_t36%(24/7)_b18%(8:00-18:00)	44.5	57	101.5		
P2	T21.5_t36%(24/7)_b18%(10:00-18:00)	44.5	57	101.5		
P3	T21.5_t36%(24/7)_b18%(24/7)	44	51.5	95.5	1.81	20.27

Appendix 6 Old construction control flow chart

Summer control scheme

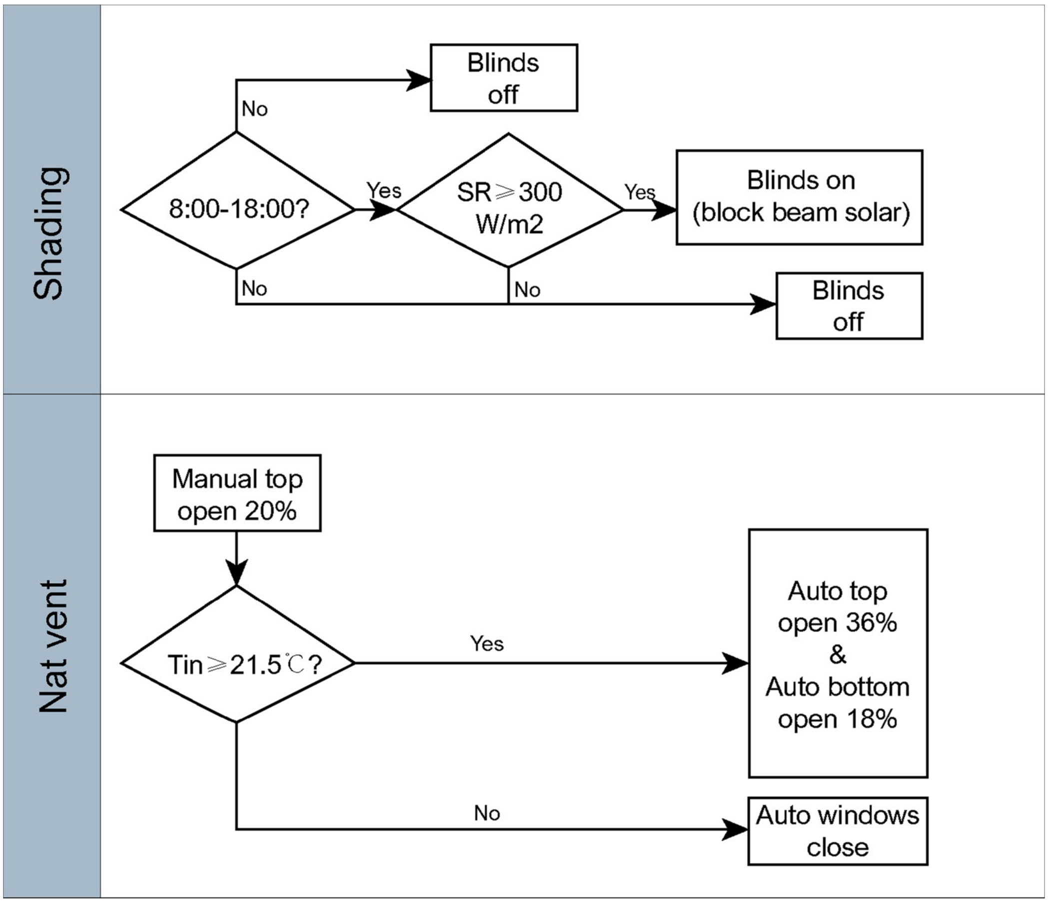


Figure 68 winter control scheme

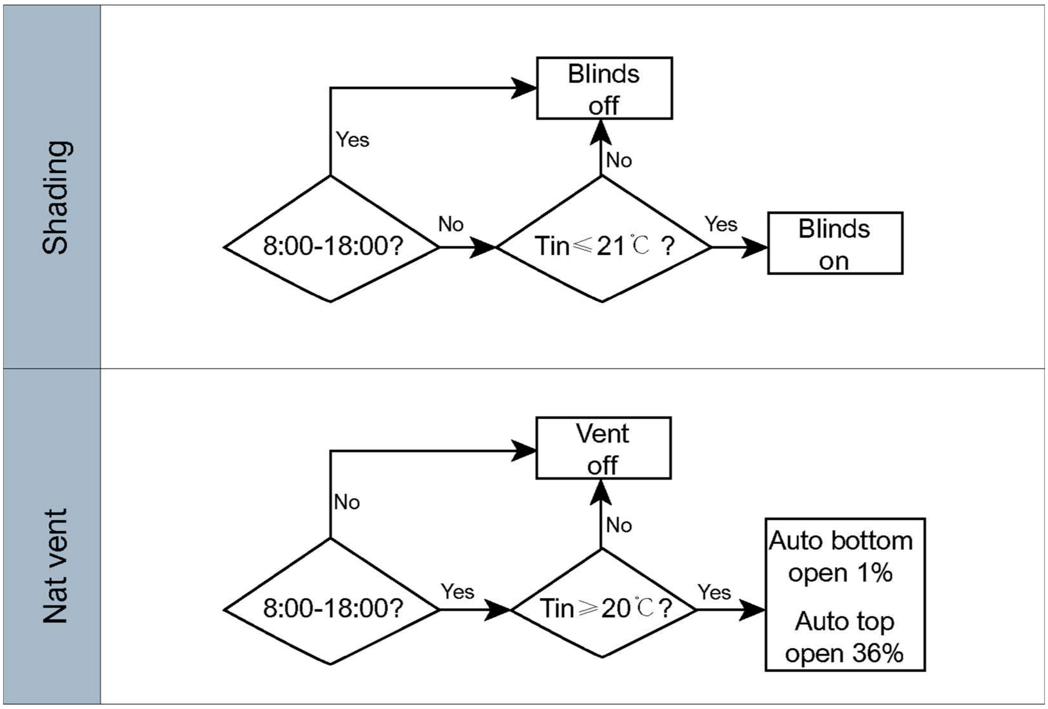
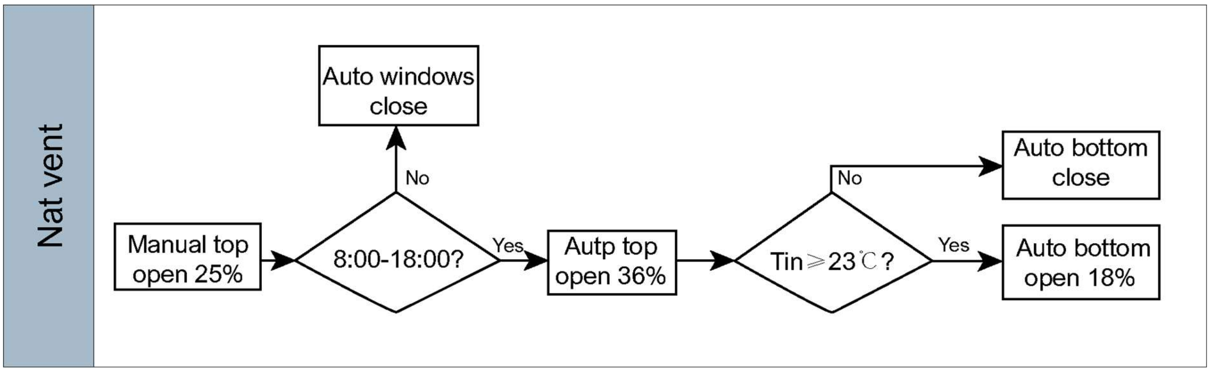


Figure 69 was the spring and autumn control scheme.



Appendix 7. Data for analysis of different proposals

Old construction without control (Reference group 1)

Season	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Lighting [kWh]	Heating [kWh]	Heating [kWh/m2]	Heating (Reality) [kWh/m2]
Spring	7	20	27	13.06	297.73	16.54	16.38
Summer	106.5	113	219.5	18.06	0.00	0.00	1.80
Autumn	12	0	13	22.39	284.64	15.81	10.51
Winter	1	0	0	120.81	1365.20	75.84	78.91

New construction without control (Reference group 2)

Season	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Lighting [kWh]	Heating [kWh]	Heating [kWh/m2]	Heating (Reality) [kWh/m2]
Spring	0	12.5	12.5	13.91	174.05	9.67	-
Summer	43.5	127.5	171	18.38	0.00	0.00	-
Autumn	0	0	0	25.89	160.03	8.89	-
Winter	1.5	0	1.5	135.73	719.05	39.95	-

Old construction with control

Season	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Air change rate[ach]	Lighting [kWh]	Heating [kWh]	Heating [kWh/m2]
Spring	0	3	3	1.17	13.06	108.62	6.03
Summer	44	51.5	95.5	1.81	20.27	-	-
Autumn	0	0	0	0.79	22.39	102.05	5.67
Winter	0	0	0	0.67	120.81	923.59	51.31

New construction with control

Season	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Air change rate[ach]	Lighting [kWh]	Heating [kWh]	Heating [kWh/m2]
Spring	0	0	0	1.05	13.91	64.01	3.56
Summer	16.5	23	39.5	1.82	25.46	-	-
Autumn	0	0	0	0.87	25.89	55.1	3.06
Winter	0	0	0	0.66	135.73	530.74	29.49

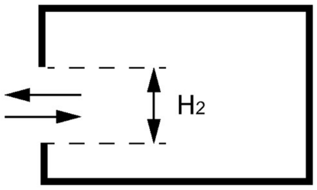
Old construction with the control of new construction

Season	Over cooling [hrs]	Over heating [hrs]	Discomfort [hrs]	Air change rate[ach]	Lighting [kWh]	Heating [kWh]	Heating [kWh/m2]
Spring	19	19	38	1.1	13.06	114.06	6.34
Summer	52	53	105	1.74	22.14	-	-
Autumn	0	19	19	0.86	22.39	106.68	5.93
Winter	0	0	0	0.67	120.81	923.59	51.31

Appendix 8 Analytical calculation

Calculation formulae & DB data

Type A Single-sided ventilation with one opening



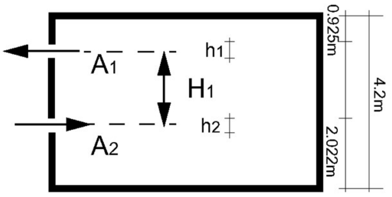
Wind effect:

$$Q = 0.025AV$$

Buoyancy effect:

$$Q = \frac{C_d A}{3}\left(\frac{\Delta T g H_2}{T_{avg}}\right)^{1/2}$$

Type B Single-sided ventilation with two openings



Wind effect:

$$Q = 0.025AV$$

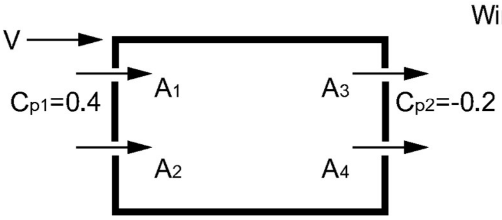
Buoyancy effect:

$$Q = C_d A\left[\frac{\varepsilon\sqrt{2}}{(1+\varepsilon)(1+\epsilon^2)^{\frac{1}{2}}}\right]\left(\frac{\Delta T g H_1}{T_{avg}}\right)^{\frac{1}{2}}$$

$$\varepsilon = \frac{A_1}{A_2};$$

$$A = A_1 + A_2$$

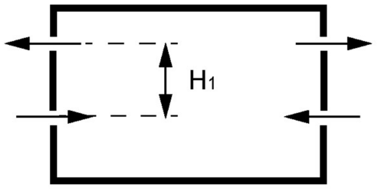
Type C Cross ventilation



Wind effect:

$$Q_w = C_d A_w (\Delta C_p)^{1/2}$$

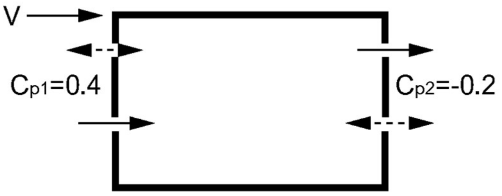
$$\frac{1}{{A_w}^2} = \frac{1}{(A_1+A_2)^2} + \frac{1}{(A_3+A_4)^2}$$



Buoyancy effect:

$$Q_b = C_d A_b\left(\frac{2\Delta T g H_1}{T_{avg}}\right)^{\frac{1}{2}}$$

$$\frac{1}{{A_b}^2} = \frac{1}{(A_1+A_3)^2} + \frac{1}{(A_2+A_4)^2}$$



Final:

$$If\ \frac{V}{\sqrt{\Delta T}} < 0.26\left(\frac{A_b}{A_w}\right)^{1/2}\left(\frac{H_1}{\Delta C_p}\right)^{1/2}$$

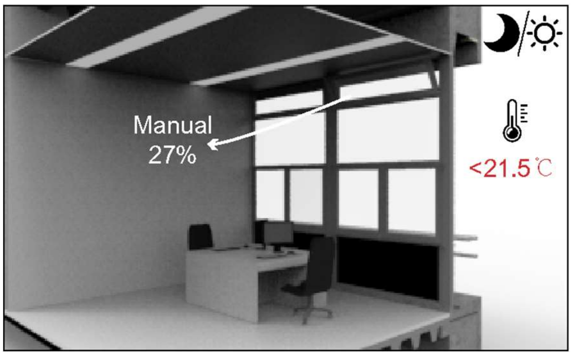
Then $Q = Q_b$

Otherwise $Q = Q_w$

DesignBuilder result						
	Summer		Winter	Spring/Autumn		Cross vent
Date	Aug 19th 13pm	Aug 13th 17pm	Dec 26th 8am	Apr 15th 12pm	May 28th 11am	Jul 17th 2pm
ACH	1.58889	5.5796	1.12949	0.992078	4.627783	3.0902
Te	16.75	19.6	5.525	9.5	20.775	21.45
Ti	20.79273	21.7586	20	20	23.23713	23.1321
V	8.85	9.8	3	9.3	5.7	5.1
T_{avg}	18.77137	20.6793	12.7625	14.75	22.00607	22.29105
ΔT	4.04273	2.15858	14.475	10.5	2.46213	1.6821
Q_{DB}	0.0334	0.1172	0.02372	0.02083	0.097183	0.20766
Type	A	B	B	A	B	C
Note	Cd=0.65					

Analytical calculation

- Summer case 1: Aug 19th 13p.m.



Buoyancy effect:

$$A = 0.566X27\% = 0.153m^2$$
$$H_2 = 0.3445X27\% = 0.093m$$

$$Q = \frac{0.65 \times 0.153}{3}(\frac{4.04273 \times 9.8 \times 0.093}{18.7714})^{1/2} = 0.01469\ m^3/s$$

Relative error:

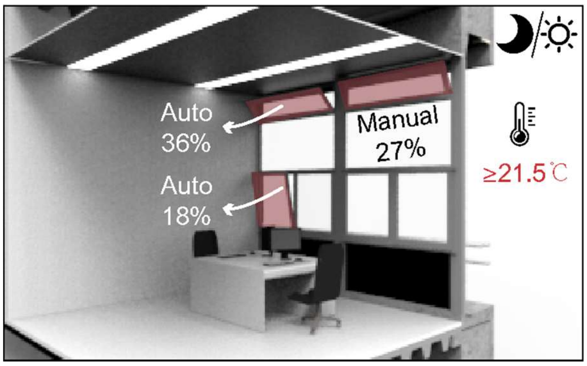
$$\frac{Q_{DB} - Q}{Q_{DB}} \times 100\% = 56.02\%$$

Wind effect:

$$Q = 0.025 \times 0.153X8.85 = 0.03385\ m^3/s$$

$$\frac{Q_{DB}-Q}{Q_{DB}} \times 100\% = -1.35\%$$

- Summer case 2: Aug 13th 17p.m.



Buoyancy effect:

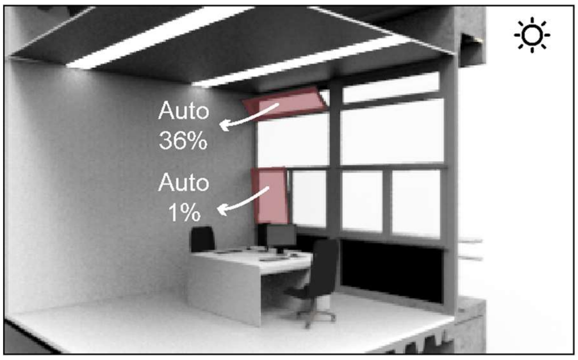
$$\mathrm{A}_1 = 0.566\mathrm{X}(27\% + 36\%) = 0.35658m^2$$
$$\mathrm{h}_1 = \frac{0.3445\mathrm{X}(27\% + 36\%)}{2} = 0.10852\mathrm{m}$$
$$\mathrm{A}_2 = 0.718\mathrm{X}18\% = 0.129m^2$$
$$\mathrm{h}_2 = 0.917\mathrm{X}18\% = 0.1651\mathrm{m}$$
$$\mathrm{H}_1 = 1.2813\mathrm{m}$$
$$\epsilon = \frac{0.35658}{0.10852} = 2.7642$$
$$\mathrm{A} = 0.35658 + 0.129 = 0.48558m^2$$

$$\mathrm{Q} = 0.65X0.48558\left[\frac{2.7642X\sqrt{2}}{(1+2.7642)(1+2.7642^2)^{\frac{1}{2}}}\right]\left(\frac{2.15858\mathrm{X}9.8\mathrm{X}1.2813}{20.6793}\right)^{\frac{1}{2}}$$
$$= 0.1277\ m^3/s$$
$$\frac{Q_{DB}-Q}{Q_{DB}} \times 100\% = -8.96\%$$

Wind effect:

$$\mathrm{Q} = 0.025 \times 0.48558\mathrm{X}9.8 = 0.11897\ m^3/s$$
$$\frac{Q_{DB}-Q}{Q_{DB}} \times 100\% = -1.51\%$$

- Winter case 1: Dec 26th 8a.m.



Buoyancy effect:

$\mathrm{A}_1 = 0.566\mathrm{X}36\% = 0.20376m^2$

$\mathrm{h}_1 = 0.3445\mathrm{X}36\% = 0.12402\mathrm{m}$

$\mathrm{A}_2 = 0.718\mathrm{X}1\% = 0.00718m^2$

$\mathrm{h}_2 = 0.917\mathrm{X}1\% = 0.00917\mathrm{m}$

$\mathrm{H}_1 = 1.19558\mathrm{m}$

$\epsilon = \frac{0.20376}{0.00718} = 28.38$

$\mathrm{A} = 0.20376 + 0.00718 = 0.21094m^2$

$$\mathrm{Q} = 0.65X0.21094\left[\frac{28.38X\sqrt{2}}{(1+28.38)(1+28.38^2)^{\frac{1}{2}}}\right]\left(\frac{14.475\mathrm{X}9.8\mathrm{X}1.19558}{12.7625}\right)^{\frac{1}{2}}$$

$$= 0.02405\ m^3/s$$

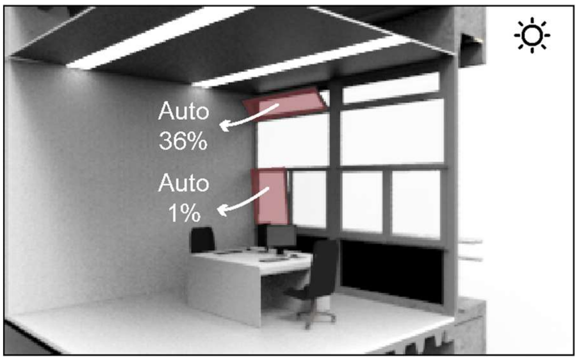
$$\frac{Q_{DB}-Q}{Q_{DB}} \times 100\% = -1.39\%$$

Wind effect:

$\mathrm{Q} = 0.025 \times 0.21094\mathrm{X}3 = 0.01582\ m^3/s$

$$\frac{Q_{DB}-Q}{Q_{DB}} \times 100\% = 33.30\%$$

- Spring case 1: Apr 15th 12 p.m.



Buoyancy effect:

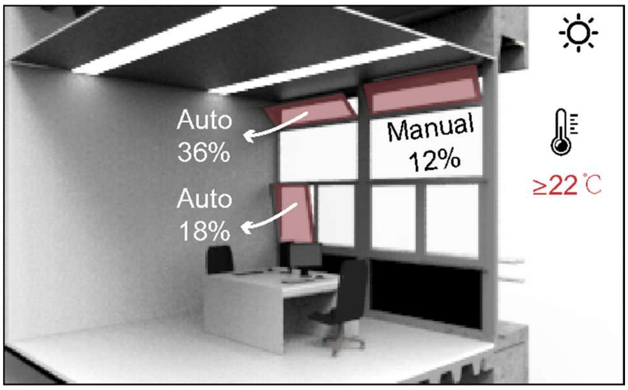
$$\mathrm{A} = 0.566\mathrm{X}(12\% + 36\%) = 0.27168m^2$$
$$\mathrm{H}_2 = \frac{0.3445\mathrm{X}(12\% + 36\%)}{2} = 0.08268\mathrm{m}$$
$$\mathrm{Q} = \frac{0.65 \times 0.27168}{3}\left(\frac{10.5 \times 9.8 \times 0.08268}{14.75}\right)^{1/2} = 0.04471\ m^3/s$$

$$\frac{Q_{DB} - Q}{Q_{DB}} \times 100\% = -114.64\%$$

Wind effect:

$$\mathrm{Q} = 0.025 \times 0.27168\mathrm{X}9.3 = 0.0631656\ m^3/s$$
$$\frac{Q_{DB} - Q}{Q_{DB}} \times 100\% = -203.24\%$$

- Spring case 1: May 28th 11a.m



Buoyancy effect:

$$\mathrm{A}_1 = 0.566(12\% + 36\%) = 0.31696m^2$$

$\mathrm{h_1 = 0.3445X(12\% + 36\%) = 0.08268m}$
$\mathrm{A_2 = 0.718X18\% = 0.129}$
$\mathrm{h_2 = 0.917X18\% = 0.1651m}$
$\mathrm{H_1 = 1.294218m}$
$\epsilon = \frac{0.31696}{0.08268} = 2.45705$
$\mathrm{A} = 0.31696 + 0.08268 = 0.44596 m^2$

$$\mathrm{Q} = 0.65X0.44596\left[\frac{2.45705X\sqrt{2}}{(1+2.45705)(1+2.45705^2)^{\frac{1}{2}}}\right]\left(\frac{2.46213X9.8X1.294218}{22.00607}\right)^{\frac{1}{2}}$$
$$= 0.02405\, m^3/s$$
$$\frac{Q_{DB}-Q}{Q_{DB}} \times 100\% = -34.63\%$$

Wind effect:
$\mathrm{Q} = 0.025 \times 0.44596X5.7 = 0.06355\, m^3/s$
$$\frac{Q_{DB}-Q}{Q_{DB}} \times 100\% = 34.61\%$$

- Cross ventilation: Jul 17th 2p.m

$\mathrm{A_1 = A_3 = 0.566X(27\% + 36\%)} = 0.35658 m^2$
$\mathrm{h_1} = \frac{0.3445X(27\% + 36\%)}{2} = 0.10852\mathrm{m}$
$\mathrm{A_2 = A_4 = 0.718X18\%} = 0.129 m^2$
$\mathrm{h_2 = 0.917X18\% = 0.1651m}$
$\mathrm{H_1 = 1.2813m}$

Buoyancy effect:
$$\frac{1}{{A_b}^2} = \frac{1}{(0.35658X2)^2} + \frac{1}{(0.10852X2)^2}$$

$$A_b = 0.24162\, m^2$$

$$Q_b = 0.65X0.24162\left(\frac{2X1.6821X9.8X1.2813}{22.29105}\right)^{\frac{1}{2}} = 0.06934\, m^3/s$$
$$\frac{Q_{DB}-Q}{Q_{DB}} \times 100\% = 67.61\%$$

Wind effect:

$$\frac{1}{{A_w}^2} = \frac{2}{(0.35658 + 0.10852)^2}$$

$$A_w = 0.34336\, m^2$$

$$Q_w = 0.65X0.34336X5.1(0.6)^{1/2} = 0.88168\, m^3/s$$

$$\frac{Q_{DB} - Q}{Q_{DB}} \times 100\% = -324.59\%$$

Final:

$$\frac{5.1}{\sqrt{1.6821}} = 3.03192 > 0.26(\frac{0.24162}{0.34336})^{1/2}(\frac{1.2813}{0.6})^{1/2} = 0.31937$$

$$Q = Q_w = 0.88168\, m^3/s$$

Analysis

- Single-sided ventilation analysis:

In the hot days, the simulated airflow rate was closer to the airflow caused by the wind effect. The relative error ranged from -1.35% to 34.61%. In the cold days, the simulated airflow rate was closer to the airflow caused by the buoyancy effect. The relative error ranged from -34.63% to 114.64%.

The analytical calculation did not consider the influence brought by shading and infiltration (caused by cracks), the wind direction, the obstruction of the window in tilt position. Also, the openings were simplified as rectangular. In addition, the simulated results calculated the buoyancy and wind effects together. In totality, the differences between simulated calculation and analytical calculation led to the differences of the results.

- Cross ventilation analysis:

According to $\frac{\mathrm{V}}{\sqrt{\Delta \mathrm{T}}} > 0.26(\frac{A_b}{A_w})^{1/2}(\frac{H_1}{\Delta C_p})^{1/2}$, airflow rate should be more closed to airflow caused by wind effect. But considering the space consisted of three zones, a huge block and two internal walls standing in the middle zone, as well as the tilt windows position obstructing the air coming in the directly, the analytical airflow rate was around 3 times larger than the simulated result.