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Implementation of ISO/DIS 52016-3 for adaptive façades: A case study of an office building

Alireza Norouziasas [a,*], Amir Tabadkani [b], Ramin Rahif [c], Mohamed Amer [d], Dick van Dijk [e], Hervé Lamy [f], Shady Attia [c]

[a] *Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway*
[b] *Stantec, Level 3/52 Merivale St., Brisbane, QLD, Australia*
[c] *Sustainable Building Design Lab, Dept. UEE, Faculty of Applied Sciences, Université de Liège, Belgium*
[d] *RenoWatt, Liège, Belgium*
[e] *EPB-research, Delft and Expert at the EPB Center, Rotterdam, the Netherlands*
[f] *The Fédération Française du Bâtiment, Paris, France*

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ABSTRACT

Adaptive building envelope technologies can increase the energy efficiency of buildings. Adaptive facades can be controlled automatically and respond to environmental changes. There is no standard method for evaluating control strategies for adaptive façade elements, particularly for dynamic shadings. Therefore, the ISO/DIS 52016–3 recommended different default control strategies to compare the energy use of various building variants. ISO/DIS 52016–3 presents the procedures for considering the effect of adaptive building envelope elements in calculating the energy needs for heating, cooling, internal temperatures, and sensible and latent heat loads. This paper presents a comprehensive study of the impacts of the newly published ISO/DIS 52016–3 on energy performances and thermal comfort in office buildings with adaptive facades. The simulations were performed for an office room in Brussels with four scenarios: no shading and fixed shading (fixed horizontal louvers) with static control, external roller blinds, and Venetian blinds employing automatic control strategies suggested by ISO/DIS 52016–3. Energy Management Systems (EMS) as a user-customized coding plugin in EnergyPlus was utilized for implementation of each control strategy algorithm. The findings indicated that in the case of roller blinds, the energy performance of the selected office was improved by 19.47% compared to the fixed shading. This study shows that the chosen roller blinds performed the best in decreasing the annual cooling loads with a value of 63.9%, 44.12%, and 8.2% compared to scenarios of no shading, fixed shading, and Venetian blind, respectively. Furthermore, the results showed that the fixed shading would occasionally outperform automated Venetian blinds.

1. Introduction

According to the International Energy Agency (IEA) [1], the building sector consumes 40% of Europe's energy. The window, a key façade element, accounts for 40% of a building's cooling and heating energy consumption [2,3]. Solar radiation through windows increases cooling demands in hot climates and decreases heating demands in heating-dominated climates. Even in continental climates, uncontrolled solar gains, especially for office buildings, can cause overheating.

One of the main strategies to decrease the energy demand and avoid the risk of overheating is using shading systems depending on building orientation, location, and window characteristics [4]. Shading systems vary based on their typology and position, such as Venetian blinds, roller blinds, louvers, and internal shades. They also come with a variety of solar-optical and daylight properties. Using exterior fixed shading reduces users' view out, daylight performance, and solar gains in the cold season, which is needed to heat the space and results in more electrical lighting consumption [5].

Exterior shading devices reduce solar heat gains through the façade, improving thermal comfort by reducing indoor temperature [6–8]. Many studies found that exterior shading devices reduce heating and cooling loads better than interior devices [5,8–11]. Shading systems can

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* Corresponding author.
E-mail address: alireza.norouziasas@ntnu.no (A. Norouziasas).

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significantly impact office lighting energy consumption. Investigating window shading devices usually involves lighting control [12].

Buildings should adapt to their environments for sustainability and improvement of thermal comfort [13,14]. Adaptive facades (AFs) could indeed balance energy demand and human comfort [15]. Conventional AFs, like Venetian blinds [16–18] and roller blinds [19–22], and non-conventional AFs, like folding systems [15,23], can be divided by motion elements. Several studies have been confirmed and introduced AF's potential [24–27].

Occupants can manually or automatically control the AFs. Open-loop and closed-loop control algorithms use automatic shading devices. Closed-loop controls consider indoor and outdoor feedback, while open-loop controls do not. Studies on dynamic shading control show that in most countries, residential buildings use manual solar shadings, while office buildings, especially new office buildings, use automated control [28–30].

Office buildings commonly use roller and Venetian blinds [31,32]. Automatically controlled roller and Venetian blinds reduce glare, increase daylight, and lower building energy use [33]. Office buildings should use automated shading control to save energy because research shows that occupants rarely change the shading position and prefer it to manual control [34–36]. Fig. 1 shows some examples of exterior dynamic shadings in office buildings.

EU [38] and US [California Public Utilities Commission Decision 07-10-032; 2007] commitments reduce building energy consumption. The accurate estimation of energy consumption in buildings has become one of the primary concerns in the energy sector [39]. The Energy Performance of Buildings (EPB) standards' algorithms are transparent, unambiguous, and based on verifiable input data. One of the cores EPB standards published by the International Organization for Standardization (ISO) in the summer of 2017 was (EN) ISO 52016–1:2017 [40].

ISO 52016-1 calculates buildings' heating and cooling energy use. ISO 13790:2008 aggregated building elements to a few lumped parameters using a quasi-steady-state approximation [41]. ISO 52016–1, like ISO 13790:2008, had an hourly and monthly calculation basis, but it was strongly advised to use the hourly basis because monthly calculations have serious drawbacks [42]. Although ISO 52016–1 was more comprehensive and offered strength, transparency, and duplicability in the fully hourly calculation procedure, it was not taken into account all positive features of adaptive elements of the building. To this end, the new ISO 52016–3 is being prepared and has been published as a draft standard (prEN ISO/DIS 52016–3) for public comment in April 2022. Later in the text, the ISO/DIS 52016–3 is referred to as ISO 52016–3. ISO 52016–3 intended to fill the gap in the calculation of energy needs for heating and cooling, internal temperatures, and sensible and latent heat loads of a building according to ISO 52016-1 by adding specific consideration of one or more adaptive building envelope elements [40].

Although ISO 52016–1 was published in 2017; there were only a few studies that investigated its validation in the literature. Van Dijk [43] validated ISO 52016–1 against BESTEST series, including lightweight and heavyweight construction models with continuous, intermittent, and no heating and cooling (free float). Ballarini et al. [44] compared ISO 52016-1 calculation and EnergyPlus simulation results and explained why they differed. Zakula et al. [45] compared ISO 52016–1 and TRNSYS dynamic simulations. They found annual calculation method differences of 40% for heating and 18% for cooling. The results showed that the main difference was due to different window properties assumed for ISO 52016–1's calculation procedures.

Fig. 1. Examples of dynamic shadings [37].

ISO 52016–3 covers active solar shadings, chromogenic glazing, and active ventilative facades. ISO 52016-3 calculated building energy needs for heating, cooling, internal temperatures, and sensible and latent heat loads hourly using the same method as ISO 52016–1. Without the default control strategies, energy performance cannot be compared since adaptive building envelop elements must be controlled. ISO 52016–3 provided default control strategies of differing complexity to compare building energy performance and thermal and visual comfort.

ISO 52016-3 suggested reference control strategies to compare building energy needs and comfort. To account for adaptive envelope elements in calculation, ISO 52016–3 adds and modifies ISO 52016–1 [46]. EN 15232–1 and ISO 52120-1 divide these control strategies into four complexity classes [47]. Environmentally activated control, passive control, manual operation, motorized operation, and automated control are these control types. ISO52016-3 calculation steps are: 1. Identifying adaptive envelope technology 2. Select the control type for active elements. 3. Obtaining input data 4. Model the adaptive element following ISO 52016–3.

Table 1 discusses how dynamic shading control strategies (Venetian blinds and roller blinds) affect office building energy use and occupant thermal and visual comfort in different climates. Designing automated solar shading systems requires choosing control sensors, control logic, actuation mechanisms, and shading device design [48]. An automatic shade control system by Luo et al. [49] improved interior lighting. Fernandes et al. [50] adjusted louver slat angles and spacing to reflect solar altitudes to the room's depth. Nielsen et al. [51] examined dynamic shadings that work better in cold climates, particularly Denmark. Dynamic shading reduced the south-facing façade room's annual energy consumption by 16% compared to static shading. Liu [52] showed that dynamic shading improved building energy use. Therefore, future high-performance buildings need intelligent dynamic facades.

End-users and development parties must understand the benefits of advanced automated solar shading methods to use them in high-performance buildings [53]. Yao et al. found that automatically controlled roller shades in south-facing façade windows reduce energy demand by 30.9% and increase visual comfort by 19.9% [54]. Carletti et al. [31] confirmed that automatic shading may reduce cooling loads and improve indoor thermal conditions. Shade devices improved occupants' thermal comfort on hot and cold days in Montreal, according to Tzempelikos et al. [55,56]. Huchuk et al. [36] examined Ontario office roller blinds' control strategies. Their control strategy reduced annual cooling, heating, and lighting demands by 49%, 12%, and 54%. Tzempelikos and Shen [57] also examined office roller blind control strategies. Windows and shade properties affect annual consumption by 10.1%–34.4%.

In addition to the research listed above, numerous similar research which discussed the impact of controllable Venetian blinds and roller blinds on energy use [9,33,35,58–72], thermal comfort [59,63,64,67,70,73–75], and visual comfort [35,58–60,63,64,66,69,72,76–79] in office buildings can be found in the scientific literature (see Table 1).

It is evident that although several studies have been carried out on the effect of dynamic shadings on the energy performance of office buildings, a more extensive study is essential to be conducted including all aspects of dynamic shadings, especially with automatic control strategies [17,18,83,84]. Based on the literature the most studied dynamic shadings were Venetian blinds and roller blinds [5,8,10,23,85]. However, researchers mostly focused on the effect of one shading technology either Venetian blinds [63,64,66,86–88] or roller blinds [73,78,89,90] on building energy performance. Therefore, the comparison

Table 1
Summary of the studies on the impact of control strategies of dynamic shadings on energy use and thermal comfort of occupants in office buildings in various climates.

Author(s)	Ref.	Year	Location(s)	Climate(s)	Shading type(s)	Shading position(s)	Focus
Inoue et al.	[75]	1998	Japan	Subtropical	Venetian blinds	External	Thermal comfort
Newsham	[67]	1994	Toronto, Canada	Cold	Venetian blinds	Internal	Thermal comfort, energy demand
Reinhart and Voss	[68]	2003	Weilheim, Germany	Cold	Venetian blinds	External	Lighting demand
Wienold	[69]	2007	Brussels, Belgium	Temperate	Venetian blinds	External	Energy demand, daylight, and visual comfort
van Moeseke et al.	[70]	2007	Brussels, Belgium	Temperate	Venetian blinds	External	Energy demand and thermal comfort
Tzempelikos and Athienitis	[33]	2007	Montreal, Canada	Cold	Roller blinds	External	Cooling and lighting demand
Inkarojrit	[80]	2008	Berkeley, USA	Subtropical	Venetian blinds	External	Occupants' blind-control behaviour
Mahdavi et al.	[71]	2008	Vienna, Austria	Cold	Venetian blinds	External	Lighting demand, Occupants' blind-control behaviour
Zhang and Barrett	[81]	2012	Sheffield, UK	Temperate	Venetian blinds	Internal	Occupants' blind-control behaviour and View
Da Silva et al.	[9]	2012	Porto, Portugal	Temperate	Venetian blinds	External	Occupants' blind-control behaviour, energy demand
Oh et al.	[72]	2012	Daejeon, South Korea	Subtropical	Venetian blinds	Internal	Visual comfort, energy demand
Atzeri et al.	[59]	2013	Rome, Italy	Subtropical	Roller blinds and Venetian blinds	Internal	Visual and thermal comfort, and energy demand
Karlsen et al.	[35]	2016	Aalborg, Denmark	Cold	Venetian blinds	Internal, external	Energy demand, visual comfort
Karlsen et al.	[82]	2015	Aalborg, Denmark	Cold	Venetian blinds	Internal, external	Visual comfort
Yun et al.	[77]	2017	Singapore	Tropical	Venetian blinds	External	Visual comfort, lighting demand
Evola et al.	[73]	2017	Catania, Italy	Warm and Temperate	Roller blinds, integrated roller blinds, external solar control film	Internal, External	Thermal comfort
Katsifaraki et al.	[58]	2017	Freiburg, Germany	Cold	Venetian blinds	Internal	Visual comfort, energy demand
Bustamante et al.	[60]	2017	Montreal, Canada	Cold	Venetian blinds	Internal	Visual comfort, energy demand
Nezamdoost et al.	[61]	2018	Boise, USA	Hot	Venetian blinds	Internal, external	Daylight, energy demand
Yeon et al.	[62]	2019	Incheon, South Korea	subtropical	Venetian blinds	Internal	Energy demand
Kheybari and Hoffmann	[63]	2020	Mannheim, Germany	Temperate	Venetian blinds, Electrochromic glazing	Internal	Visual comfort, thermal comfort, energy demand
Naderi et al.	[64]	2020	Tehran, Iran	semi-arid	Venetian blinds	Internal, external	Visual comfort, thermal comfort, energy demand
de Vries et al.	[78]	2021	Amsterdam, The Netherlands	Temperate	Roller blinds, vertical blinds	Internal	Visual comfort, energy demand
Montaser Koohsari and Heidari	[66]	2022	Tehran, Iran	semi-arid	Venetian blinds	Internal	Visual comfort, energy demand

of the impact of different technologies on energy use and user comfort in office buildings has rarely been taken into account.

Furthermore, as mentioned above, there is no standardized way to the assessment of different control strategies regarding the adaptive façade elements, especially for dynamic shadings [91]. As a result, ISO 52016–3 offered default control strategies based on the building type and type of adaptive façade elements. Even though there are only a few studies [39,45,92–94] that have examined the building energy need based on ISO 52016–1, researchers have not studied the effectiveness of the automated control strategies proposed by the new ISO 52016–3. Therefore, considering the importance of providing a standardized way to assess buildings' energy use through control strategies regarding the adaptive façade elements, especially for dynamic shadings, this research is developed to address the abovementioned gaps. The aim of this paper is to broaden the present knowledge about the limitations and possibilities of the new ISO 52016–3 and improve the energy performance of buildings with adaptive envelope elements. More specifically, in this research, the following questions are answered.

1. How do the control strategies recommended by ISO 5216–3 for Venetian blinds and roller blinds affect the energy saving of an office building located in Bulgium?
2. How do the control strategies recommended by ISO 52016–3 for Venetian blinds and roller blinds influence internal temperatures, thermal comfort, and visual comfort in an office building?
3. Which control strategy and dynamic shading technology (Venetian blinds and roller blinds) is more efficient in decreasing cooling demand and electrical lighting?

The following are some of this study's contributions. Firstly, this paper provided a valuable contribution to the new body of knowledge from an international point of view to better understand the effects of the recommended control strategies by ISO 52016–3 for dynamic shadings. Based on the climate zone classification by ANSI/ASHRAE 169–2020 [95], Brussels was classified as 4A climate zone. ASHRAE169-2013, which included climatic zoning based on heating degree-days (HDDs) and cooling degree-days (CDDs) ranging from 0 to 9000. Based on the HDD and CDD, ASHRAE169-2013 categorizes its climate zones into eight regions. As can be seen in Fig. 2, in addition to numerous cities in Europe with similar climate condition, there are several cities with comparable climates in other parts of the world, including Seattle, Vancouver, Miami, Beijing, Tokyo, Shanghai, Hong Kong. Therefore, the results of this study can enable a comparison of such strategies' effects on worldwide building energy use.

Secondly, the authors prepared flowcharts for implementing the control strategies of ISO 52016–3. These flowcharts are more understandable and pave the way for other researchers to model and simulate the recommended control strategies by ISO 52016–3. Thirdly, the authors used the real case study office room in a calibrated, high-performance office building for the Implementation of ISO 52016–3,

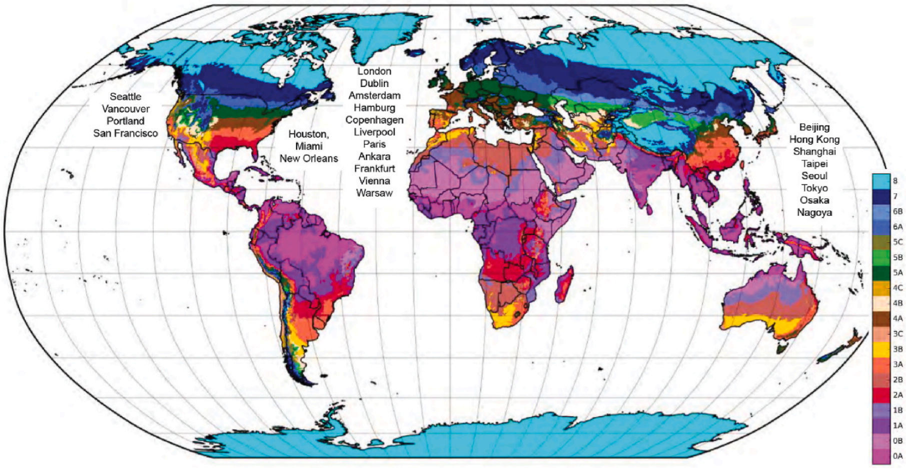


Fig. 2. ANSI/ASHRAE 169–2020 world climate zones map (modified from ANSI/ASHRAE 169–2020 [95]).

which is novel and still under development. Fourthly, this paper prepared the recommendations for improvement of ISO 52016-3 by testifying the accuracy and applicability of control strategies suggested by ISO 52016–3. Moreover, this paper shed light on the impact of automated control strategies on the energy performance of office buildings with dynamic shadings and occupants' comfort. It can lead to the improvement of thermal and visual comfort and enhance energy performance in office buildings. Therefore, architects, building engineers, facade engineers, and researchers can also benefit from the results of this research. Finally, the results of this paper are valuable for national building code developers, building owners, and occupants to promote the use of adaptive façades to reduce heating and cooling loads in the office building sector based on ISO 52016–3.

This research involved different stages, including data collection, parametric study, and dynamic simulations. The performance of fully automated control strategies recommended by ISO 52016–3 for exterior roller blinds and Venetian blinds in an existing high-performance office building in Brussels was evaluated. Two more scenarios, including no shading and fixed shading (fixed horizontal louvers), were also considered to understand better the effects of control strategies and shading devices on building energy needs. Finally, the results of user comfort and building energy use were reported, including heating and cooling loads and internal temperature covered by ISO 52016–3 and artificial lighting demand covered by EN 15193–1.

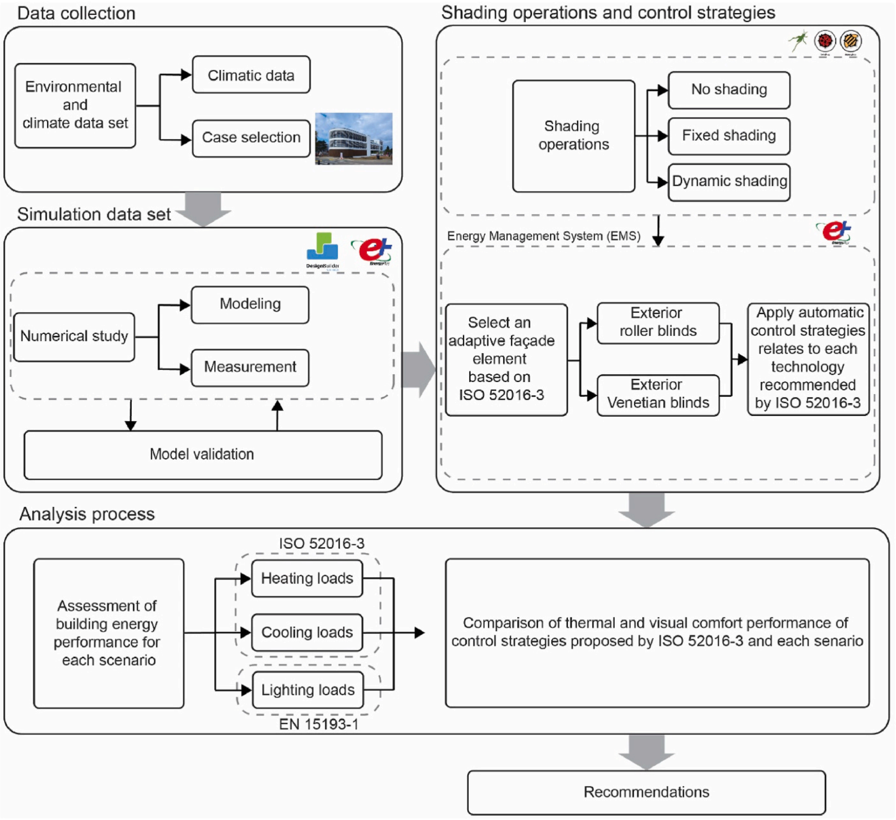


Fig. 3. Conceptual study framework.

2. Methodology

This research methodology consisted of stages that started with the data collection and the simulation data set. After that, it continued with the parametric study and results analysis, leading to obtaining some recommendations, as shown in Fig. 3. The details of the different stages are described in the following sections.

2.1. Data collection

The first step of the methodology was the data collection in which the environmental and climatic inputs were collected. Then, an office room located on the first floor of Brussels' existing high-performance office building as a case study was selected.

2.1.1. Climate

For the implication of the automated control scenarios, especially the ISO 52016–3, the climate files from ASHRAE IWE2C have been collected and used as EnergyPlus Weather File (EPW) in the building simulations. The simulation was carried out for the climate of Brussels (50°51′N, 4°21′E). The Brussels climate is categorized as Oceanic (Cfb) in the Köppen climate classification, with warm summers and cool winters [96, 97]. Some of the key environmental indicators for this research, such as dry bulb temperature, global solar radiation, and global horizontal illuminance, are shown in Fig. 4.

2.1.2. Case study building

Since the Energy Performance of Building Directive (EPBD) is concerned with the Member States of the European Union (EU) [98,99], Brussels Capital Region in Belgium, as the capital of Europe, a case study was chosen at this location. The building was constructed to provide a passive office for the Clinique Saint-Pierre in Ottignies. The construction area is about 3090 m^2 of offices, meeting rooms, multipurpose spaces, and 1140 m^2 of basement and parking spaces. The selected case study building is presented in Fig. 5.

This project was certified by the passive house platform via Project Certified Passive House Platform (PHPP). The characteristics and performance of passive house buildings based on monitored values have been published in a document [100]. It is worth mentioning that passive house standards have specific characteristics in each country. For example, in Germany, the passive house standard considers the condition that the indoor air temperature higher than 25 °C should not exceed more than 10% of the occupied time, while in Belgium should not occur more than 5% when the place is occupied. It is worth mentioning that the selected case study building was studied by Amaripadath et al. [101]. In their study, authors evaluated time-integrated thermal discomfort, primary energy use, and greenhouse gas (GHG) emissions.

Fig. 5 depicts the different perspective views of the selected building and the location of the selected office room in the plan. The characteristics of the chosen office are explained in the following sub-section.

2.2. Simulation data set

2.2.1. Model characteristics

A south-oriented office room has been selected from the reference case study building for conducting energy simulations. The selected office was encompassed by two other rooms on the west and east sides (Fig. 5). The model represented a single-zone office space on the first floor of the reference building with 5.55 m * 4.00 m * 3.40 m (depth * width* height), as shown in Fig. 6. The south wall, which has three windows, was exposed to the outdoor environment without obstructions. The dimensions of the windows were equal, with a height of 2 m and a width of 0.93 m located at the sill height of 0.8 m. The north-oriented wall of the room faced the corridor while the sides walls were shared with other office rooms. It should be noted that the interior walls, roof, and floor were assumed as adiabatic surfaces. Moreover, different orientations are considered to investigate the impact of ISO 52016–3 control strategies on building energy consumption. Generally,

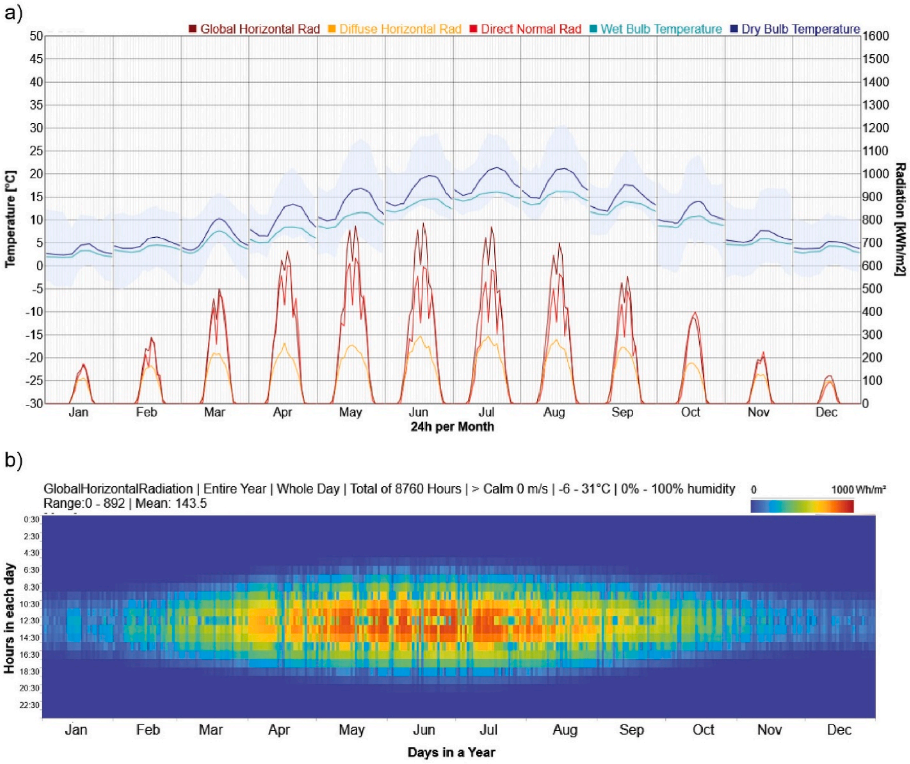


Fig. 4. The climate data for the case study building; a) Diurnal averages (global horizontal radiation, diffuse horizontal radiation, direct normal radiation, wet bulb temperature, and dry bulb temperature); b) Hourly heatmap of global horizontal radiation.

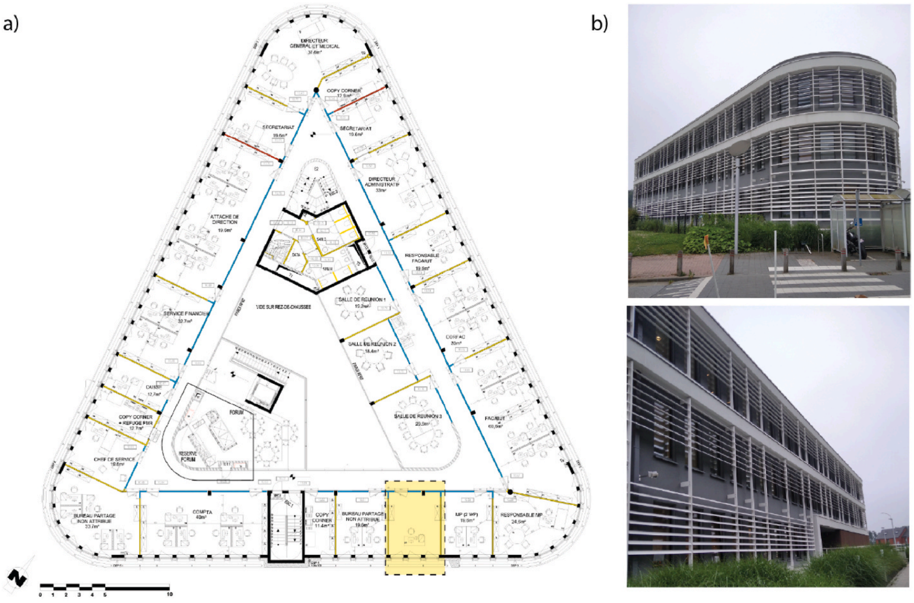


Fig. 5. Case study building: a) First-floor plan of Clinique Saint-Pierre building (highlighted area represented the selected office room); b) Perspective view of the building.

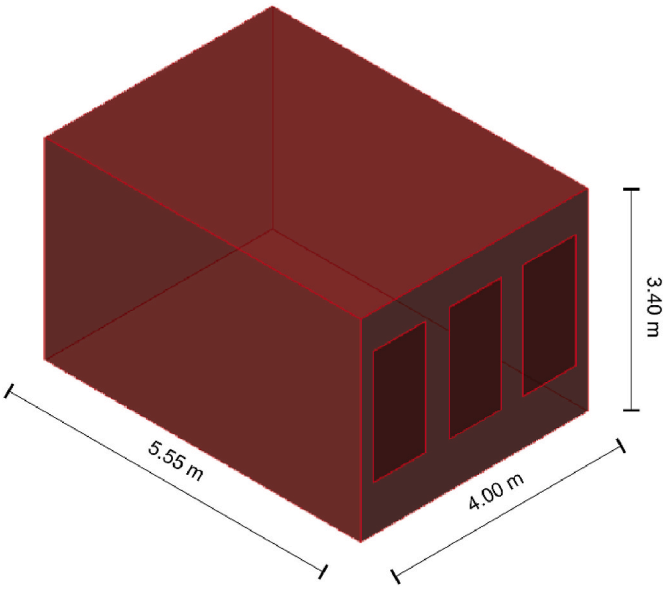


Fig. 6. Office geometry model.

four orientation, East, West, North, and South, has been parametrically simulated with other shading materials variations that will be explained accordingly.

The transparent part of the façade was triple glazing windows with low emissivity coating. The exterior wall and window properties are shown in Table 2. The external wall facing the south consists of two layers and a thickness of 450 mm. The exterior wall was constructed with 200 mm of cast concrete, and 250 mm extruded polystyrene-$CO2$ blowing (XPS) insulation on the outer surface, with a U-value of 0.123 W/m^2.K. The external wall also has three triple-glazing windows, resulting in a Window to Wall Ratio (WWR) of 40%. Windows are made of low-emissivity triple-glazing with an average U-value of 0.50 W/m^2k, Solar Heat Gain Coefficient (SHGC) of 0.50, and 0.661 light transmission. The same setting except the shading control strategies has been considered during a year in all simulations.

Table 2

Properties of the office room considered for energy simulation.

Parameters	Assigned value (s)
Space type	Single Office Space
Roof/Ground floor	Adiabatic
Interior walls	Adiabatic
Exterior wall	U-Value: 0.123 W/m^2k
Window	U-Value: 0.5 W/m^2k, SHGC: 0.50, VT: 0.661
Internal loads Equipment	12.9 W/m^2
Infiltration ratio	0.6 ac/h
Lighting density	2 W/m^2
Number of people	1 occupant
Natural ventilation	Not assigned
Shadow calculation method	Time step frequency
HVAC system	Fan Coil Unit (4-Pipe), Air-cooled Chiller
Heating set-point/set-back	21 °C/12 °C
Cooling set-point/set-back	25 °C/35 °C
Reference point 1 (P1)	0.75 m (height) for target task illuminance
Reference point 2 (P2)	1.2 m (height) for glare index (DGI)
Solar distribution method	Full interior and exterior with reflections
Shading calculation method	Polygon Clipping
Shading calculation update frequency method	Timestep
Timestep duration	1
Heat Balance Algorithm	Conduction Transfer Function
Surface convection algorithm (inside)	TARP
Surface convection algorithm (outside)	DOE-2

Internal loads for lighting, occupancy, and equipment are considered according to the actual condition of the building. The working hours are from 8:00 to 18:00 on weekdays, aligning with the occupancy rate in IES LM-83-12 [102]. The office is occupied by a single user seated facing the window. Consequently, the occupancy load is 0.045 ppl/m^2, and the internal equipment load is 12.9 W/m^2 related to the computer and printer in a room. The electric lighting is a dimmable lamp controlling based on the target illuminance of 500lux at the task height level of 75 cm from the floor. The peak load of artificial lighting is equal to 2 W/m^2.

For the reference model Fan Coil Unit (4-Pipe), an Air-cooled Chiller has been assigned for the (heating, ventilation, and air conditioning) HVAC system according to the actual building system. Setpoint values of 21 °C and 25 °C are considered for controlling the heating and cooling, respectively, during occupied hours, and 12 °C and 35 °C set-back temperature for unoccupied hours. The infiltration rate at 50 pa, equal to 0.6 ac/h, was considered for the external façade. Furthermore, as this study analyzes different automated control scenarios, the Air Handling Unit (AHU) and Domestic Hot Water (DHW) are not considered for this model.

Two reference points were considered to measure the values related to illuminance. The reference point 1 (P1) was located at 0.75 m and measured the task illuminance values. However, reference point 2 (P2) was chosen to obtain eye-level vertical illuminance for calculating the Daylight Glare Index (DGI) at the height of 1.2 m facing the windows. It is worth mentioning that both of the points are located at a 1.5 m distance from the exterior wall.

2.2.2. Model calibration

The case study building has been monitored since it was built. The data on heating, cooling, and electrical lighting is constantly measured and stored monthly. The monthly consumption data relating to the electricity (lighting, cooling, and auxiliary electricity used by the HVAC system) and natural gas (heating) of the whole case study building during 2020 were used to validate the simulation model. To this end, the entire building was modeled and simulated using DesignBuilder, and the energy simulation results are reported in Fig. 7. It is worth mentioning that the case study building energy model is studied and validated in the previous research by Amaripadath et al. [101].

The ASHRAE Guideline 14–2002 provided a minimum acceptable performance level for measuring energy and demand savings from energy management projects applied to residential, commercial, or industrial buildings [103]. Based on ASHRAE Guideline 14–2002, two indicators of the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE) were utilized to validate the building energy and thermal model's good-to-fit [104–106]. The acceptable range for each indicator is presented in Table 3. MBE is connected to the average difference between each month's actual monitored energy consumption data and the simulation results [103]. RMSE, which indicates the root of the mean of the error frames, is another metric. The disparities between measured and simulated energy consumption data are squared every month. The square root of the mean error squares acquired for each month is computed, and the Coefficient of Variation of the Root Mean Square Error (CVRMSE) value is determined [107]. The formula for MBE and CV(RMSE) are shown in the first and second equations, respectively.

$$\mathrm{MBE} = \sum_{i=1}^{Np} (m_i - s_i) \Big/ \sum_{i=1}^{Np} m_i [\%] \tag{1}$$

$$\mathrm{CV\ (RMSE)} = \sqrt{\sum_{i=1}^{Np} (m_i - s_i)^2 \Big/ Np} [\%] \tag{2}$$

Where ***mi***: (i = 1, 2, 3 …, Np) represents monitored data points and ***si***: (i = 1, 2, …, Np) represents simulated data points. The MBE and CVRMSE values obtained for calibrating building energy simulation models are based on a number of standard criteria defined by monthly or hourly data measurements [103]. Both of the indices units are addressed in percentages. The building energy simulation model is widely regarded as "reliable as long as the findings match the requirements stated in Table 3 as established by the [103]."

As presented in the guidelines of ASHRAE 14–2002 in Table 3, the maximum threshold for MBE is 5% for monthly calibrated data points and 10% for hourly calibrated data points. However, CVRMSE recommends a maximum limit of 15% for monthly calibrated data points and 30% for hourly calibrated data points.

Fig. 7 compares the measurement and simulation results for the building's monthly heating and electricity energy use. Based on the results, the MBE and CVRMSE for heating energy use were equal to 4.75% and 5.95%, respectively. At the same time, the values of the monthly delivered electricity were equal to 4.54% and 5.22%, respectively. It is worth mentioning that, however, the space heating and delivered energy (electricity) meet the requirements of ASHRAE 14–2002, the model did not accurately represent the dynamic behaviour of the actual building. The simulated model overestimated heating energy use in the year's first half and underestimated it in the rest of the year. These biases could be explained by some uncertainty in the simulated model, such as the occupancy schedule, weather data, and the U-value of the materials used in the actual building, which could be different from the actual one. Since the monitored data gathered during 2020, the COVID-19 pandemic situation, which affected the number of people in the building, may have contributed to differences between heating energy use in the first and second years in the actual building. Reducing the number of occupants decreased the building's heat gain, leading to an increase in the actual building's heating energy use. The calibration parameters for heating and delivered electricity meet the requirements stated in ASHRAE 14–2002 and ensure that the simulation model is reliable enough to be

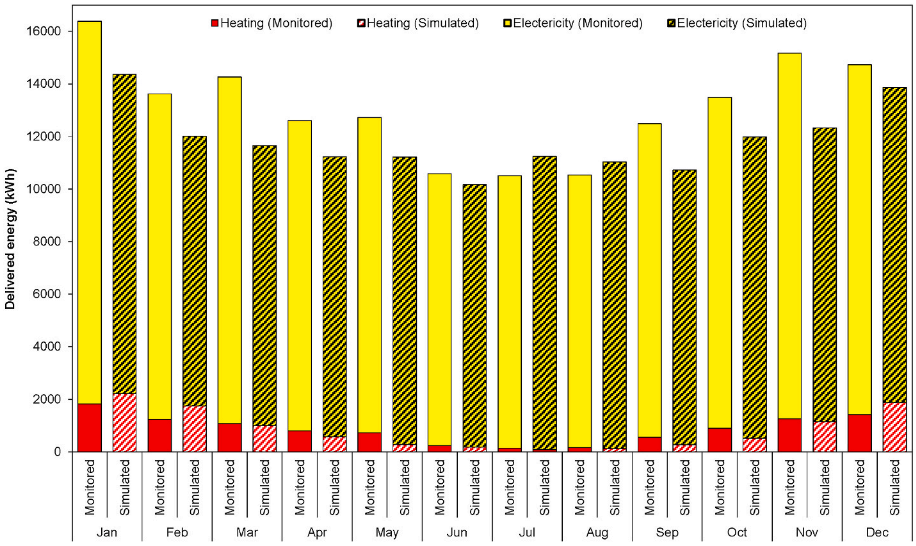


Fig. 7. Calibration values for delivered heating energy use and delivered electricity of the whole building in kWh.

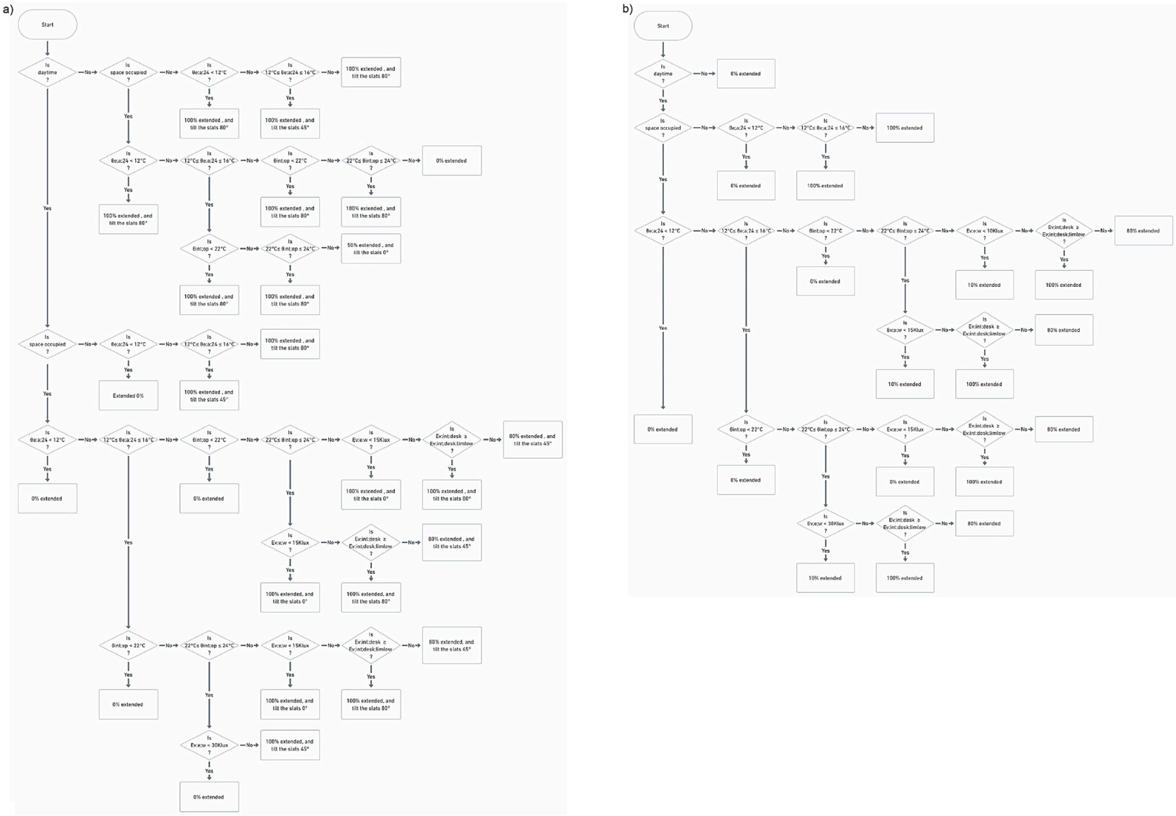


Fig. 8. Flowcharts of automated control strategies for non-residential buildings recommended by ISO 52016–3; a) Control strategy recommended for Venetian blinds; b) Control strategy recommended for roller blinds.

Table 3
Guideline for calibration of building's energy simulation model [103].

	Monthly criteria (%)		Hourly criteria (%)	
	MBE	CVRMSE (monthly)	MBE	CVRMSE (hourly)
ASHRAE	5	15	10	30

utilized in the study.

2.3. Shading operations and control strategies

The open office model has been created to analyze and compare the influence of different automated controls on building energy consumption. Three shading operations were considered in this study, including fixed shading, no shading, and dynamic shadings. Since the fixed horizontal louvres devices were already installed on the exterior facades of the case study building, the fixed shading operation was assumed as a base case model. Also, the model with no shading devices has been simulated and added to this research as one scenario for a comprehensive analysis of the dynamic shading's effects. The third shading operation was dynamic, which was controlled based on two different control strategies recommended by ISO 52016–3 for two dynamic shading technologies. As explained in the literature, Venetian blinds (T1) and roller blinds (T2) were selected as two technologies covered by ISO 52016–3. Therefore, the simulation was conducted for four scenarios in this study: no shading, fixed shading (base case), roller blinds, and Venetian blinds. These scenarios were named scenario 1 (S1), scenario 2 (S2), scenario 3 (S3), and scenario 4 (S4), respectively. According to the criteria given by ISO 52016–3, the influence of exterior roller blinds and external Venetian blinds on the heating, cooling, and lighting loads and internal air temperature were simultaneously assessed. The considered scenarios and descriptions of each scenario are presented in Table 4.

2.3.1. Automatic control strategies and ISO 52016-3

Since this research implemented the control strategy provided by ISO 52016–3, automatic control algorithms introduced for non-residential buildings for each of the selected technologies (external roller blinds and external Venetian blinds) were simulated. The control strategies were acted separately for each window utilizing the Energy Management Systems (EMS) feature in EnergyPlus.

The ISO 52016-3 standard adds adaptive envelope features like dynamic shadings to EPB standards (ISO 52000 family) to calculate building energy demands for heating, cooling, and internal temperature for a building zone. This standard adds adaptive building parts to the building energy demands calculation method and revises ISO 52016–1 [94]. For that, this standard includes default control situations with different levels of automation. These default conditions allow façade system comparisons without being simplistic or optimistic [46].

This study used ISO 52016–3's exterior roller and Venetian blind control strategy. ISO 52016-3 defined reference control scenarios for building envelope active adaptive elements. The European Solar Shading Organization (ES-SO) developed these strategies. In terms of

Table 4
Overview of simulated control scenarios.

Scenario	Description of scenario
Scenario 1 (S1): No shading	No solar shading was applied for the simulation
Scenario 2 (S2): Fixed shading (base case)	Based on the case study building, fixed shading was modeled and simulated as a base case model
Scenario 3 (S3): Roller blinds (T2)	According to the control strategy presented in Fig. 8 (a)
Scenario 4 (S4): Venetian blinds (T1)	According to the control strategy presented in Fig. 8 (b)

applicability to ISO 52016–3 for automated control levels, a flow diagram has been provided as a guideline for the control strategy model. The flowchart presented in Fig. 8 illustrates how the roller blinds and Venetian blinds are automatically controlled. These flowcharts were created based on the master and detailed scheme of automated control strategy for controlling exterior roller blinds and Venetian blinds in non-residential buildings.

In these flowcharts, different sensors were used to control the building envelope's adaptive element. Where:

$\theta_{e;a;24}$: $External\ (outdoor)air\ temperature\ of\ last\ 24\ hours\ [^{\circ}C]$

$\theta_{int;op}$: $Internal\ operative\ temperature\ [^{\circ}C]$

$E_{V;e;w}$: $External\ global\ illuminance\ on\ adaptive\ building\ envelope\ element$

$(total\ hemispherical, perpendicular\ to\ adaptive\ building\ envelope\ element)\ [lux]$

$E_{V;int;desk}$: $Internal\ illuminance\ at\ desk\ level\ [lux]$

$E_{V;int;desk;limlow}$: $A\ specific\ limit\ of\ internal\ illuminance\ at\ desk\ level\ [lux]$

$E_{v;int;desk;limlow}$ for the control strategy provided by ISO52016-3 is considered equal to 300 lux. In the flowchart, 100% extended meant when the adaptive building element was pulled down and covered the window; conversely, 0% extended was when the adaptive building element do not cover the window.

Various sensors have been used to control the exterior roller blinds and Venetian blinds in each time step. Six sensors in the office room have been used to perform the ISO control strategies. Solar irradiance on window (W/m^2), illuminance level at task level (lux), external global illuminance (lux), exterior air temperature (°C), internal air temperature (°C), and view luminance (Cd/m^2) were the sensors which were located in different position of the room. The schematic section in Fig. 9 depicts the sensors used for the automatic control algorithm of ISO 52016–3.

Also, this study used a schedule to detect occupants and occupancy hours while the sensor should be used in the real environment. These control variables have frequently been utilized in earlier research [34, 35,60,108,109], but no study precisely specifies the reference control strategies with multivariable control parameters. ISO 52016–3 controls the adaptive façade elements based on the solar radiation on the window, horizontal solar radiation, operative temperature, and exterior solar irradiance. Furthermore, the control conditions provided by the ISO 52016–3 included occupancy and daytime.

Because each of the control algorithms in each scenario has incoming signals from a different environment, each has been written separately. The ISO was a closed-loop algorithm. It means that the control mechanism embeds a feedback loop from the indoor environment. The luminance sensor was located at the height of 1.2 m and 1 m distant from the window looking towards the window. The sensor captured the horizontal illuminance at the task level (0.75 m). The ISO algorithm employed the operative temperature (OT) as setpoints calculated in the center of the room. The sensor in the center of the zone captured the internal air temperature and sent signals to the controller. Furthermore, some sensors reported the outdoor environmental conditions such as vertical solar radiation capturing the solar incident on the window surface and global horizontal illuminance. Also, the outdoor air temperature was employed for controlling the roller shade in the ISO algorithm.

2.3.2. Building simulation tools

Several building simulation tools are available for modeling the static and no shading types for the exterior facades; however, few tools can be used for the dynamic shading type. All the building performance simulation tools were mainly developed to simulate static shading devices. Dynamic shadings require more complex calculation procedures to predict their performance correctly based on indoor and outdoor variables [15]. To this end, various interface plugins have been introduced to add the ability to control such devices. Energy Management System (EMS) for EnergyPlus, user-defined control macros in IDAICE, APpro in IESVE, and W-editor in TRNSYS are plugins to support users in modeling and controlling dynamic shading elements [110].

As noted earlier, using customized control algorithms, the EMS feature in EnergyPlus controls commonly used dynamic shadings such as Venetian blinds and roller blinds. Although EMS provides a high level of super visionary control in EnergyPlus, it requires a high level of coding to override the EnergyPlus source code [111]. For employing EMS to control adaptive dynamic envelope elements, exterior roller blinds, and Venetian blinds in this study, different sensors read the data and then send them to the actuators. Finally, this control logic will convert to the physical reaction of dynamic shading elements. EnergyPlus Runtime Language (Erl) is employed to describe the control strategies for EnergyPlus when the model is running. All windows in all automated control algorithms have been controlled by the roller shades through EMS, and each window was separately controlled based on the local conditions and various sensors. A built-in plugin in Grasshopper, Ladybug-tools, was used for the simulation procedure. Ladybug tools interface to the validated simulation engines OpenStudio and EnergyPlus, conducting parametric energy simulations with high accuracy and reliability in complex buildings [112,113].

2.3.3. Material properties of fixed shading and dynamic shading

The selected case study building employed fixed shadings to control solar shading. Therefore, the selected office room's fixed shading has been considered the simulation's base case. Table 5 presents the

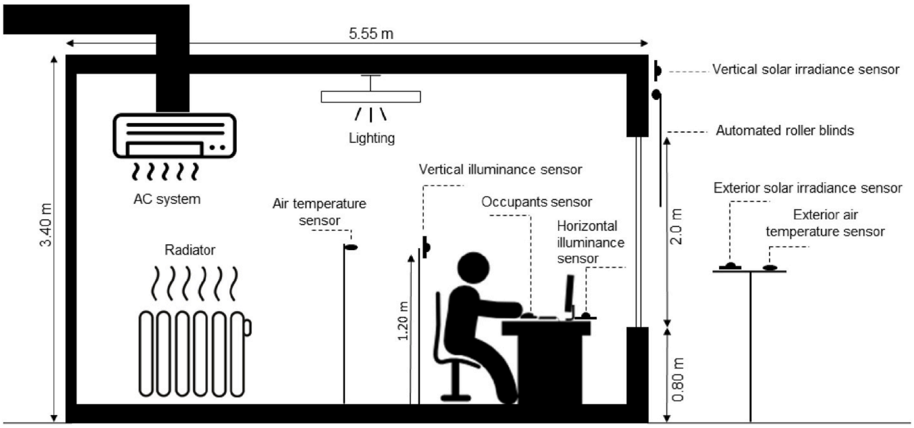


Fig. 9. Schematic position of the sensors in control strategy recommended by ISO 52016-3.

Table 5
Properties of fixed shadings.

Properties	Input value
Blade material	Steel
Blade thickness	0.0300 m
number of blades	7
Vertical spacing	0.250 m
Blade angle	30°
Distance from window	0.250 m
Blade depth	0.2 m
Vertical offset from window top	0 m
Horizontal window overlap	0.10 m
Conductivity	50 W/(m-K)
Specific heat	450 J/(kg-K)
Density	7800 kg/m3
Thermal absorptance(emissivity)	0.3
Solar absorptance	0.3
Visible absorptance	0.3
Roughness	Rough

material properties of installed fixed shades on the case study building façade.

As mentioned in the literature, roller blinds Venetian blinds are relatively common shading devices and capable of being programmed to operate automatically.

Proper shading control strategies are required for adjustable roller blinds and Venetian blinds. The impression of the occupants, specifically the perception of glare and outside views, significantly impacts the success of automated control strategies. Since such systems are widely utilized in practice, automated exterior roller blinds and Venetian blinds are used as dynamic façade elements. Therefore, to perform a simulation with automated control strategies recommended by ISO 52016–3, exterior roller blinds and Venetian blinds were selected. The material properties of exterior roller blinds and Venetian blinds provided in Table 6 were assumed for ISO 52016–3 control strategies.

2.4. Analysis process

Two automated control strategies for two adaptive façade elements (roller blinds and Venetian blinds) were investigated, and their results were compared with other scenarios. The parametric study stage simulation was done for the south-faced office room with three windows with a fixed shading device. The heating, cooling, and electrical lighting loads were analyzed, and the results were provided during the simulation procedures. The operative temperature and indoor air temperature were simulated to investigate the indoor environment. Moreover, Daylight availability was assessed using spatial daylight autonomy 300/50% ($sDA_{300/50\%}$), defined as the proportion of the analysis area that meets the lighting criterion of 300 lux for 50% of the analysis period. Although ISO 52016–3 combined with ISO 52016–1 covers in itself only the heating and cooling loads and internal temperatures, the electrical lighting consumptions are also assessed. The lighting consumption is introduced and explained in EN 15193–1 [114]. Finally, some recommendations were concluded to improve the criteria ISO 52016–3 for the exterior roller shades.

Table 6
Material properties of exterior dynamic shadings; a) Roller blinds; b) Venetian blinds.

a)

Properties	Input value
Thickness	0.8 mm
Openness factor	3%
Conductivity	0.3 W/(m-K)
Total shortwave transmittance	0.0358
Total shortwave reflectance	0.0328
Diffusion transmittance	0.1194
Diffusion reflectance	57%
Longwave transmittance	0.03
Emissivity	0.87
Solar absorptance	0.03
Visible reflectance	0.033
Visible transmittance	0.0355

b)

Properties	Input value
Slat orientation	Horizontal
Slat thickness	0.0025 m
Slat separation	0.05 m
Slat width	0.05 m
Slat angle	Ranges from 0° (fully closed) to 90° (fully open)
Front side slat reflectance	90%
Back side slat reflectance	90%
Slat emissivity	0.9
Slat conductivity	221 W/(m-K)
Distance to glass	0.035 m

3. Results

There are different control strategies for automatically controlling adaptive façade elements, such as daylight autonomy (DA) [58], interior air temperature [73], solar radiation on the window [115], glare occurrence [77,116], and task illuminance [109]. The impact of automated shading varies depending on the perspective of users. Some control scenarios were considered to reduce thermal loads, while others focused on visual comfort. This is mostly due to the possibility of each control scenario and the environmental triggers that activate the shade operation hourly. However, there is no consensus on the standard control strategy for various shading devices based on prior research studies. Therefore, the standard ISO 52016–3 provided a unique control strategy according to the building type and adaptive element of the façade regardless of location. In this study, two technologies, roller blinds, and Venetian blinds, have been modeled and simulated based on the control strategies provided by ISO 52016–3. Furthermore, the results related to the base case (fixed shading) and no shading scenario were compared and reported to analyze the effect of automated scenarios.

Therefore, simulations were conducted in an office room in Brussels for four scenarios. The results of energy consumption and indoor air temperatures with static and dynamic shading devices were compared in the following sections.

3.1. Comparison of annual energy consumption of different scenarios

For the selected office room in Brussels, Fig. 10 shows the annual performance of the solar shading control strategies in terms of energy usage in each scenario. The highest energy consumption was related to the no shading condition (S1), with annual energy consumption of

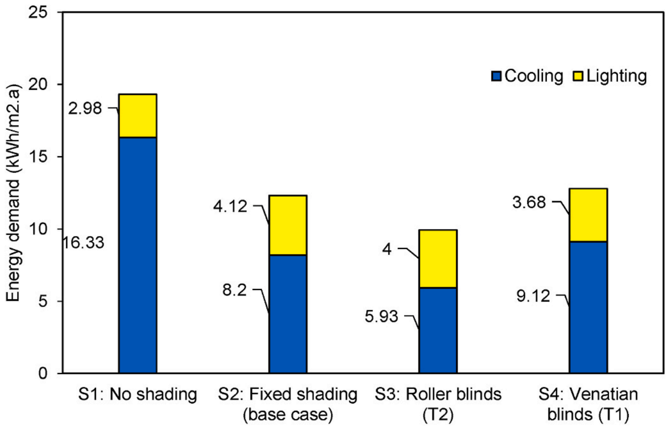


Fig. 10. Comparison of the annual energy demand of different scenarios.

19.31 kW h/m^2. a. followed by Venetian blinds in S4 with a value of 12.8 kW h/m^2. a. When fixed shading was considered, the total energy consumption was 12.32 kW h/m^2. a. The best performance of shading devices was related to the roller blinds, with total energy consumption of 9.93 kW h/m^{2}a. However, the total energy consumption for automatic control scenarios was decreased compared to fixed solar shading in roller blinds. The total energy consumption of fixed shading was 11.75 kW h/m^{2}a. Therefore, the simulation results revealed that the roller blinds in the considered office buildings performed better than Venetian blinds.

It is worth mentioning that since the selected office room was well insulated, and other surfaces except the south wall were considered adiabatic, the heating energy consumption for the case study chosen was negligible (about zero). Therefore, the results of heating demand were not presented in Fig. 10.

As mentioned in the literature, the ISO 52016–3 covers the energy consumption of the building related to heating and cooling. Therefore, comparing the cooling energy consumption when the ISO was applied for controlling the shading devices was needed. As shown in Fig. 10, the annual cooling consumption of the ISO 52016–3 with the technology of roller blinds and Venetian blinds were 5.93 kW h/m^{2}a and 9.12 kW h/m^{2}a, respectively. The cooling load for fixed shading was 8.2 kW h/m^{2}a. The total cooling consumption for S1 was the highest compared to other scenarios, with a value of 16.33 kW h/m^{2}a. In contrast, the cooling consumption of roller blinds was the lowest compared to other scenarios. There is a significant difference (57.4%) between the cooling consumption of roller blinds and Venetian blinds.

When the lighting consumption was concerned, the lowest value was related to the no shading with 2.98 kW h/m^{2}a. It was not a surprise since there was no considered solar shading in this scenario, which led to higher solar radiation entering the interior space. The lighting consumption for fixed shading was 4.12 kW h/m^{2}a, which was higher than the roller blinds and Venetian blinds, with values of 4 kW h/m^{2}a and 3.68 kW h/m^{2}a, respectively.

These results are primarily intended to demonstrate the merits of ISO 52016–3 and its application in building simulation. The results will change if shadings with different solar and visual properties are used.

3.2. Monthly energy demand of the office with Venetian blinds (T1) and roller blinds (T2) with control strategies recommended by ISO 52016-3

For analysis of energy demand of control strategies provided by ISO 52016–3 for Venetian blinds and roller blinds, the monthly energy consumption was calculated and presented in Fig. 11. Based on the results, cooling was consumed from April to October, while this value was negligible for other months. In April, the cooling load related to the scenarios of roller blinds and Venetian blinds was 2.82 kW h and 3.07 kW h. This value increased to the peak amount of 42.1 kW h and 67.1 kW h in July for roller blinds and Venetian blinds, respectively. In general, the cooling demand of the office with Venetian blinds was constantly higher than the cooling demand when roller blinds were considered. In August, the cooling demand of the office with Venetian blinds was 60.04 kW h, while the correspondence value for roller blinds was 36.7 kW h. The highest difference occurred in July and August, when the cooling demand difference reached 25 kW h.

However, the lighting demand was used in all months. The minimum and maximum values for lighting demand for roller blinds were 5.9 kW h and 9 kW h in March and July, respectively. However, the highest and lowest value of lighting demand for Venetian blinds was 7.95 kW h, obtained in January, and 5.6 kW h in March, respectively. The main energy demand for both technologies was related to cooling demand, while the lighting demand was very close. Therefore, the highest energy demand was associated with the summer months, with the highest amount in July, followed by August and June. According to the results, the performance of roller blinds in all months was better than Venetian blinds.

3.3. Scenario-based comparison of internal air temperature

Fig. 12 shows the frequencies and standard normal distribution of internal temperature for all scenarios.

The mean value of internal air temperature was calculated during a year for each scenario. The mean value for no shading, fixed shading, roller blinds, and Venetian blinds was 25.5 °C, 25.3 °C, 25.2 °C, and 25 °C, respectively. In all cases, 70% frequencies of internal air temperature were observed for 25 and 25.5 °C. For higher temperatures, about 28% of the time in S1, the indoor air temperature was more than 26 °C. While in S2, S3, and S4, the frequencies higher than 26 °C were 24.2%, 20.3%, and 13.6%, respectively. Also, the standard deviation for each scenario was obtained. The standard deviation of S1 was higher than all other scenarios with a value of 0.85. on the other hand, the standard deviation of roller blinds and Venetian blinds was the same value (0.46). The same standard deviation shows that roller blinds and Venetian blinds acted in the same way in terms of internal air temperatures.

The standard normal distribution was dissipated between the temperature of (22.5–28 °C), (23.5–27 °C), (24–26.5 °C), and (23.5–27 °C) for scenarios of no shading, fixed shading, roller blinds, and Venetian blind, respectively. The roller blinds performed better in internal air temperature compared to the above scenarios, with a standard deviation of 0.45. the lowest standard error was also achieved in S3 with 0.004. While in the case of S1, the standard error was 0.009, and in S2 and S4

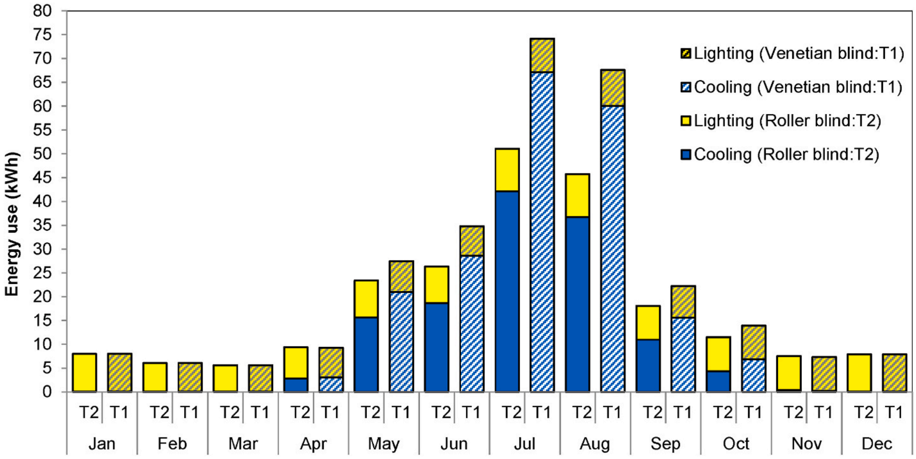
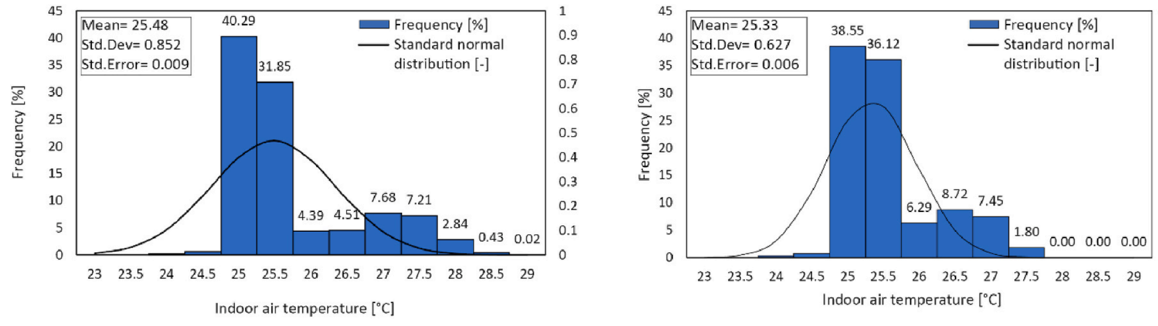
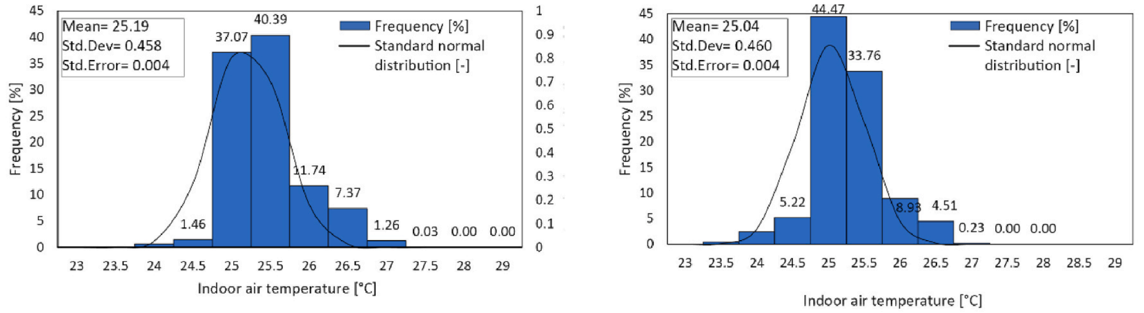


Fig. 11. The monthly breakdown of energy demand of the office room with Venetian blinds and roller blinds according to the control strategies of ISO 52016-3.



a) S1: No shading

b) S2: Fixed shading



c) S3: Roller blinds

d) S4: Venetian blinds

Fig. 12. The frequency and standard normal distribution of internal air temperature during a year for each scenario and control strategy; a) S1: No shading; b) S2: Fixed shading; c) S3: Roller blinds; d) S4: Venetian blinds.

with the same value of 0.006.

3.4. *Scenario-based comparison of operative temperature*

To understand the thermal comfort performance of each scenario, the effect of each control scenario has been compared, and the results are presented in Fig. 13. The box plot visually presents the distributional characteristics of operative temperature when each control scenario was applied. The mean values of operative temperature for control scenarios of no shading, fixed shading, roller blinds, and Venetian blinds were observed at 26 °C, 25.6 °C, 25.3 °C, and 25.4 °C, respectively. In addition, the least and the maximum values of operative temperature were recorded at 26.2 °C in roller blinds and 27.9 °C in S1. Similarly, the least minimum values were related to the control scenario of no shading with

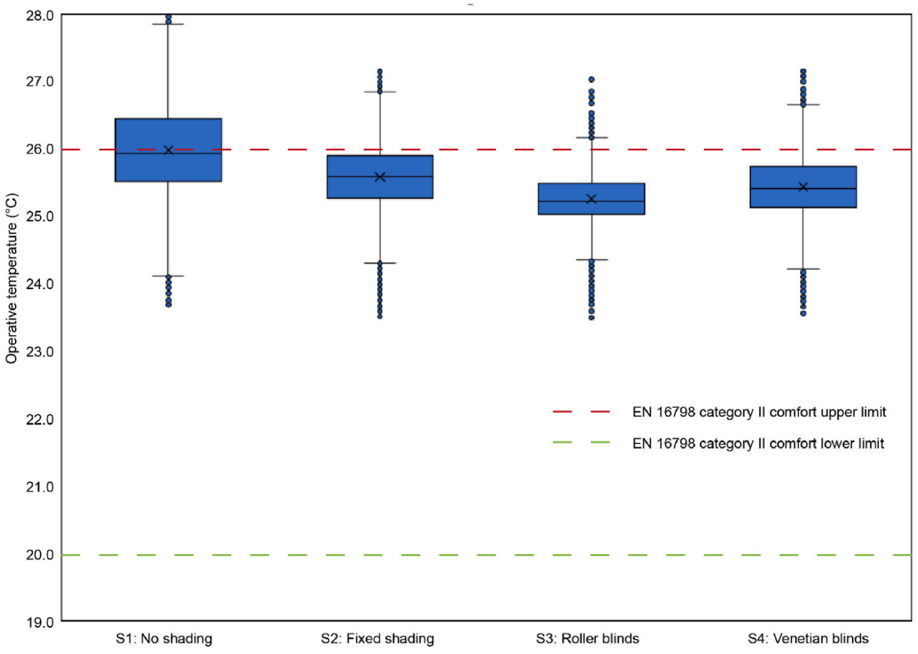


Fig. 13. Distribution of internal operative temperature for each scenario according to EN16798 category II.

the value of 24.1 °C. In comparison, the highest minimum value was 24.3 °C equally happened in roller blinds and fixed shading scenarios.

The operative temperatures for each case were mainly accumulated between the first and third quartiles of the Box and Whisker plot, as shown in Fig. 13. These operative temperatures for no shading, fixed shading, roller blinds, and Venetian blinds were within the range of 25.5–26.5 °C, 25.3–25.9 °C, 25–25.5 °C, 25.1–25.7 °C, respectively. Furthermore, the maximum and minimum values of operative temperature for no shading, fixed shading, roller blinds, and Venetian blinds were 24.1–27.9 °C, 24.3–26.9 °C, 24.3–26.2 °C, and 24.2–26.7 °C, respectively.

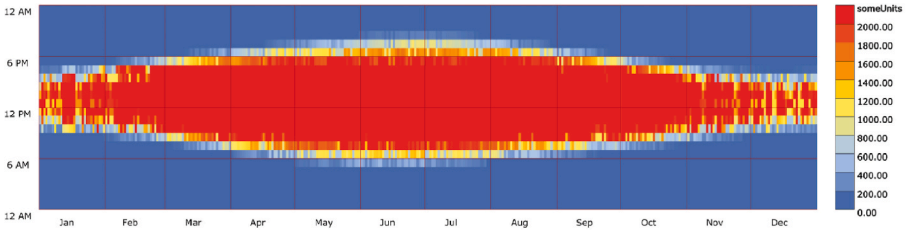
Based on the EN16798 [117] static comfort model related to the office room, the maximum and minimum indoor operating temperature fixed thresholds of 26 °C, and 20 °C of Category II (single office with mechanical cooling systems) are depicted in Fig. 13. Considering the operation of the automated shading device prevents solar radiation from entering space when a high solar incident happens on the facade. Therefore, indoor operative temperatures were much more within the comfortable range when the shading devices were closed in S3 and S4. Following this, not closing the shading devices for the S1 and S2 showed that their operative temperature ranges (25.5–26.5 °C and 25.3–25.9 °C) were less than the comfortable operative temperature (23–26 °C).

As results show, the best performance of indoor operative temperature was related to the roller blinds as the maximum is 26.2 °C which happened for limited hours. The correspondence value was followed by Venetian blinds and fixed shading with 26.7 °C and 26.9 °C, respectively. The worst scenario was S1 (no shading), exceeding the EN 16798 category II upper limit most of the time. In the shading scenario, even the mean value of indoor operative temperature was 25.9 °C, meaning that more than half of the values exceeded the upper comfort limit.

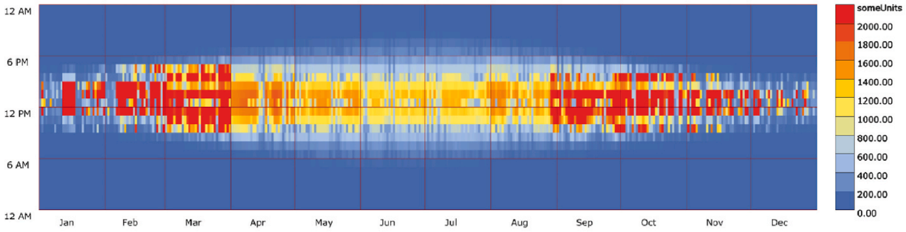
3.5. Scenario-based comparison of illuminance

As highlighted in Fig. 14, the value of task illuminance was compared during a year for each scenario. The values are hourly and show each scenario's performance in providing indoor task illuminances.

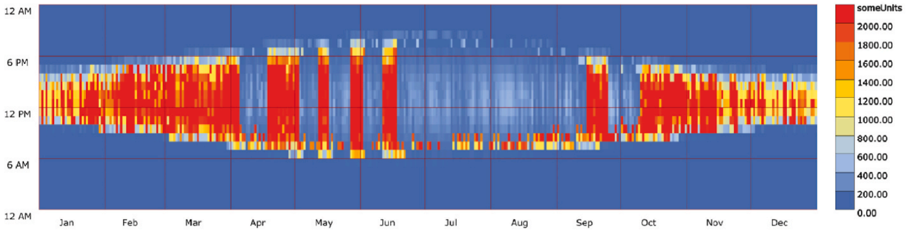
The highest amount of task illuminance was captured in scenario no shading. In this scenario, most of the time in a year, the task illuminance was more than 2000 lux. However, when shading devices were considered in other scenarios, the amount of task illuminance was decreased. In S2, from April to August, the task illuminance was between 1000 and 1200 lux, while these values increased to more than 1600 lux for the rest of the year. In S3 and S4, the task illuminance was obtained with similar values. It can be explained as the similar control strategy recommended by ISO 52016–3 for Venetian blinds and roller blinds with



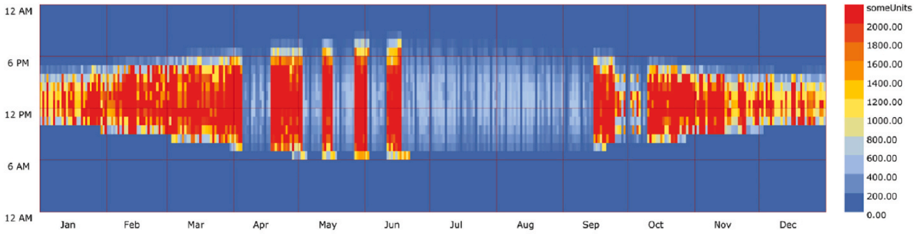
a) S1: No shading



b) S2: Fixed shading



c) S3: Roller blinds



d) S4: Venetian blinds

Fig. 14. The task illuminance value for each scenario on an hourly basis during a year.

a slight difference. The difference happened in the exact values from July to September when the shading blocked the solar incident. In these months, when roller blinds were activated, the obtained task illuminance was between 200 and 600 lux, while Venetian blinds were 400–800 lux. It could be due to the solar entrance from the spaces between slats when the slats were positioned with an angle lower than 80°. However, in the case of roller blinds, when the solar shading was activated, it blocked daylight entrances completely, leading to a lower value of illuminance in this period.

3.6. Scenario-based comparison of comfort performance

Table 7 compares the data on the comfort performance of each scenario. Cooling and lighting load, exceeded hours of indoor operative temperature, exceeded hours of air temperature, spatial daylight autonomy, and insufficient task illuminance hours are shown in Table 7.

The lowest cooling demand was obtained with the ISO 52016–3 control strategy with roller blinds with 5.93 kW h/m^2. a. It was followed by fixed shading and Venetian blinds with 8.2 kW h/m^2. a, and 9.12 kW h/m^2. a, respectively. However, the highest cooling demand happened in the no-shading scenario, with a value of 16.33 kW h/m^2. a. In contrast, when the lighting demand was concerned, no shading scenario acted better than other scenarios with the value of 2.98 kW h/m^2. a. Scenarios of roller blinds, Venetian blinds, and fixed shading with a demand of 4 kW h/m^2. a, 3.68 kW h/m^2. a, and 4.12 kW h/m^2. a ranked after no shading scenario.

Based on ISO 52016–3 the task illuminance limit values were considered 300 lux [46]. It represented the number of hours that the task illuminance of the interior space was lower than 300 lux was presented in Table 7. The highest insufficient illuminance hours happened in S3, with 6693 h. In the case of fixed shading and Venetian blinds, the insufficient hours of task illuminance were similar (6450 and 6458). Moreover, the highest $sDA_{300/50\%}$ happened in S1 when no shading device was considered for the office room. The value of $sDA_{300/50\%}$ for the no shading scenario was 75.6% and for fixed shading, Venetian blinds, and roller blinds, the value of 24.5%, 19%, and 26.3%, respectively. According to the Illuminating Engineering Society (IES) recommendation, the minimum acceptable $sDA_{300/50\%}$ for an office room with an occupancy time from 8 a.m. to 6 p.m. was 55% [118]. Comparing the $sDA_{300/50\%}$ revealed that none of the scenarios meets the requirement of $sDA_{300/50\%}$ except no shading. However, the office with roller blinds performed better than Venetian blinds in terms of receiving more daylight.

The best performance in terms of operative temperatures was related to roller blinds which had 6846 h exceeded hours of operative temperature and maintained in the acceptable range according to EN 16798.

4. Discussion

4.1. Summary of the main findings and recommendations

The energy performance of an office building in Brussels with different façade technologies was tested. Roller blinds and Venetian blinds with control strategies recommended by ISO 52016–3 were simulated. It reduced the cooling demand of the office room by 32.13% compared to the fixed shading scenario, which was considered as a base case. However, in the case of Venetian blinds, the cooling demand increased by 10.62% compared with fixed shading. Moreover, the lighting demand of offices with roller blinds and Venetian blinds decreased by 2.91% and 10.68%, respectively compared to the condition that fixed shading was considered. The total energy use of the studied office room with roller blinds, Venetian blinds, and fixed shading was 9.93 kW h/m^2. a, 12.80 kW h/m^2. a, and 12.33 kW h/m^2. a, respectively. Therefore, the fixed shading outperformed Venetian blinds in terms of total energy use. Our findings do not support previous research in this area. However, it should be noted that the differences in results depend on the fixed shading design. Fixed shading could be a single “brise-soleil” or like in this study, fixed louvers. For example, a study by De Luca et al. [5] studied the effect of static and dynamic shadings on office buildings’ energy consumption. Their results showed that dynamic blinds had a more uniform performance and outperformed fixed shadings. In the experimental analysis of an office building conducted by Carletti et al. [31], the authors concluded that the automated Venetian blinds guarantee increased indoor thermal and lighting performance more than other shading devices. However, the results of this study confirmed that the roller blinds med better than Venetian blinds.

In fact, contrary to what was previously thought, we found that in some cases, the fixed shading would perform better than automated Venetian blinds. The difference between the results of this study and others [5,50,66,119] could be defined as every building having unique characteristics and different buildings in terms of climate, façade orientation, thermal properties, and window-to-wall ratio could benefit from different control strategies. As mentioned above, differences could be also raised from fixed shading design and type of fixed shading. It could be concluded that standardized control strategies are required for compliance-based calculations of energy use in different buildings worldwide. Also, it should be noted that, since the selected case study was a nearly zero energy building with relatively low energy demand, the energy performance of the selected office was improved by 19.47% in the case of roller blinds compared to the base case (fixed shading). Therefore, there is a higher potential for improvement of the energy performance of existing office buildings with low energy efficiency.

All scenarios’ mean internal air temperature values were close, with slight differences. The lowest mean value was related to roller blinds at 25.19 °C, while the highest value for that was recorded in no shading condition (25.48 °C). The only surfaces exposed to the exterior environment were the south walls, and others were considered adiabatic surfaces. Therefore, the small changes between the mean value of internal air temperature could be high performance and well-isolated selected office room. Another possible reason could be the case study climate zone. The selected office’s climate zone was temperate, with an average annual temperature of 10.7 °C. Also, the solar radiation ranged between 0 and 892 W h/m^2 with an annual mean average of 143.5 W h/m^2 (Fig. 4). Therefore, the mean indoor air temperature hardly reached higher values, and shading devices’ effect on internal mean air temperature was negligible. As results indicated, the standard deviation of roller blinds in S3 was the lowest among scenarios, which indicates that the values tend to be close to the mean of the set. In contrast, a high standard deviation indicates that the values spread over a wider range which happened in no shading condition (S1).

According to EN 16798–1:2019, the comfortable operative temperature range for office building category II is 20–26 °C [120]. Based on Fig. 13, this range for the roller blinds was 25–25.5 °C, the nearest range to the comfortable operative temperature. It can be said that the ISO

Table 7
Energy and comfort performance of each scenario.

Scenario	Cooling (kWh/m^2.a)	Lighting (kWh/m^2.a)	Exceeded T_o (hours)	$sDA_{300/50\%}$ (%)	Insufficient illuminance (hours)
No shading	16.33	2.98	8154	75.6	4935
Base case	8.2	4.12	7595	24.5	6450
ISO T1	9.12	3.68	7341	19	6458
ISO T2	5.93	4	6846	26.3	6693

control scenario considered multi-indicators, including operative temperature, external solar radiation, and glare occurrence (in the case of non-residential buildings). However, in scenarios of fixed shading and no shading, direct solar radiation can enter the office room. That is why the indoor operative temperature range for the latter scenarios (S3 and S4) was closer to the comfortable operative temperature than the former scenarios (S1 and S2). Meanwhile, the fixed shading scenario with the operative temperature of 25.3–25.9 °C provided an indoor operative temperature range similar to a Venetian blind. The worst scenario was observed for no shading with the operative temperature range of 25.5–26.5 °C because of the lack of shading devices, demonstrating the capability of automated control scenarios to achieve a comfortable operative temperature.

The operation of automated control strategies recommended by ISO was also assessed by analyzing the scatter of the data. According to the results, the difference between the maximum and minimum values of operative temperature for the roller blinds scenario (24.3–26.2 °C) was the lowest among all scenarios, with a value of 1.9 °C and followed by the Venetian blinds scenario (24.2–26.7 °C) with 2.5 °C. It demonstrated that the dynamic shading scenarios adequately prevented scattering operative temperature. The difference mentioned above for fixed shading and no shading increased by 2.6 °C and 3.8 °C, respectively.

Note that these results are primarily intended to demonstrate the merits of ISO 52016–3 and its application in building simulation. The results will change if shadings with different solar and visual properties are used.

For the chosen examples the following recommendations can be extracted from the calculations.

- It is recommended to select the shading device technology between roller blinds and Venetian blinds to implement exterior roller blinds to reduce the energy demand of office buildings in oceanic temperate climates.
- To provide a thermally comfortable indoor environment, it is recommended to control the shading automatically to avoid dissipating operative temperature inside the office room.
- The energy demand of the office room with automated Venetian blinds and fixed shading was very similar; therefore, it is highly recommended to designers and engineers for further investigation and simulation in an early design stage to select the most efficient shading devices.

4.2. Strengths and limitations of this research

There are some strengths in this study that can be mentioned. The first strength of this paper was that the authors used the real case study office room in a calibrated, high-performance office building. The second strength was the Implementation of ISO 52016–3, which is novel and still under development. The third strength of this study could be preparing the flowchart of automatic control strategies recommended by ISO 52016-3 according to the building type and shading façade technology by authors. These flowcharts could be more understandable and paved the way for other researchers to model and simulate recommended control strategies by ISO 52016–3. ISO 52016–3 is complementary to ISO 52016–1, by including the adaptive element of the façade in the energy calculation of the buildings. No studies have been published on this new ISO 52016–3 control strategies. The authors used state-of-the-art software packages to conduct this study and implement the automated control strategies of ISO 52016–3. Based on the literature, few studies analyzed and compared the impacts of roller blinds and Venetian blinds on building energy performance. Therefore, the fourth strength of this study was a comprehensive comparative study on the effect of control strategies recommended by ISO 52016–3 for two dynamic shading elements (roller blinds and Venetian blinds) on heating, cooling, internal air temperature, and operative temperature. It is worth mentioning that the model was revised and checked with standard experts for validation and implementation of control strategies in this study (ISO 52016–3 committee members). Note that these results were primarily intended to demonstrate the merits of ISO 52016–3 and its application in building simulation. If shading devices with different solar and visual properties are used, the results would change.

We are aware that our research may have some limitations. The first is related to implementing automated control strategies for controlling shading devices. It was hard to model adaptive façade elements based on this study's multi-criteria and automatic control strategies. It required much coding and scripting to implement the control strategies recommended by ISO 52016–3, and different software needed to be connected. The second was connected to occupants' involvement with the control strategies. There was no real occupant interaction with automated control strategies, and the investigated control strategies were mainly based on the sensors. The third limitation that could be mentioned was that there were few studies about the new ISO 52016–3 in the literature, and there is a shortage of factual data, like the setpoints for controlling and activating the automated shading devices. The fourth limitation of the study could be related to the thermal transfer of the walls and roof of the considered office room. As mentioned in the methodology the interior walls and roof were considered adiabatic which was different from the reality of the office condition. The single room chosen for this study could be regarded as the fifth limitation. Simulations were run for a single room, but the building as a whole also had to be considered in order to determine how much of an impact the control strategy would have on the building's overall energy efficiency. These limitations underline the difficulty of collecting data on automated control strategies.

4.3. Implication on practice and future works

The present findings have considerable managerial implications. Based on the findings, user-friendly software is needed to implement the control strategies in a real environment. Our findings would not be practical, and the designer will not use such standards that are difficult to simulate. Results also agree with the findings of Loonen [110] in the review paper about adaptive façades. He mentioned that we need more accessible and smooth control strategies to allow the integration of the standard and different technology into the mainstream simulation software. According to the results of this study, automated shading devices are not always the only answer to reducing the energy demand of office buildings.

In some cases, such as the case study used in this study, we can greatly impact building energy demand with a fixed shading. It would be a more cost-efficient solution for building owners and occupants. On (EN) ISO 52016–1 a spreadsheet has been made available, to demonstrate and validate the calculation procedures [121]. A new version is in preparation in which the control algorithms of (EN) ISO 52016–3 are integrated [122]. We are looking forward to using and comparing this tool.

This research has given rise to many questions in need of further investigation. First, further study is recommended to perform the in-depth sensitivity analysis of control strategies suggested by ISO 52016–3 to find the most influential parameters to control shading devices. Second, conducting the study with real experimental testing facilities is highly recommended to testify and compare the results with numerical analysis. Third, as mentioned in the literature, ISO 52016–3 covered three types of façade technologies dynamic shadings, chromogenic glazing, and ventilative facades. Therefore, it is highly recommended as a future study to expand and implement control strategies recommended by ISO 52016–3 for other types of façade technologies. Fourth, in this paper, the control strategies of ISO 52016–3 were applied to one climate zone (oceanic temperate climate) as the case study building was in Brussels. Hence, future research is encouraged to evaluate the effectiveness of automatic control strategies provided by ISO 52016–3 in different climate zones. Fifth, As mentioned in previous sections, in this study authors only focused on a specific case study with two chosen technologies in a specific climate to testify to the control strategies recommended by ISO 52016–3. Therefore, there is a need for conducting a full parametric study to test all standard variations and their consistencies. Moreover, however, the main focus of this study was the implementation of ISO 52016–3; for comparative purposes, it would be possible for future investigation to compare how the rule-based control strategies of ISO 52016–3 would be performed concerning the model-based predictive controls. One approach could be to use rule-based strategies to design the system's overall control architecture, with model-based and reinforcement learning methods employed to optimize the system's behaviour in response to changing conditions. This could potentially lead to improved performance and energy savings compared to rule-based control alone. Additionally, further research could be conducted to evaluate the robustness and adaptability of these hybrid control strategies in various real-world scenarios. Overall, exploring the combination of different control techniques could lead to novel and effective solutions for dynamic shading in building automation systems. Last but not least in addition to mentioned future works above, another possibility for a future study would be comparing and assessing the energy and comfort performance deviations of the control strategies suggested by ISO 52016–3 to those of default and simplified (built-in control strategies) in energy simulation software such as EnergyPlus.

5. Conclusions

As indicated in the literature, there is no standardized method for evaluating control systems for adaptable façade elements, particularly dynamic shadings. As a result, ISO 52016–3 offered a series of default control strategies to compare buildings' energy demands. Therefore, this paper aims to increase current knowledge about the new ISO 52016-limitations and opportunities and to enhance the energy performance of office buildings incorporating adaptive envelope elements.

This research consists of successive stages, from data collection to parametric study and dynamic simulations. The performance of fully automated control strategies of exterior roller blinds and Venetian blinds was evaluated afterward. A south-facing office room was chosen from an existing high-performance office building in Brussels to perform energy simulations. The results of two scenarios, roller blinds and Venetian blinds controlled automatically by strategies proposed by ISO 52016–3 were assessed for different orientations. Two more scenarios, including no shading and fixed shading, were also considered to understand better the effects of control strategies and shading devices on building energy needs. The results of building energy demand, including heating and cooling loads, internal temperatures (indoor air temperature and indoor operative temperature) covered by ISO 52016–3, and artificial lighting demand covered by EN 15193–1 with exterior roller blinds and Venetian blinds, were reported. In order to conduct the simulation, different software was used. The model was created in Grasshopper, and the simulation procedure was carried out using a built-in Grasshopper plugin called Ladybug-tools. The control strategies were acted separately for each window employing the EMS feature in EnergyPlus.

The findings of this study indicate that, for the chosen example cases and shadings, the ISO52016-3 control plan with roller blinds resulted in the lowest cooling demand of 5.93 kW h/m^2. a. Fixed shading and Venetian blinds came in second and third, with 8.2 kW h/m^2. a and 9.12 kW h/m^2. a, respectively.

Roller blinds were the most effective in lowering the energy demand of the chosen office room. It reduced the office room's cooling usage by 32.13% to the fixed shading scenario, deemed the base case. However, in the case of Venetian blinds, cooling demand increased by 10.62% compared to fixed shading. In providing a thermally comfortable indoor environment, the roller blinds perform better than in other scenarios.

CRediT authorship contribution statement

Alireza Norouziasas: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amir Tabadkani:** Software, Investigation, Formal analysis. **Ramin Rahif:** Writing – review & editing, Visualization, Investigation. **Mohamed Amer:** Writing – review & editing, Validation, Software. **Dick van Dijk:** Writing – review & editing, Validation, Resources. **Hervé Lamy:** Writing – review & editing, Data curation. **Shady Attia:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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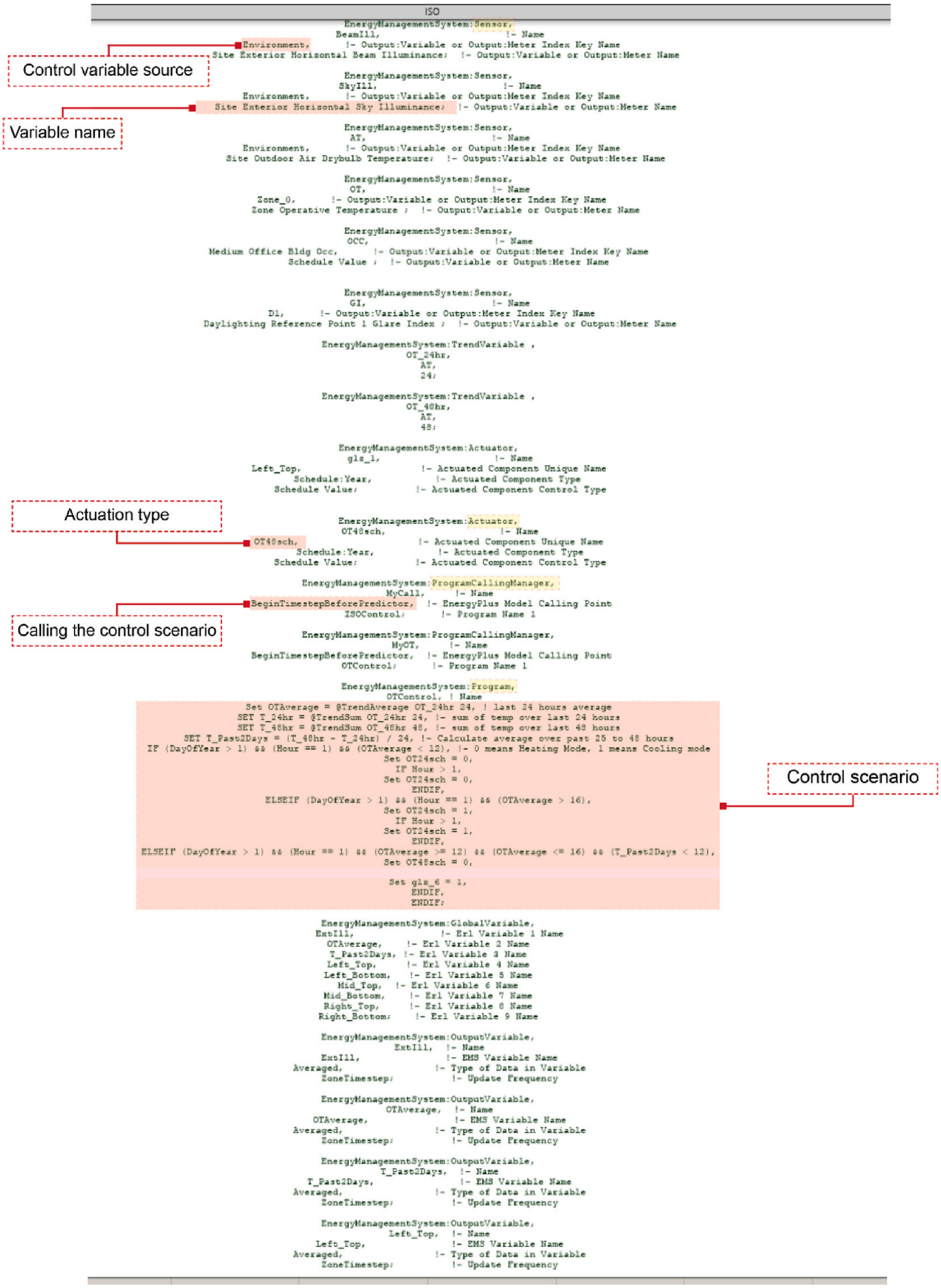
Appendix

The following Figure shows the sections of the control strategy of ISO 52016–3 as an example of EMS scripting.



```
                 EnergyManagementSystem:Sensor,
                BeamIll,                           !- Name
   Environment,       !- Output:Variable or Output:Meter Index Key Name
 Site Exterior Horizontal Beam Illuminance;  !- Output:Variable or Output:Meter Name

                 EnergyManagementSystem:Sensor,
                SkyIll,                           !- Name
   Environment,       !- Output:Variable or Output:Meter Index Key Name
 Site Exterior Horizontal Sky Illuminance; !- Output:Variable or Output:Meter Name

                 EnergyManagementSystem:Sensor,
                  AT,                           !- Name
   Environment,       !- Output:Variable or Output:Meter Index Key Name
  Site Outdoor Air Drybulb Temperature;  !- Output:Variable or Output:Meter Name

                 EnergyManagementSystem:Sensor,
                  OT,                           !- Name
     Zone_0,       !- Output:Variable or Output:Meter Index Key Name
    Zone Operative Temperature ;  !- Output:Variable or Output:Meter Name

                 EnergyManagementSystem:Sensor,
                  OCC,                           !- Name
 Medium Office Bldg Occ,       !- Output:Variable or Output:Meter Index Key Name
            Schedule Value ;  !- Output:Variable or Output:Meter Name


                 EnergyManagementSystem:Sensor,
                  GI,                           !- Name
       D1,       !- Output:Variable or Output:Meter Index Key Name
 Daylighting Reference Point 1 Glare Index ;  !- Output:Variable or Output:Meter Name

              EnergyManagementSystem:TrendVariable ,
                          OT_24hr,
                            AT,
                            24;

              EnergyManagementSystem:TrendVariable ,
                          OT_48hr,
                            AT,
                            48;

                EnergyManagementSystem:Actuator,
                  gls_1,                          !- Name
      Left_Top,                  !- Actuated Component Unique Name
          Schedule:Year,            !- Actuated Component Type
        Schedule Value;          !- Actuated Component Control Type


                EnergyManagementSystem:Actuator,
                 OT48sch,                          !- Name
   OT48sch,                    !- Actuated Component Unique Name
          Schedule:Year,            !- Actuated Component Type
        Schedule Value;          !- Actuated Component Control Type

            EnergyManagementSystem:ProgramCallingManager,
                      MyCall,        !- Name
   BeginTimestepBeforePredictor,  !- EnergyPlus Model Calling Point
                 ISOControl;       !- Program Name 1

            EnergyManagementSystem:ProgramCallingManager,
                       MyOT,        !- Name
   BeginTimestepBeforePredictor,  !- EnergyPlus Model Calling Point
                 OTControl;       !- Program Name 1

                EnergyManagementSystem:Program,
                      OTControl, ! Name
            Set OTAverage = @TrendAverage OT_24hr 24, ! last 24 hours average
           SET T_24hr = @TrendSum OT_24hr 24, !- sum of temp over last 24 hours
           SET T_48hr = @TrendSum OT_48hr 48, !- sum of temp over last 48 hours
       SET T_Past2Days = (T_48hr - T_24hr) / 24, !- Calculate average over past 25 to 48 hours
  IF (DayOfYear > 1) && (Hour == 1) && (OTAverage < 12), !- 0 means Heating Mode, 1 means Cooling mode
                          Set OT24sch = 0,
                            IF Hour > 1,
                          Set OT24sch = 0,
                              ENDIF,
            ELSEIF (DayOfYear > 1) && (Hour == 1) && (OTAverage > 16),
                          Set OT24sch = 1,
                            IF Hour > 1,
                          Set OT24sch = 1,
                              ENDIF,
ELSEIF (DayOfYear > 1) && (Hour == 1) && (OTAverage >= 12) && (OTAverage <= 16) && (T_Past2Days < 12),
                          Set OT48sch = 0,

                           Set gls_6 = 1,
                              ENDIF,
                              ENDIF;

              EnergyManagementSystem:GlobalVariable,
             ExtIll,                   !- Erl Variable 1 Name
               OTAverage,     !- Erl Variable 2 Name
                T_Past2Days, !- Erl Variable 3 Name
               Left_Top,      !- Erl Variable 4 Name
              Left_Bottom,    !- Erl Variable 5 Name
                 Mid_Top,  !- Erl Variable 6 Name
              Mid_Bottom,     !- Erl Variable 7 Name
              Right_Top,      !- Erl Variable 8 Name
             Right_Bottom;     !- Erl Variable 9 Name

              EnergyManagementSystem:OutputVariable,
                          ExtIll,  !- Name
              ExtIll,                  !- EMS Variable Name
          Averaged,                !- Type of Data in Variable
              ZoneTimestep;             !- Update Frequency

              EnergyManagementSystem:OutputVariable,
                        OTAverage,  !- Name
            OTAverage,                 !- EMS Variable Name
          Averaged,                !- Type of Data in Variable
              ZoneTimestep;             !- Update Frequency

              EnergyManagementSystem:OutputVariable,
                       T_Past2Days,  !- Name
           T_Past2Days,                !- EMS Variable Name
          Averaged,                !- Type of Data in Variable
              ZoneTimestep;             !- Update Frequency

              EnergyManagementSystem:OutputVariable,
                         Left_Top,  !- Name
             Left_Top,                 !- EMS Variable Name
          Averaged,                !- Type of Data in Variable
              ZoneTimestep;             !- Update Frequency
```

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