Comparison of control parameters for roller blinds

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Comparison of control parameters for roller blinds

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ABSTRACT

Roller blinds can reduce the heating and cooling building energy consumption required to maintain thermal comfort. The effectiveness of roller blinds is influenced by the strategies and input parameters for their control. This study is the first to identify the most effective of seven alternative control parameters to control roller blinds. It further defines the benefits from using paired control parameters to maximise energy savings and optimise occupants' comfort. For the particular case studies and conditions examined, it is concluded that operating roller blinds using indoor air temperature as a single control parameter with rule-based controller provided, 16 %, 19 % and 45 % in heating, cooling and lighting energy savings in Dublin, Berlin and Madrid respectively compared to a window without roller blinds, with an average 51 % daylight discomfort reduction. Using both internal temperature and outdoor ambient temperature to control the roller blinds had little effect on energy need, with only a further 0.6 %, 0.5 % and 0.3 % energy savings and an average of 2 % reduction in daylight discomfort achieved compared to using solely indoor temperature as the control parameter.

1. Introduction

Buildings represent 40 % of global primary energy consumption. Operation of buildings produced 10 $GtCO_2$ in 2020, which accounted for 28 % of global energy-related CO_2 emissions (Alkhatib et al., 2020). As the interfaces between outdoor weather conditions and indoor occupant comfort, facades with adaptive thermophysical properties can contribute to providing optimal indoor conditions (Eltaweel and Su, 2017) with minimal building energy use.

As well as maintaining visual contact with the outdoor environment, windows admit daylight, the best light source of light for colour rendering, that obviates the need for artificial lighting. Windows can also provide thermal insulation and solar heat gains (Li, 2010; Knoop et al., 2020). In sunny/hot climates, excessive solar gains can be minimised using fixed and movable shading and coatings on the window glass. In cloudy/cold climates, highly-insulated windows can retain accumulated solar heat. In temperate seasonally-varying climates with cold winters and warm summers, less energy-use ensues when solar heat gain is modulated by adaptive facade technologies. In such climates in highly thermally-insulated and airtight buildings, control over solar heat gained through windows is necessary to minimize overall combined annual heating and cooling loads (Ghosh and Norton, 2018; Raushan et al., 2022).

Adaptive building façades combine features, materials and technologies whose properties alter according to the changing weather to modulate, convert, and store energy and mass flows (Attia et al., 2020). There are multiple adaptive shading technologies that work to maximize occupancy comfort and minimize the energy consumption of the building such as movable shading devices and switchable windows (Alkhatib et al., 2020). Movable shading devices are an established means of providing adaptive window properties. Blinds are the most used types of shading devices in buildings (Kirimtat et al., 2016; van den Wymelenberg, 2012; Andrews, 2017; Alkhatib et al., 2023). Blinds can control a window's solar transmission to provide thermal and visual comfort. Manually operated blinds are inefficient in terms of providing daylight comfort and minimal energy consumption (Konstantoglou and Tsangrassoulis, 2016) mainly because of occupant operating of blinds (Koo et al., 2010; Kim et al., 2007).

This paper consists of six sections; Section 2 discusses previous work on the control parameters and strategies for blinds, Section 3 presents the methodology of this study, Section 4 provides the boundary

Abbreviations: CO_2, Carbon dioxide; *HVAC*, Heating Ventilation and Air Conditioning; Met, Metabolic equivalent task; DG, Double-glazed.

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Nomenclature

Symbol	Definition
DR	Direct solar irradiance W/m^2
ID	Indoor Daylight illuminance lx
IT	Indoor temperature °C
OP	Operative temperature °C
OT	Outdoor temperature °C
ST	Sky temperature °C
TR	Total solar radiation W/m^2
SHGC	Solar heat gain coefficient
VT	Visual transmittance

(Reinhart, 2004), (ii) outdoor or indoor air temperature (Georg et al., 1998; van Moeseke et al., 2007), (iii) indoor daylight illuminance level (Motamed et al., 2020) and (iv) heating and cooling energy load of the building (Palmero-Marrero and Oliveira, 2010; Nielsen et al., 2011).

Numerous studies have investigated the influence of blinds on building energy need and the occupant comfort. In an office building in Abu Dhabi, Hammad et al. (Hammad and Abu-Hijleh, 2010) used dynamic blinds and a light reduction control strategy in a south facing 8 m × 4 m × 4 m office zone. By setting the internal temperature to be maintained at 24 °C, it achieved 34.02 % energy savings compared to a window without blinds. Tzempelikos et al. (Tzempelikos and Shen, 2013) compared four different control strategies of roller blinds using constant and variable switching thresholds, the blind was controlled by total solar irradiation on the façade, cooling mode (solar gains control) and internal luminous intensity. For the 4 m × 4 m × 3 m office façade, it

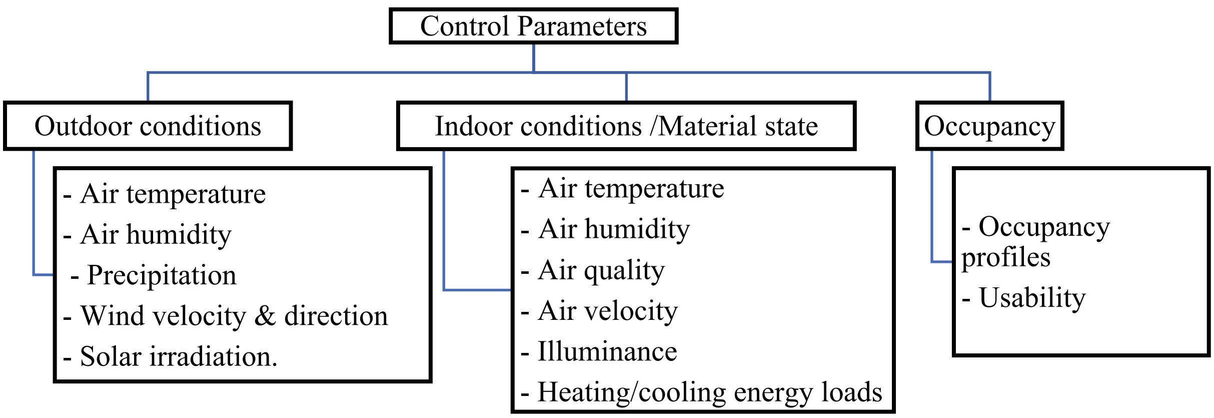

Fig. 1. Types of control parameters (adapted from (Alkhatib et al., 2020)).

conditions and methodology used in this study, Section 5 presents the results of this study and Section 6 concludes with findings and suggests future research.

was found that each facade orientation required specific control strategies. Zhong et al. (Zhong et al., (2020)) compared controlling roller blinds using seven strategies including conventional rule-based control and genetic-algorithm-based predictive control and found that for a 150 m high-rise residential building with a 670 m^2 footprint in Hong Kong, using a predictive strategy reduced cooling energy consumption by 55 %. Tzempelikos et al. (Tzempelikos and Athienitis, 2007) used solar irradiation as a control parameter with a switching threshold of 120 W/m^2 to control roller blinds. For a 4 m × 4 m × 3 m private office zone in Montreal, the control strategy achieved a 50 % cooling load reduction compared to a window without blinds. Shen et al. (Shen and Tzempelikos, 2012) compared model predictive control with manual control for a 4 m × 4 m × 3 m zone in Chicago and Los Angeles, and found that controlling blinds using model predictive control achieved a 35 % reduction in energy loads. Dabbagh et al. (Dabbagh and Krarti, 2021) evaluated the performance of switchable insulated shades deployed as blinds combined with switchable windows using On/Off controller, the study used a 12 m × 12 m × 3 m residential building model and achieved 59.1 % to 64.9 % saving in annual heating and cooling energy consumption in Golden, Colorado. Do et al. (Do and Chan, 2020) evaluated the performance of multi-section façade for a 3 m × 7 m × 3.3 m test space in Taipei and New York City. The study used two different control strategies based on daylight glare probability using different combinations of roller, fixed and venetian blinds. The study found that combining roller and venetian blinds can increase daylight near the wall.

2. Relevant previous work

Previous studies have examined roller blinds and venetian blinds (Jain and Garg, 2018). Roller blinds are controlled to achieve specific pre-defined goals (Bavaresco and Ghisi, 2020) including (i) heating, cooling and lighting energy savings (Shen et al., 2014), (ii) glare discomfort reduction (Wienold, 2007) (iii) accessing outdoor environment views (Yamín Garretón et al., 2021) and (iv) privacy. Roller blinds are driven by inputs selected from the possible control parameter(s) (Gago et al., 2015) shown in Fig. 1.

Controlling roller blinds can be done using (i) single control parameter, where only one sensor is used to activate a desired output, or (ii) multi-parameter control, where two or more physical sensors are used. A switching threshold is the trigger value at which the controller sends a signal to active the desired response. For example, if the outdoor temperature (OT) was chosen to be the control parameter that controls the roller blind and 21 °C OT is set as the switching threshold, then as soon as the OT reaches or exceeds 21 °C the controller will send a signal for the roller blind to move to the desired position.

Determining the best control parameter and its threshold to control a shading technology has impacts on energy performance and occupant visual comfort (Alkhatib et al., 2020; Hoon Lee et al., 2020; da Silva et al., 2012; de Luca et al., 2021) as well as costs associated with hardware, software and complexity of integration. Using rule-based control or on/off control is the most used control strategy for active shading devices (Isaia et al., 2021). Various studies have used different control parameters to control roller blinds: (i) solar irradiation

There is no general agreement from previous studies on the best control parameters and control strategy for roller blinds due to; (i) focus on a limited range of control parameters, (ii) lack consistency in controller types used with various control parameters, (iii) use of diverse building morphologies and characteristics, (iv) lack comparative

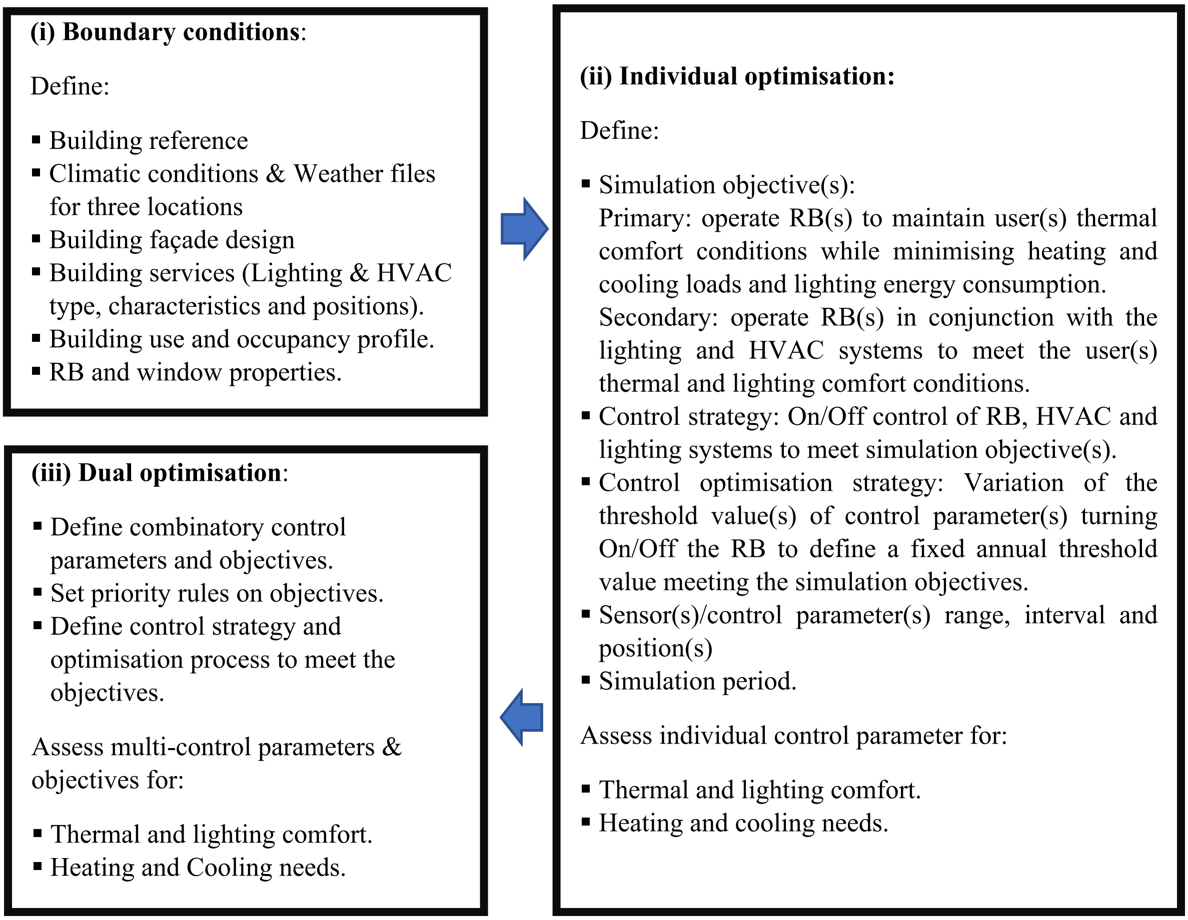

Fig. 2. Overview of methodology used.

information and (v) no sharing of information between shading system control and artificial lighting control (Shen et al., 2014). A holistic approach is required to define the most cost-, energy-, and comfort-efficient solution to specific scenarios.

Previous studies typically investigated individual control parameters that can be captured with a single type of sensors. These typically fail to address combining multiple control parameters to operate roller blinds. Following the literature research, this research appears to be the first to investigate the simultaneous use of multiple control parameters, translating in the use of two or more sensor types, to control roller blinds to maximise energy savings and optimise comfort to occupants. In this study, seven control parameters were investigated: total solar irradiation (TR), direct solar radiation (DR), indoor daylight illuminance (ID), outdoor air temperature (OT), indoor air temperature (IT), sky temperature (ST), and operative temperature (OP). The aim of this study is to determine the best control parameter(s) to be used with rule-based controllers to control roller blinds in adaptive facades in terms of energy consumption, thermal comfort and daylight discomfort. The control parameters are investigated via simulation of an ASHRAE standard office building located in Dublin, Berlin and Madrid to represent respectively temperate oceanic, temperate moderately continental and Mediterranean climates.

3. Methodology

The methodology is summarised in Fig. 2. The comparisons in this methodology are based on the ability to achieve desired operating conditions (the desired comfort levels) with the lowest heating, cooling and lighting energy needs. The energy needs used for the comparison is the end energy use of the building, no weighting factors were applied.

Table 1
Definition of comfort parameters.

Time	Indoor comfort range specifications.	
	Mean Air Temperature (ASHRAE, 2019; 2020)	**Illuminance** (Ticleanu, 2019)
Work Hours: 06 h – 18 h	Dublin: 18–21 °C Berlin: 20–23 °C Madrid: 20–25 °C	200–500 lx
18 h – 06 h	Not controlled	

This research defines an optimum control parameter as that which minimises energy needs while the maintaining thermal and visual comfort conditions in Table 1. The building model used is considered to be an office working zone. Thermal comfort levels were defined using ANSI/ASHRAE Standard 62.1 and ANSI/ASHRAE Standard 55 (ASHRAE, 2019; 2020). Lighting comfort levels were defined based on recommended illuminance levels in office workplace from British Standards Institution (BSI) for indoor workplaces (Ticleanu, 2019; British Standards Institute, 2018). Following the standard, the recommended average illuminance in the zone must be within the 200–500 lx range at a height of 1.2 m above the floor level, this ensures that daylight comfort is maintained, and glare is avoided (Ghosh et al., 2018; Ghosh et al., 2016). The range identified in BSI standard is a conservative limit approach designed to ensure productivity and avoid glare, however this does not mean that illuminance levels above the limit will result in glare (Institute, 2018) In this study, daylight comfort is calculated depending on the number of hours in which the average illuminance is not within the 200–500 lx recommended range during the work hours defined in Table 1. The thermal comfort being constantly achieved during the work

Table 2
Definition of three chosen locations and their climate type.

City and country	Latitude and longitude	Climate type (Kottek et al., 2006)	Outdoor temperature range [lowest –highest] (Kottek et al., 2006; Ritter, 2022)
Dublin, Ireland	53.3498° N, 6.2603° W	Temperate oceanic climate	[4 °C – 15.7 °C]
Berlin, Germany	52.5200° N, 13.4050° E	Temperate moderately continental	[-3 °C to 23 °C]
Madrid, Spain	40.4168° N, 3.7038° W	Mediterranean climate (Dry summer climate)	[7.5 °C – 25.5 °C]

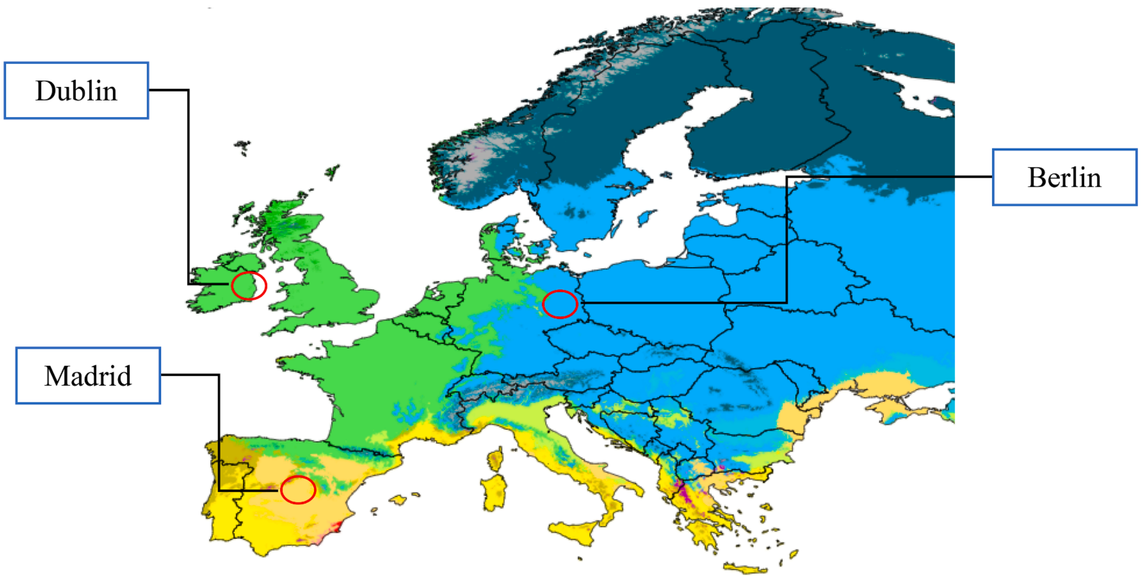

Fig. 3. Climate zones in Europe (Adapted from (Beck et al., 2018)).

hours, the only comfort parameters considered is the period when daylight comfort is not achieved. Maintaining thermal comfort impact on the heating and cooling needs that are then expressed in terms of energy savings.

The methodology presented in Fig. 2 has been used to specify the most effective control parameter(s). After defining simulation boundary conditions, control parameters were investigated individually with those results used to investigate multi-control parameters (two or more control parameter used together to control an electrical system) with rule-based controller(s).

The methodology comprised three stages:

(i) Simulation boundary conditions are defined according to the following parameters: building reference (zone size, shape, window-to-wall ratio, orientation), climatic conditions, building façade specification, building services (heating, cooling,

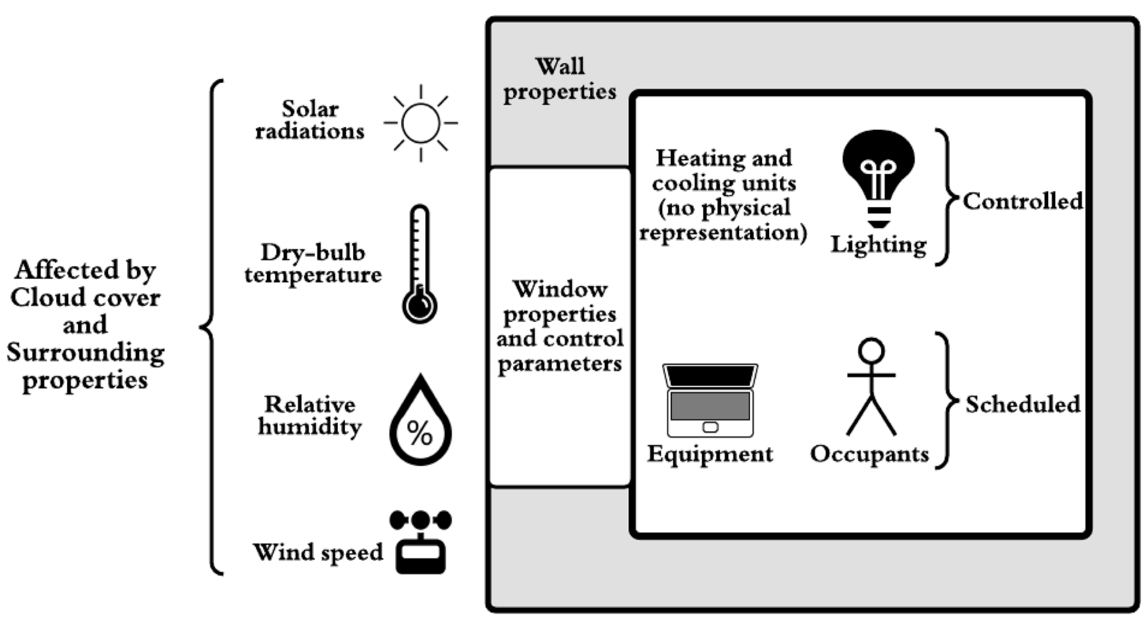

Fig. 4. Boundary conditions of building simulation.

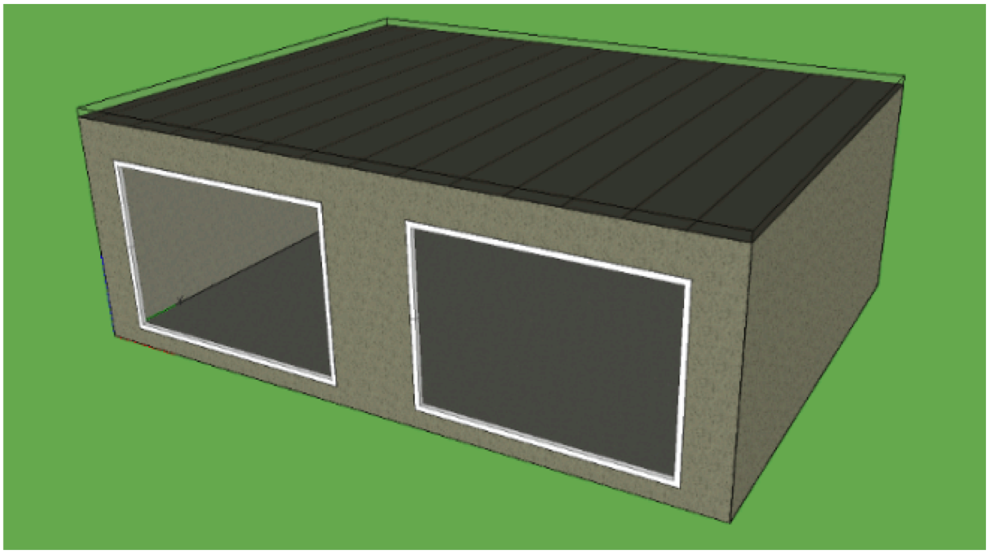

Fig. 5. Building model visualised in IDA ICE.

lighting), occupancy, control objectives (firstly comfort levels and secondarily minimization of heating/cooling energy usages and lighting energy needs during occupancy periods), control parameters and control strategy.

(ii) Individual optimisations consist of initial simulations in each control parameter's range; i.e. the range values within which comfort levels are achieved together with electrical heating and cooling energy usages being minimal. Trigger values switching thresholds for each control parameter are then optimised over this range.

(iii) Dual optimisations consist of simulations utilising the three most effective control parameters from the previous stage in pairs. Initial values in this optimisation stage are decided depending on most effective threshold from the previous stage.

In this study, lighting is scheduled to maintain 200 lx but turned-off when illuminance reaches 500 lx. This is based on the recommend office daylight level at workspace level from the British Standards Institution' standard "BS EN 17037 Daylighting of Buildings" (Ticleanu, 2019). Outside the scheduled occupancy time (06 h – 18 h) and on weekends, there is no constraint on the targeted indoor lighting and thermal comfort meaning that no lighting, heating and cooling energy consumption occur. In the second part of the methodology the control parameters will be investigated separately, which may lead to high levels of indoor light and discomfort glare.

Three cities, shown in Table 2, were selected to represent three main climate types in Europe, as shown in Fig. 3 to compare the effectiveness of the control strategies. The ASHRAE IWEC2 database was used to integrate weather data (ASHRAE, 2021). Weather data contain hourly dry-bulb temperature, solar radiations (direct normal radiation and diffused radiation on horizontal and vertical surfaces), relative humidity, cloud cover, wind speed and direction. Energy simulations typically use typical meteorological year (TMY) weather files averaging climate condition over at least 12 years (British Standards Institute, 2018).

4. Simulation boundary conditions

Boundary conditions shown in Fig. 4, include defining weather according to the location, building specifications adopted from ASHRAE 140 standard geometry (Case 600), internal gains and building services. This section presents boundary conditions of the simulations.

4.1. IDA ICE and GenOpt

The IDA Indoor Climate and Energy (IDA ICE) software or simulating building indoor climate and energy characteristics (Tällberg et al., 2019;

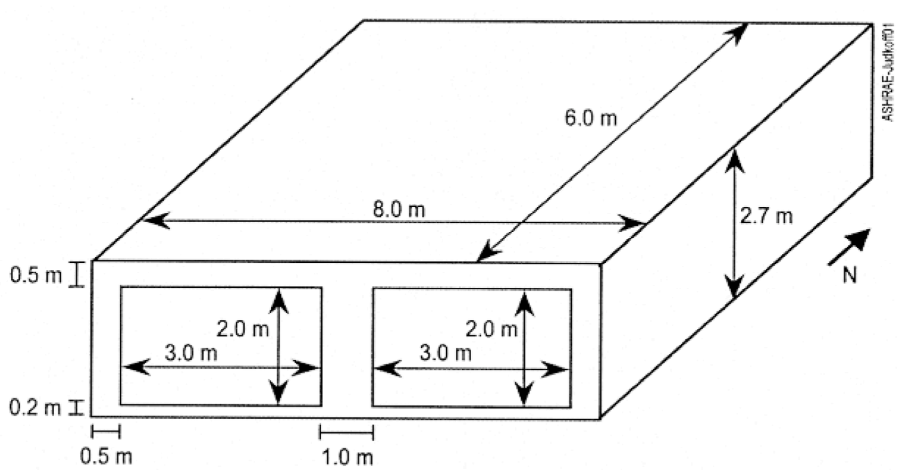

Fig. 6. Building model specification (Crawley et al., 2008).

Table 3
Building material specifications (Crawley et al., 2008).

Envelope Type	Area (m^2)	Thickness (mm)	U-Value ($W/m^2.K$)	Layers (Inside to Outside)	Density (kg/m^3)	Specific heat constant (J/(kg.K))
Light weight exterior wall	63	87	0.510	Plasterboard	950	840
				Fiberglass quilt	12	840
				Wood siding	530	900
Light weight roof	47	141	0.3156	Plasterboard, Fiberglass quilt	950	840
				Roof deck	12	840
					530	900
Floor	47	1028	0.039	Timber	650	1200
				Insulation	0.0001[a]	0.0001[a]

[a] Following ASHRAE standard 140–2017.

Table 4
Double-glazed window properties with and without roller blinds (Smart Films Intrenational, 2021).

Window Properties				
Optical State	Area (m^2)	U-Value ($W/m^2.K$)	Visible transmittance (VT)	SHGC
Roller blinds at top position	6	1.1	0.55	0.41
Roller blinds at bottom position	6	1.1	0.1	0.1

Mäkitalo, 2013) was used in this study based on its capability (i) to log the output values of variables, (ii) to perform various pre-defined control strategies and (iii) to develop custom control algorithms that will be exploited in Section 4.5.

GenOpt is a generic optimisation program, written in Java, typically used for minimizing a specific value by coupling it with an external simulation software such as IDA ICE (Wetter, 2009). GenOpt has multiple optimisation algorithms that can deal with discrete and continuous variables to probabilistically identify simulation objectives optima. In this study, GenOpt was used in the dual optimisation stage by coupling it with IDA ICE. GenOpt was used to find the optimum threshold value for each control parameter, switching On/Off controller, to obtain the desired (min, max and targeted) indoor comfort values at the minimum energy consumption. It was used in the dual optimisation stage to decrease the computational time required to identify the combinatory threshold values of two control parameter leading to the minimum energy consumption while, as before, satisfying the indoor comfort requirements.

4.2. Building model

Fig. 5 and Fig. 6 illustrate the ASHRAE 140 standard geometry (Case 600) (Crawley et al., 2008) benchmark single zone model (8 m wide × 6 m long × 2.7 m high) with (i) two south-facing windows 12 m^2 of total area (ii) no internal walls are in the zone, and (iii) all outer walls were considered external walls. The zone has a volume of 128 m^3, with a window to wall ratio of 55.3 % and a window to envelope ratio of 7 %. The walls, roof and floor material and properties are shown in Table 3. The ASHRAE 140 standard geometry was selected in this study because this building is specifically designed for solar analysis and was proven in previous studies to effectively investigate the influence of façade technologies such as roller blinds. The surrounding of the zone consists of a ground floor made of grass with a reflection considered being Lambertian (perfectly diffusing) and an albedo factor of 15 % over the entire solar range. No tree and buildings surround the zone considered, therefore shading is not a concern other than the cloud coverage.

For comparative purposes, standard double-glazed (DG) windows were used as reference. The properties of the DG window with roller blinds shown in Table 4 Is based on a double-glazed product datasheet (Smart Films Intrenational, 2021). A DG window without roller blinds is used as a base case to calculate the energy savings that occurred from controlling the roller blinds and idealised heating and cooling systems with each control parameter.

Previous studies show that there are three main parameters influence the thermal and optimal performance: (i) Thermal transmittance (U-value), Visible transmittance (VT) and (ii) solar heat gain coefficient (SHGC), so to have a reasonable comparison, the window with roller blinds will have the same properties as the one without.

4.3. Building use, services and internal gains

Ideal heater and cooler were selected in IDA ICE. They have no physical representation inside the zone. Since the heating/cooling optimum start/stop is out of the scope of this article, 10 kw heating/cooling capacity to always be able to achieve the required temperature set points and to avoid any thermal discomfort at the beginning of the working hours. The efficiency of the heater and the cooler was assumed to be 100 %. Losses due the thermal bridges were accounted for in the simulation. Three internal gains are defined as follows:

(i) Two lighting units of 350 W with an efficacy of 20 lm/W positioned at the centre on the building model.
(ii) Indoor equipment producing 200 W of heat.
(iii) Two occupants with a metabolic rate for each person is set to 1 metabolic equivalent task (met) (Tällberg et al., 2019; Jetté et al., 1990).

Lighting was controlled using comfort levels defined in Table 1. Equipment and occupants are set to be active from 06 h to 18 h from Monday to Friday.

4.4. Assumptions

The study made the following assumptions:

i. Since the switching speed of the shading devices has almost no effect on the thermal energy performance of the building due to thermal mass of the building (Mäkitalo, 2013), switching time is set to be zero.
ii. This study was done using fixed inside air temperature set points to (i) reasonably compare control parameters and (ii) be able to fix the optimization range of each control parameter. Different results would have arisen if set points had been changed depending on (i) location (ii) occupancy profile (iii) season and (iv) daytime.
iii. Building simulation results are highly influenced by the type of weather data used. The accuracy of a weather file compared with the real weather conditions have been shown to create up to 40 % difference on the annual energy consumption (Zhong et al., (2020)). So, dissimilar results may appear if a different weather was used.

Table 5
Individual control parameters and descriptions.

Control parameter	Description
Total solar Radiation (TR)	Total incident solar radiation on vertical façades including the (i) direct and (ii) diffused solar components, and (iii) the albedo with ground reflection.
Direct solar Radiation (DR)	Direct solar radiation incident on the vertical and horizontal façades.
Indoor Daylight illuminance (ID)	Average daylight illuminance in the room on workplace level.
Outdoor Temperature (OT)	Outdoor ambient air temperature from the weather files.
Indoor Temperature (IT)	Indoor mean air temperature in the zone.
Sky Temperature (ST)	Average sky temperature from the weather files.
Operative Temperature (OP)	Average between the indoor mean air temperature (IT) and mean radiant temperature. Note that this control parameter would use two types of sensors and it is therefore defined as a dual-control parameter in this study. In contrast all previous control parameters are individual control parameter.

iv. In this study, the same SHGC and U-value were used in the three locations, different regulations might affect the U-value selected in different locations. Using the same U-value in this study meant building performance in the three locations to be solely due to how the applied control parameters interacted with weather conditions.

4.5. *Control parameters*

Seven individual control parameters shown in Table 5 were tested with a sensor range covering the climatic minima and maxima of the three cities. Each range is split in discretisation steps, to minimise the number of necessary calculations and still have sufficient details as to find the minimum annual energy consumption for heating, cooling, and lighting to continuously satisfy the scheduled occupants' comfort targets. The range has then been split into fifteen intervals to select sixteen points. These points were used as transient threshold values for the shading signal with the full On/Off. The threshold value of a control parameter, controlling the On/Off operation of systems, is fixed over the

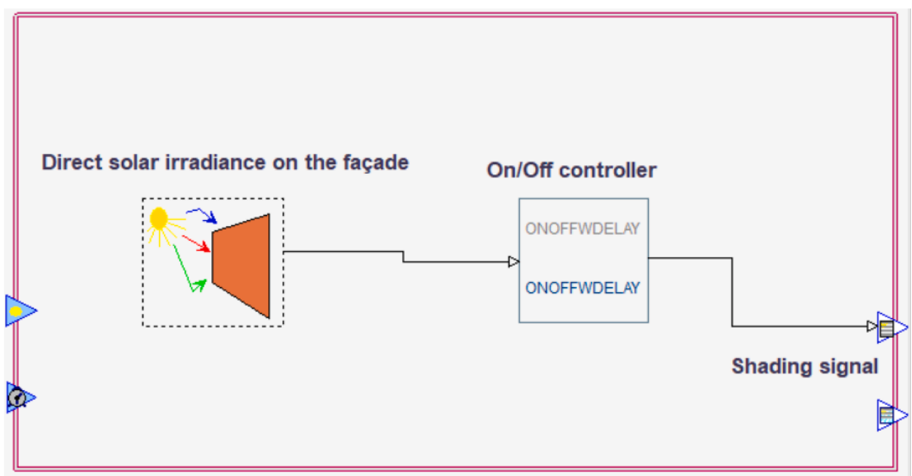

Fig. 7. Control strategy in IDA ICE using DR as control parameter.

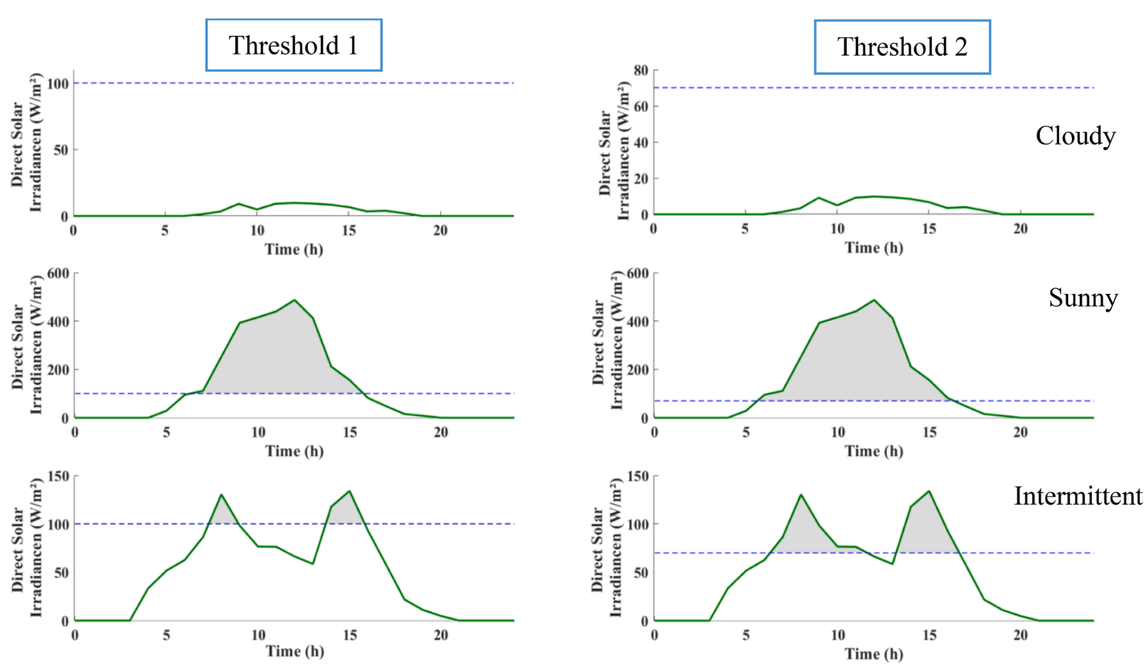

Fig. 8. DR as control parameter in three days using two thresholds.

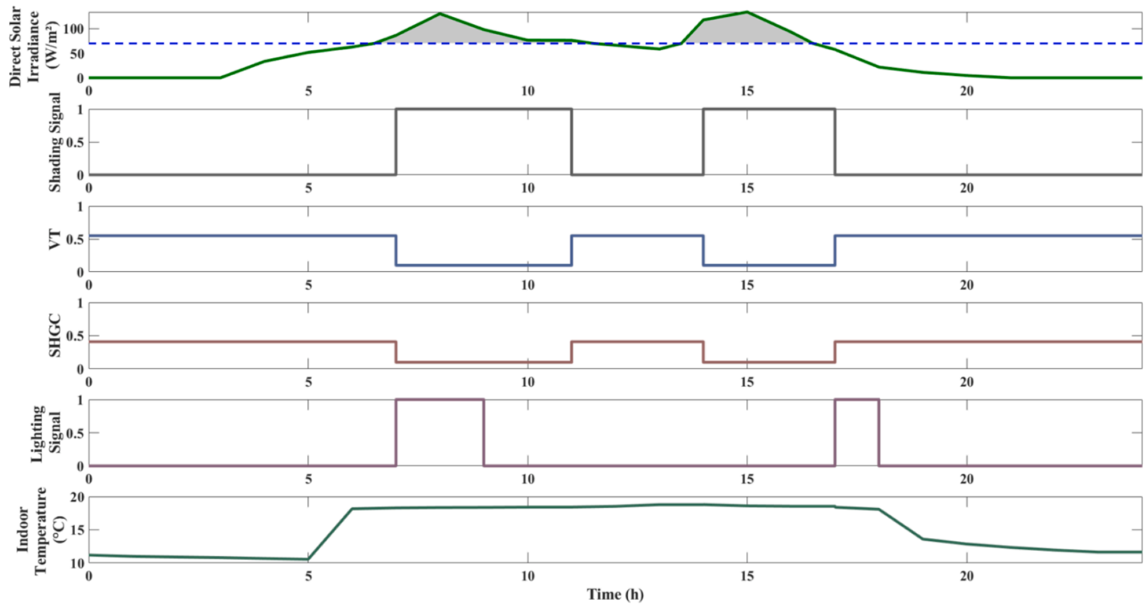

Fig. 9. Window's properties change using DR as control parameter.

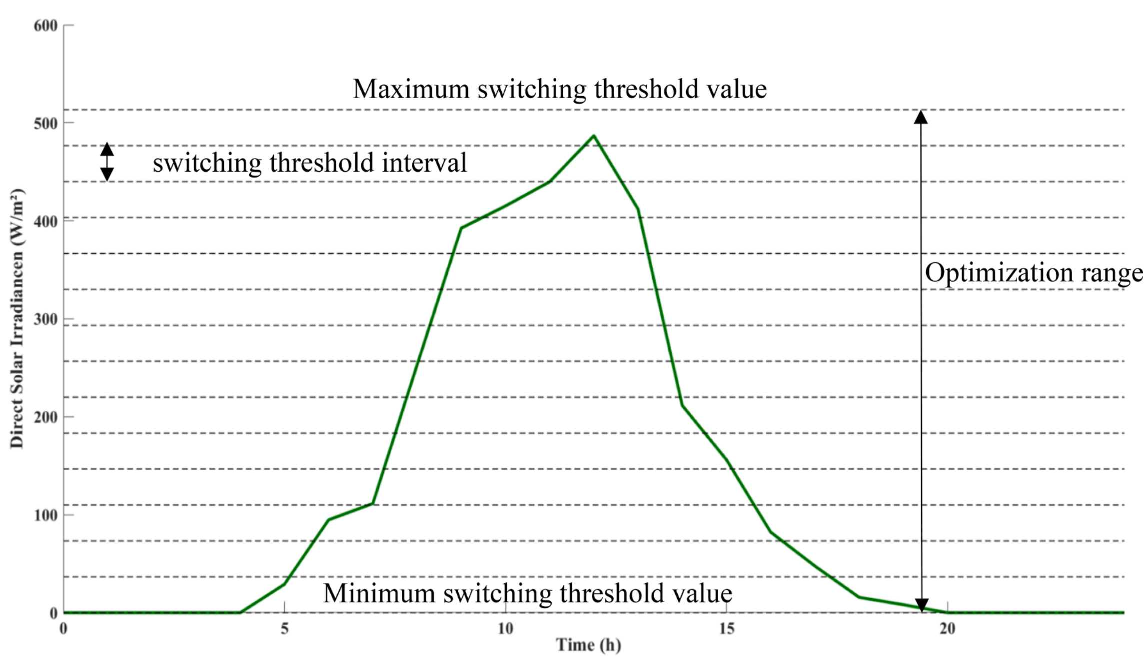

Fig. 10. Threshold values and intervals for the direct solar radiation control parameter presented on a sunny day.

entire year and continuously being optimized to meet the simulation objectives (see Table 1). The variation of the threshold value over the year and seasons is expected to lower the overall building energy consumption.

The Indoor daylight illuminance (ID), air temperature (IT) and operative temperature (OP) sensors represent average values over the indoor space. Consequently, these sensors do not have a real physical location within the simulated zone.

Operative temperature in buildings, where air speed is less than 0.1 m/s, is defined as the arithmetic average between the indoor mean air temperature and mean radiant temperature (Mäkitalo, 2013; Wiki, 2020).

The operative temperature requires two types of sensors, thereby measuring two distinct control parameters, and can consequently be referred to as a multi-control parameter as opposed to previous studies referring to OP as a single control parameter. To align with these previous studies OP will be treated as a single control parameter in the optimisation processes in section 3.7.

To interpret how the shading signal, emulating the window's transmission state, responds to different control parameter and various switching threshold values (trigger values), three distinguishable climatic days, representing sunny, cloudy and intermitted cloudy days, are selected from the Dublin weather file to be used as an example. Fig. 7 *and* Fig. 8 illustrate the use of direct solar irradiance (DR) on the façade as the control parameter, and the thresholds values (blue dashed line) used are 100 W/m^2 and 70 W/m^2 for the three days. The shaded areas present the period where roller blind is at the bottom position while the clear area presents periods where roller blinds is at the top position.

Fig. 9 shows the window's solar heating gain coefficient (SHGC) and visual transmittance (VT) changing with the shading signal for the solar

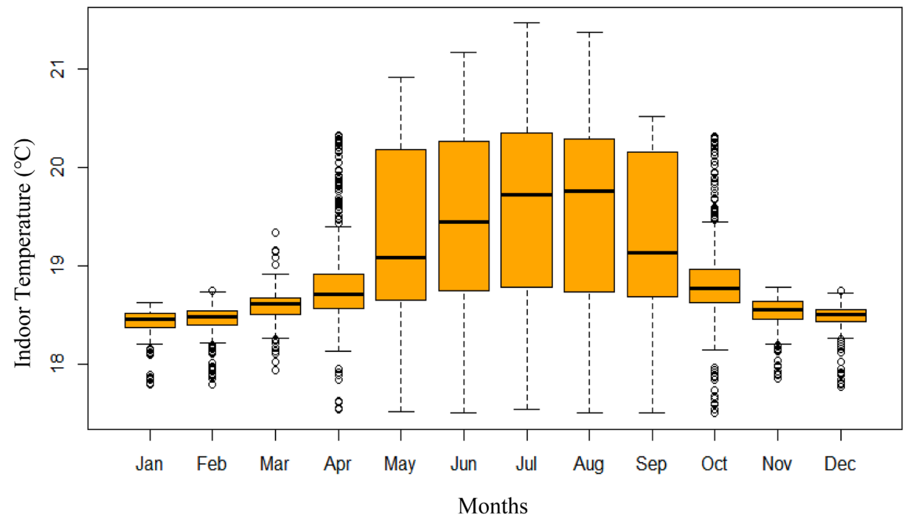

Fig. 11. Hourly indoor air temperature during occupancy hours in Dublin using 100 W/m^2 direct solar radiation as threshold.

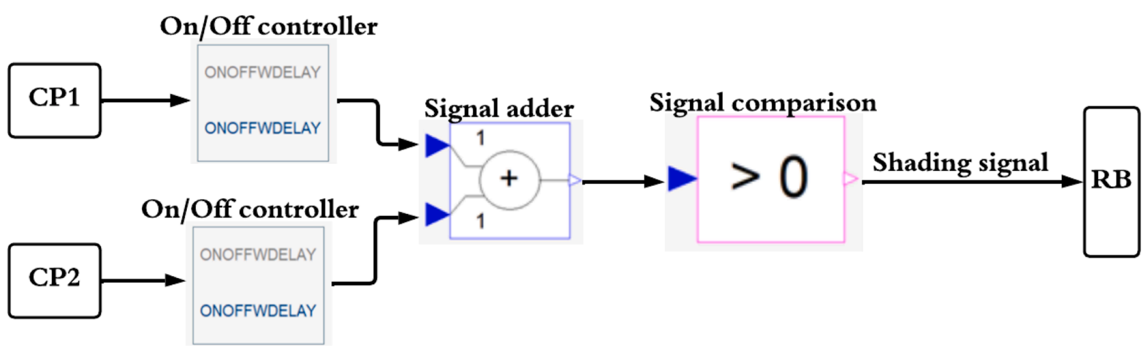

Fig. 12. Control strategy for dual control parameters.

intermittent day. It also shows the lighting signal and the IT during the same day. When the DR value crosses the specified threshold, the On/Off controller switch is seen with the signal changing from zero (roller blinds is up) to one (roller blinds is down). Scrolling the roller blinds from the top position to the bottom position, VT and SHGC change from 0.55 to 0.1 and from 0.41 to 0.1 respectively. Every control parameter in this study was optimised over a defined range. Fig. 10 shows the DR optimisation range (0–550 W/m^2), intervals and the switching thresholds values (dashed line) in the sunny day.

Fig. 11 plots the hourly indoor mean air temperatures over a year during the working hours (06 h – 18 h) using DR as the control parameter with a switching threshold value of 100 W/m^2 to operate the window in Dublin. The median temperature is presented by the black line in the box. The orange boxes, dash lines, and individual points represent the interquartile ranges (IQR), the whisker limits (1.5 times the IQR), and outlier temperatures respectively. The mean indoor air temperatures typically meet the comfort range defined in Table 1 during the working hours (06 h – 18 h), that is 18 °C to 21 °C in Dublin. One notes that temperatures outside that range still occur and the percentage of total occupant hours with thermal dissatisfaction was calculated to be 9 % during working hours. This mostly occurs during the first hour of the day because, as the building temperature drops during the night and the heating system switches on only at 6:00 am, there is a small period of time required for the building to reach its desired mean air temperature. Additionally, using the output on/off controller signal, the total shading time, when the roller blinds window is in the opaque state, was calculated to be 702 h per year.

For multi control parameter simulation, a different control strategy was created. Fig. 12 shows the control strategies created in IDA ICE and Table 6 shows the optimisation ranges. The control strategy investigates performance of roller blinds by combining two control parameters, the code was set in a way that allowed the roller blinds initially to be in the top position, if either/both control parameters crosses the defined threshold, then the on/off controller(s) will send a value of 1 as an output signal to the adder, the adder will then add the two signals from two controllers and send either positive value or zero as the output. If the final output was positive the roller blinds will go into a bottom position. If it was zero it will stay in the top position.

Table 6
Dual control parameters' ranges.

Control parameters	Optimisation ranges
Indoor Temperature	IT: [17°C – 27°C]
Outdoor Temperature	OT: [-1°C – 27°C]
Operative Temperature	OP: [19°C – 27°C]

4.6. Optimisation processes

In this research, two optimisation processes have been done to find the most effective thresholds for each control parameter. A first optimisation process looks at individual control parameters and the second looks at control parameters taken in pairs corresponding to step two and three of the methodology in Fig. 2.

Single control parameter optimisation: The first set of analyses investigated the impact of single control parameter on roller blinds using

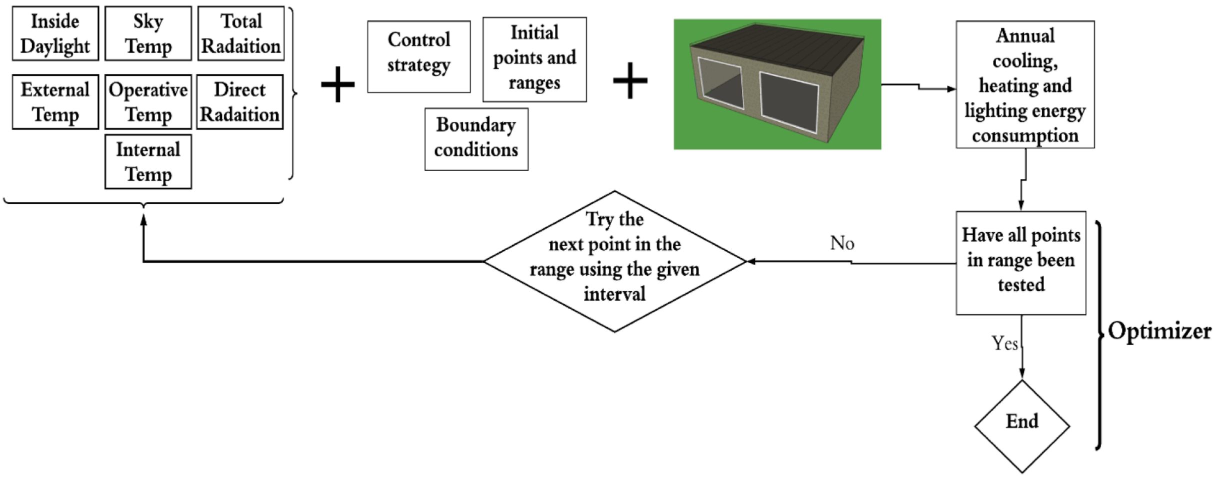

Fig. 13. Single control parameter optimisation flow chart.

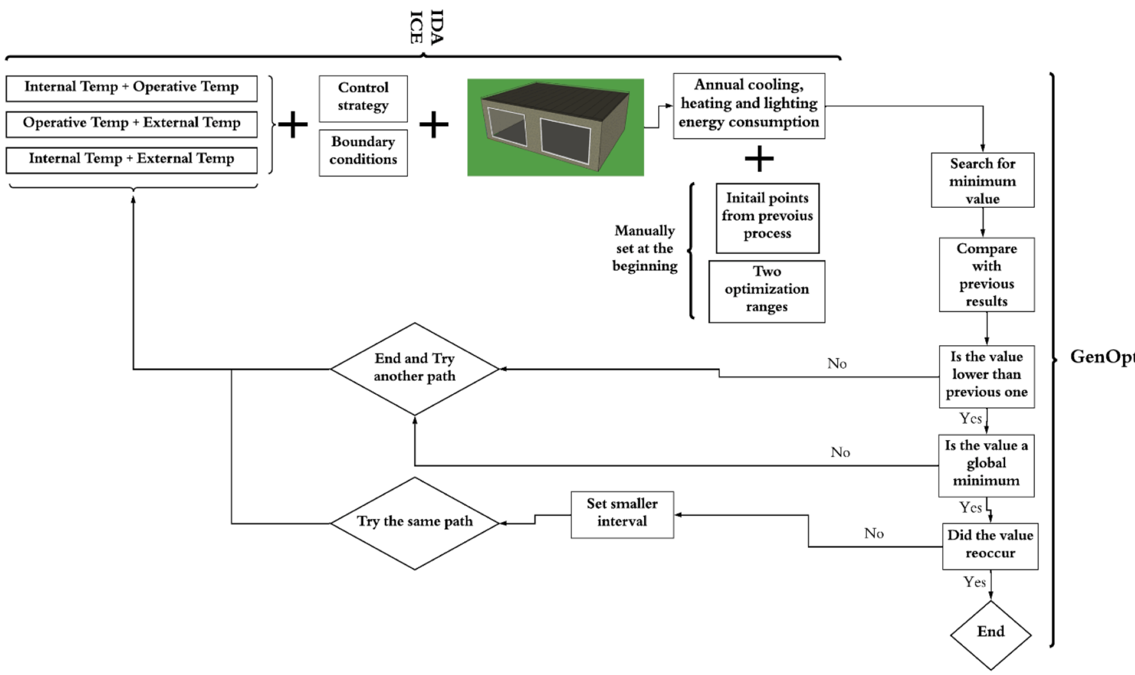

Fig. 14. Multi control parameters optimisation flow chart.

optimisation over a certain range. The optimisation process is shown in Fig. 13. Each parameter was optimised using an IDA ICE built in optimizer to find the threshold that will result in the minimum cooling, heating and lighting energy consumption while meeting the defined thermal comfort conditions. To select a representative range for each control parameter, five initial runs were done. After that each control parameter range has been evenly split into 16 points.

Multi control parameter optimisation: For the second optimisation process GenOpt was coupled with IDA ICE, the main objective of the second optimisation process is to search for the minimum annual energy consumption used for heating, cooling and lighting. Ranges for each control parameter were set as the same ranges in the first optimisations. The resultant optimal thresholds from the first optimisation were used as initial values of the second optimisation process. The flow chart of the optimisation process is shown in Fig. 14.

5. Result and discussion

In this section, the results from both the individual and the multi-control parameter optimisation process are presented.

5.1. Results of individual control parameter optimisation

For the single parameter optimisation, control parameters that can be used as inputs for controlling the window transparency were identified, and an optimisation process has been done on each control parameter to find the optimum switching threshold. The resultant heating, cooling and lighting energy consumption and the period of time that daylight comfort was not achieved for each control parameter optimisation are shown in Fig. 15.

These tests revealed that all control parameters in the three locations followed the same trend. Fig. 16 illustrates the annual energy consumptions for each control parameter investigated over a range of switching threshold values in the three climates. Plots' values start to

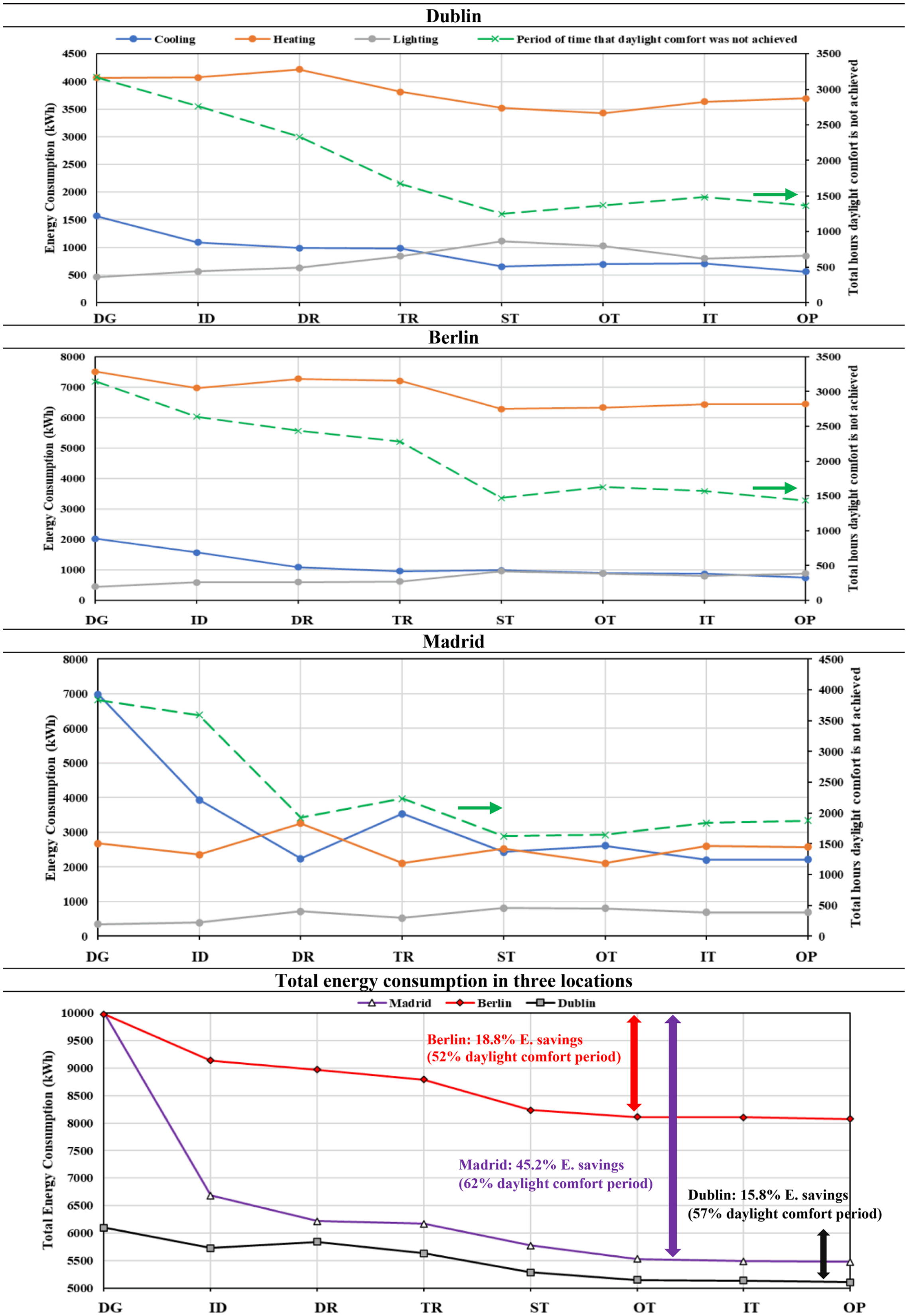

Fig. 15. Energy consumptions from for each control parameter compared to double-glazed (DG) windows without roller blind in three locations.

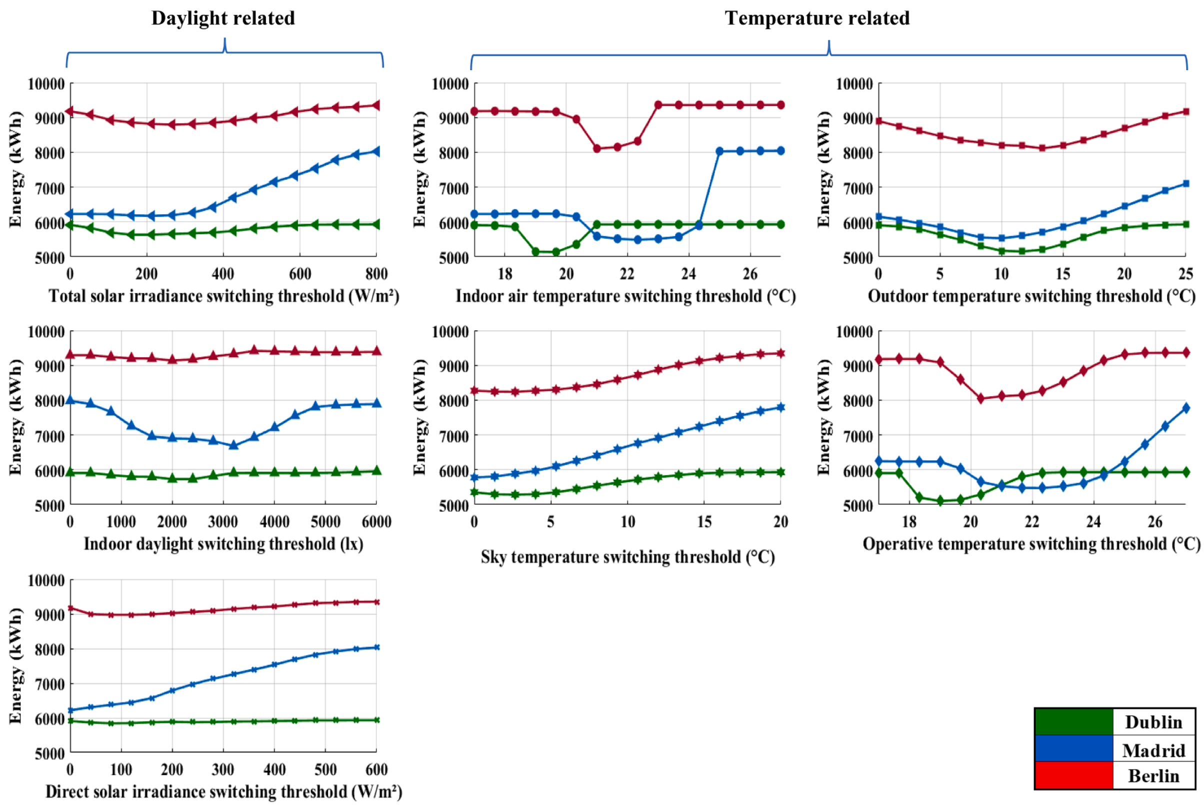

Fig. 16. Annual energy consumption vs different control parameters in three cities.

Table 7
Minimum energy consumption, optimal value and savings from single control parameters (Yellow: minimum value, Orange: 10% above the minimum value).

Control Parameter	Cooling (kWh)	Heating (kWh)	Lighting (kWh)	Total Energy (kWh)	Occurred at	Period of time that daylight comfort was not achieved (H)
Dublin						
DG	1565.9	4067.6	464.5	6098		3174
ID	1092.2	4071.3	567.6	5731.1	2400 lx	2765
DR	988.9	4220.9	632	5841.8	80 W/m^2	2334
TR	983.3	3811	838.8	5633.1	160 W/m^2	1673
ST	654.4	3519.4	1112.1	5285.9	2.7 °C	1249
OT	694	3428.2	1027.4	5149.6	11.7 °C	1370
IT	705.9	3632.8	797.9	5136.6	19.7 °C	1482
OP	560.6	3696.8	848.1	5105.5	19.0 °C	1364
Berlin						
DG	2020.7	7509.9	450	9980.6		3146
ID	1576	6975.9	587	9138.9	2000 lx	2640
DR	1093	7276.5	603.6	8973.1	120 W/m^2	2435
TR	963.5	7205.9	622.7	8792.1	267 W/m^2	2279
ST	988.5	6286.2	962.5	8237.2	2.8 °C	1470
OT	897.3	6327.4	885.3	8110	13.3 °C	1629
IT	870.9	6433.1	801.3	8105.3	21.0 °C	1571
OP	744	6448.3	880.2	8072.5	20.3 °C	1435
Madrid						
DG	6988.3	2675.6	347.9	10011.8		3837
ID	3938.6	2355.9	388.7	6683.2	3200 lx	3591
DR	2244.7	3256.7	719.4	6220.8	40 W/m^2	1923
TR	3539.9	2102.9	529.5	6172.3	213 W/m^2	2236
ST	2431.9	2530.6	816.2	5778.7	0 °C	1623
OT	2615.3	2109.4	806.9	5531.6	10.0 °C	1644
IT	2200.7	2600.7	688.4	5489.8	22.3 °C	1840
OP	2216.7	2576.7	683.4	5476.8	22.3 °C	1876

decay until they reach a minimum and rise as switching threshold values are increased, until they plateau.

Table 7 shows the minimum energy consumption values of each control parameter in the three locations and the switching threshold values that they occurred at. Minima are highlighted in yellow and other accepted efficient values (defined as 10 % above the minimum value, in particular to identify the secondary most influential control parameter minimising the period of daylight comfort) are highlighted in orange. Results of controlling window with roller blind with each control parameter are compared to the results using the same window without

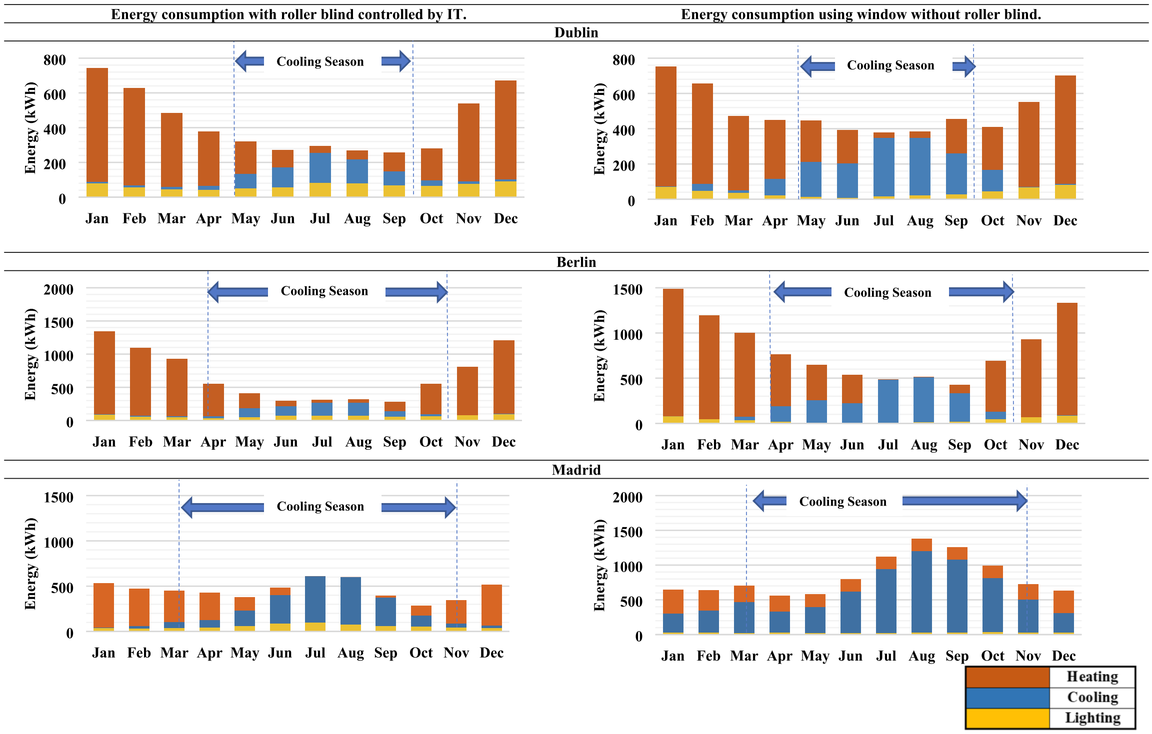

Fig. 17. Total and disaggregated energy consumption (kWh) of a DG window without roller blind compared to roller blind windows.

roller blind. Table 7 shows that, in the three locations, the three most effective control parameters were, in order, (i) the operative temperature, (ii) indoor mean air temperature and (iii) outdoor ambient air temperature. In most cases the difference between OP, IT and OT was less than 1 %. The three control parameters were then combined in pairs and used in the second optimisation process. The switching threshold values that achieved minimum energy consumption were used as the initial values in the second optimisation process.

As expected, switching roller blind down will dim indoor lighting conditions resulting in an increase of the electrical lighting load when considering any control parameters. However, the selection of a monitored control parameter which has the primary goal to minimise the overall heating, cooling, and lighting load also strongly influence the period of indoor daylight comfort. When using a single control parameter to control roller blind, Indoor daylight illuminance level (ID) generates the least lighting load while simultaneously resulting in the highest overall energy consumption and the highest period of daylight discomfort. The minimum period of daylight discomfort is achieved by monitoring the sky temperature (ST) which generates close to minima on the cooling and heating energy needs for the three cities but simultaneously generate the highest lighting load. The second-best option to maximise the lighting comfort duration may be OP, IT, or OT depending on the local climate conditions.

The operative temperature was the most effective control parameter

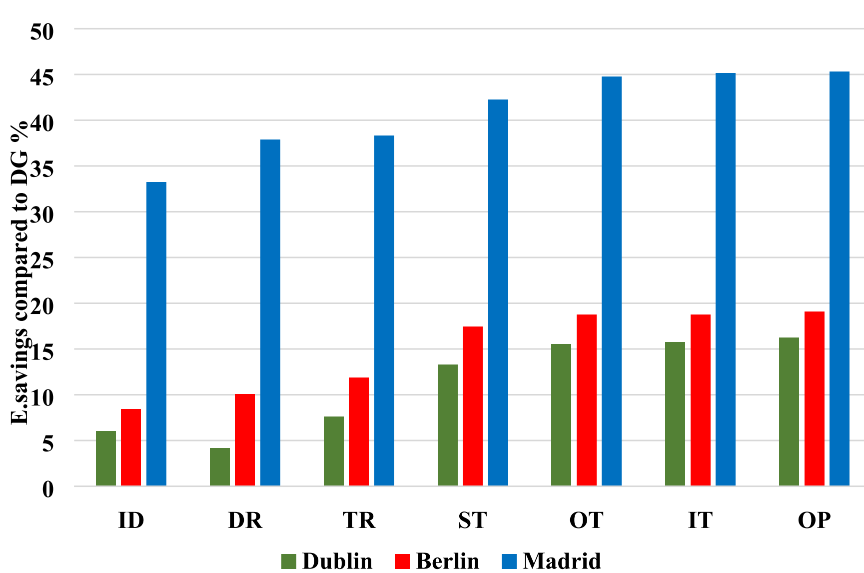

Fig. 18. Single control parameter savings compared to the base case.

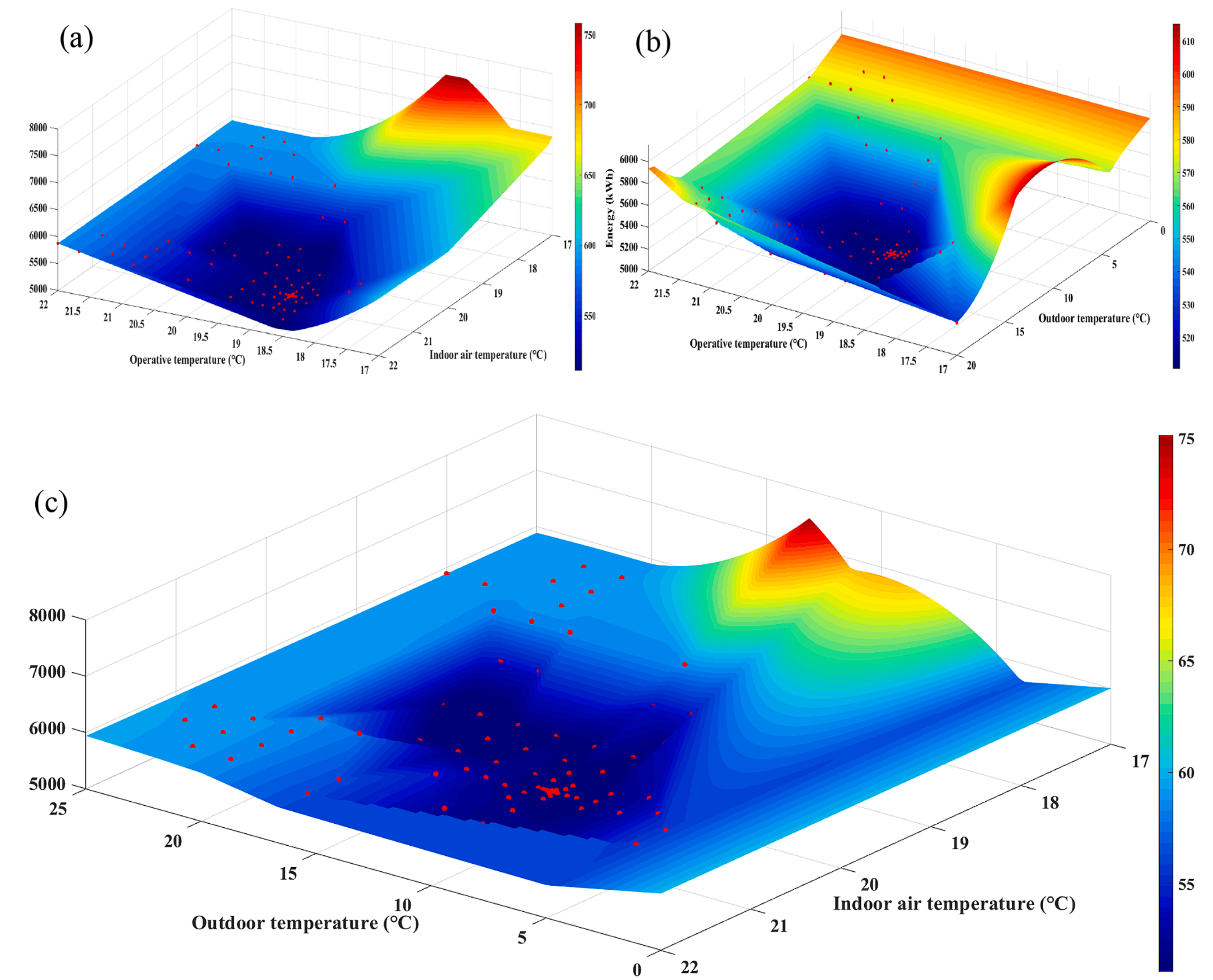

Fig. 19. Dublin multi control parameter optimisation results. (a) (IT + OP), (b) (OT + OP) and (c) (OT + IT).

to minimise the annual energy consumption, which is in line with Tällberg (Tällberg et al., 2019) who investigated different control strategies for shading systems. but as explained in *Section 4.5*, OP might be considered as multi-control parameter. In that case, IT is the most effective individual control parameter. This study shows that using OT enables to minimise the heating energy needs across all climates but can lead to additional annual cooling needs, in particular in Madrid with a Mediterranean climate.

Compared to ID (the least effective control parameter), choosing IT as the control parameter enhanced the roller blind performance by 9.7 %, 10.4 % and 11.9 % in Dublin, Berlin and Madrid respectively. For a window without blind, the annual heating, cooling, and lighting energy consumption in Dublin, Berlin and Madrid were 6,098 kWh, 9,980 kWh and 10,012 kWh respectively or 127 kWh/m^2, 207 kWh/m^2 and 208.6 kWh/m^2 respectively. These values are within the range provided in previous studies done in these three locations (Tällberg et al., 2019; Wehrmann, 2019; Gangolells et al., 2016; Mure, 2018). The total and disaggregated energy consumptions using IT as control parameter in the three locations compared to the window with roller blind are shown in Fig. 17, and the total energy saving for each control parameter is illustrated in Fig. 18. Using IT as control parameter to control roller blind, annual energy savings of 961 kWh, 1,875 kWh, and 4,522 kWh, representing 15.8 %, 18.8 % and 45.2 % energy savings, are achieved compared to window without roller blind in Dublin, Berlin, and Madrid respectively. The cooling energy use reduced by 54.9 % (860 kWh), 56.9 % (1,150 kWh), and 68.5 % (4,788 kWh); the heating energy use reduced by 10.7 % (435 kWh), 14.3 % (1,077 kWh), and 2.8 % (75 kWh); and the lighting energy use increased by 71.8 % (333 kWh), 78.1 % (351 kWh), and 97.9 % (341 kWh) in the three cities respectively. Average primary energy factors can be used to convert the end use energy needs to primary energy needs (SEAI, 2021; Hitchin, 2020), the individual control parameter IT therefore provided the highest primary energy savings that are 1,876 kWh, 4,500 kWh, and 10,8 kWh in Dublin, Berlin and Madrid respectively. This means that roller blind windows achieve the most energy savings in Mediterranean climates (Dry summer climate) followed by temperate moderately continental climates and temperate oceanic climates. Most energy saving appeared by minimising the cooling load in Madrid. In Berlin, absolute energy savings are equally achieved in the cooling and heating energy needs. In Dublin, the energy savings of the cooling load is twice that of the heating load. Interestingly, the additional energy load required for indoor lighting to optimise the daylight comfort values is quasi constant over the three cities. This means that, for similar window-to-wall ratio of a building zone and similar façade orientation, the electrical daylighting demand compensating the solar absorption by the roller blind to maintain lighting comfort can be standardised over multiple climates. Similarly,

Table 8
Minimum energy consumption, optimal value and savings from multi control parameters.

Control parameters	Minimum total energy used (kWh)	Respectively occurred at (°C)	Period of time that daylight comfort was not achieved (H)
Dublin			
OT & IT	5101.7	11.9 & 20.2	1268
OT & OP	5103.7	12.3 & 19.2	1175
IT & OP	5104.7	20.7 & 19.0	1222
Berlin			
OT & IT	8052.1	11.7 & 23.7	1458
OT & OP	8035.8	11.6 & 21.6	1382
IT & OP	8047.6	21.5 & 20.8	1411
Madrid			
OT & IT	5456.7	23.0 & 11.1	1540
OT & OP	5451.8	11.3 & 22.5	1553
IT & OP	5462.7	22.6 & 22.1	1490

the period for which daylight comfort is not achieved reduced between 50.1 % and 53.3 % with the roller blind window compared to the window without roller blind over the three climates considered.

Similarly, to the example provided with Fig. 11, the percentage of total occupant hours with thermal dissatisfaction and the total shading time over the year are measured in Dublin for the optimised IT and OP threshold values. The thermal dissatisfaction periods for IT and OP are 9 % and 8 % respectively. ASHRAE 55 (ASHRAE, 2020) indicates that thermal comfort is achieved based on 80 % of occupant satisfaction or more, this means that the thermal comfort was achieved in the simulation. The shading periods (roller blind is in the bottom position) for IT and OP are 1346 hrs/annum and 1603 hrs/annum. Considering Ireland has an average of 4383 hrs/annum of daylight and about 1300 hrs/annum of sunshine in Dublin (The Irish Meteorological Service and Statements, 2021), the shading periods appears to cover most of the sunshine periods. In Ireland, the roller blinds are for 30.7 % to 36.6 % of the daylight hours in the bottom position using the on/off controller.

5.2. *Results of the multi-parameter optimisation*

Fig. 19 shows the result of the optimisation processes over a given range in Dublin. The area with the highest density of points represents the global minimum where intervals between values constantly get smaller. Table 8 shows the optimal threshold values for each set of control parameters in the three locations. Fig. 20 shows the savings from the control parameter pairs compared to a DG window without roller blind.

There was no significant difference between the three pairs in terms of energy consumption and savings in the three locations. As explained in Section 4.5, considering OP as a dual control parameter, optimising OP with IT or OT might be considered as a triple control parameter optimisation. Therefore, combining OT and IT was the most effective dual control parameter achieving 16.3 %, 19.3 % and 45.5 % savings in Dublin, Berlin and Madrid respectively. Which is only 0.57 %, 0.53 % and 0.33 % more savings than using IT as the individual control parameter.

Using Dual parameters improved the daylight comfort in the zone compared to single control parameter, the difference however was not significant, it resulted in 1175 h, 1382 h and 1540 h, which on average lowered the discomfort period in the three locations by 87 h per year.

Using two or three control parameters to control roller blinds has a small effect on the energy consumption and daylight discomfort compared to using only indoor temperature as single control parameter. For that reason, adding more than one parameter to roller blinds operated to lower the overall heating, cooling, and lighting energy consumption would be cost prohibitive and will not result in significant savings.

6. Conclusions

In the context of the efficient control of roller blinds, this paper goes beyond the state of the art by:

- comparing seven control parameters to maximise energy savings and occupants' comfort,
- investigating the benefits from the simultaneous use of multiple control parameters to control roller blinds to maximise energy savings and optimise comfort to occupants in three different weather conditions.

The limitations of this study are:

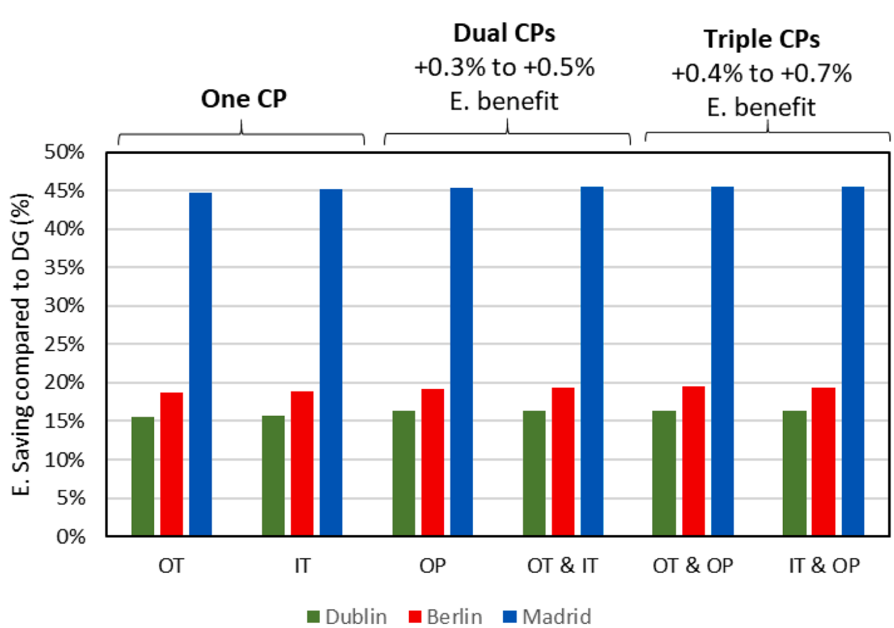

Fig. 20. Comparison of energy savings from roller blind windows compared to DG without roller blind operated with a rule-based control with one, two and three control parameter(s).

Table 9
Optimum control parameter to use according to the energy services to minimise.

Control parameter	Best to optimise	Benefits across three climates compared to DG window without roller blind.
Indoor Temperature	Cooling	54–69 % energy savings
Outdoor Temperature	Heating	16–21 % energy savings
Sky Temperature	Daylight comfort	53–61 % improvement on the period of daylight comfort

- On/off controller was used in this study; which means that the effect of intermediate states was not investigated.
- Fixed temperature was set during the optimization over the year, this approach is typically used in studies on control parameters to make the comparison fair (Hoon Lee et al., 2020; Tällberg et al., 2019). dissimilar results might have a risen if variable temperature was used.
- Previous studies before have proven that changing different weather files have a huge effect on the results of any simulation and can reach up to 40 % difference.
- This study used same U-value for the three locations for comparison purposes. However, countries have different regulations over the U-value used in buildings

Using individual control parameters with rule-based controllers, indoor temperature (IT) was found to be the most effective control parameter achieving 15.8 %, 18.8 % and 45.2 % overall energy savings compared to DG window without roller blind in Dublin, Berlin and Madrid respectively and representing three different climates. Simultaneously the period of daylight comfort is improved by more than 50 % in the three cities. Table 9 summarises the individual control parameter to use to minimise the energy consumption associated to building services across the three climates. Monitoring indoor temperature appears to be the best to control roller blind to minimise the cooling load, while the outdoor temperature (OT) is the best control parameter to minimise the heating load. Maximisation of the period of daylight comfort is achieved using sky temperature as the control parameter. The second-best individual control parameter is IT or OT depending on the climate conditions.

Using roller blind, which by purpose intercept daylight, resulted in an increase of the lighting energy consumption. The lighting energy consumption is then the result of maintaining the desired lighting comfort while using the control parameter to minimise the cooling and heating loads. However, one notes that the minimum lighting energy consumption occurs with indoor daylight as control parameter which simultaneously leads to the longest time period of lighting discomfort and to the highest overall energy consumptions over the three climates.

Controlling roller blinds with multiple control parameters provided marginal energy savings on the heating, cooling, and lighting energy consumption. This result includes the operative temperature (OP) that is considered in this study as a dual-control parameter in contrast with previous studies. Overall, additional energy savings between + 0.3 % and + 0.5 % and between + 0.4 % and + 0.7 % were achieved with two and three control parameters respectively. For example, using two control parameters, combining outdoor temperature and indoor temperature was the most effective pair in achieving 16.34 %, 19.32 % and 45.50 % savings in Dublin, Berlin, and Madrid respectively. Therefore, further investigation of four or more control parameter is not needed. These results lead to conclude that the most cost-, energy-, comfort-efficient method to control adaptive façade technologies with On/Off controllers is to use a single control parameter.

Future simulations and experiments must be performed with other controller types using IT as control parameter to estimate the benefits on the annual energy savings, thermal and indoor daylight comfort levels and percentage satisfaction. Such an approach would provide standardised comparison of windows performances and the most efficient control strategies using reference buildings/zones covering a range of traditional building architectures.

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.

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Further reading

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