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Optimizing Automated Shading Systems in Office Buildings by Exploring Occupant Behaviour

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For my grandfather
For my parents
For my friends

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Nomenclature

Abbreviation	Description
ACH	Air changes per hour
AMV	Actual mean vote
AOV	Average occlusion value
ARM	Association rules mining
BAS	building automation systems
DGP	Daylight Glare Probability
DGPs	Simplified Daylight Glare Probability
BPS	Building performance simulation
df	degree of freedom
DTU	Technical University of Denmark
EU	European Union
EPS	Expanded Polystyrene insulation
FFP-OBm	Fit-for-purpose occupant behaviour method
FP growth	Frequent pattern growth algorithm
GHG	Greenhouse Gas
GSV	Glare sensation vote
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
IEA	International Energy Agency
IEQ	Indoor environmental quality
MS_dw	User-shade lowering
MS_up	User-shade raising
MSO	Mean shade occlusion
N/A	Not available
OB	Occupant behaviour
PMV	Predicted mean vote
POE	Post-occupancy evaluation
PPD	Predicted percentage dissatisfied
RH%	Relative Humidity
SA-L	Shade lowering
SA-R	Shade raising
SD	Standard deviation
SET	Standard Effective Temperature
SMR	Shade movement rate
UNDP	United Nations Development Program
UOAs	User shade override adjustments
VDU	Visual Display Units
WWR	Window-to-wall ratio

Notation	Description	Unit
I_r	Incident solar radiation on the facade	W/m2
T_{in}	Indoor air temperature	°C
T_{op}	Indoor operative temperature	°C
T_{com}	Comfort temperature	°C
T_{out}	Outdoor air temperature	°C
T_{pma}	Prevailing mean outdoor air temperature	°C
T_{rm}	Running mean temperature	°C
W_p	Workplane illuminance	lux
E_v	Vertical illuminance at the eye level	lux
$I_g l$	Global horizontal irradiance	W/m^2
E_{out}	External vertical illuminance	klux
C	Comfort vote (Griffiths' method)	
C_n	Comfort vote of neutral (Griffiths' method)	
t-value	a ratio of the difference between the mean of the two sample sets and the variation that exists within the sample sets.	

Abstract

Automated shading systems represent a promising solution for improving indoor thermal and visual conditions as well as saving energy. However, previous studies indicate that many existing automated shading systems fail to improve occupants' visual comfort and reduce the energy use as intended in the design phase. Thus, occupants frequently override or disable these systems, indicating their discomfort or desire for a customized indoor environment. Therefore, neglecting occupants' needs and expectations in the building design and operation process may cause discrepancies between the predicted and actual energy performance and sub-optimal design decision-making. To address this issue, this research aims to explore and evaluate the use and function of automated shading systems in office environments for optimizing automated shading system design and operation in existing and new buildings.

To achieve the objectives of this research, three phases were completed. In **Phase 01**, the current practice of automated shading design and operation was investigated in 19 case studies through a questionnaire. The commonly-used shading setpoints were identified and tested. The performance of two commercial shading control devices was examined by an experimental and field studies. Results indicate that commercial devices' limited quality and accuracy for automatic shading control could be due to economic constraints and sensors' positions or inclinations. Therefore, designers may consider other design strategies such as an intermediate blind position or combined internal/external shading systems.

In **Phase 02**, an experimental study was conducted in a full-scale test cell to evaluate the performance of an automated shading system in terms of user behaviour and acceptance, thermal and visual comfort under six scenarios. After each scenario, a self-reported questionnaire was completed by the participant. Indoor and outdoor environmental parameters, user and system-triggered adjustments were recorded. Different performance indicators were used. The key findings suggest that a robust shading system (i.e., few override actions) can be achieved by: a multi-objective control strategy with an intermediate position, an acceptable range of irradiance thresholds, and a decent level of adaptive control options over the workplace.

Phase 03 introduces a field study, including design investigation, data monitoring, a questionnaire, and simulation-based analysis. The study focused on using

automated shading systems in a real office building to derive occupant-centric rules for optimal shading design. The monitored data and questionnaire analysis showed similar results, a relatively few interactions between the occupants and the shadings systems. The statistical analysis of the monitored data showed the limited approach of the regression model used in this study, while data mining techniques showed advantages in exploring occupant behavioural patterns. The extracted lessons for designers and researchers include: the use of double shading systems (internal/external) can improve user satisfaction of automated shading systems (i.e., few override actions), the definition of control thresholds is essential, and the deployment of light sensors is beneficial.

Kurzfassung

Automatisierte Beschattungssysteme sind eine vielversprechende Lösung zur Verbesserung der thermischen und visuellen Bedingungen in Innenräumen und zur Energieeinsparung. Frühere Studien haben jedoch gezeigt, dass viele der bestehenden automatischen Beschattungssysteme nicht in der Lage sind den visuellen Komfort der Nutzer zu verbessern und den Energieverbrauch wie in der Planungsphase vorgesehen zu senken. Daher setzen die Nutzer diese Systeme häufig außer Kraft oder deaktivieren sie, um ihr Unbehagen oder ihren Wunsch nach einem individuell angepassten Innenraumklima zum Ausdruck zu bringen. Die Vernachlässigung der Bedürfnisse und Erwartungen der Nutzer bei der Planung und dem Betrieb von Gebäuden kann daher zu Diskrepanzen zwischen der vorhergesagten und der tatsächlichen Energieleistung und zu suboptimalen Planungsentscheidungen führen. Um dieses Problem anzugehen, zielt diese Forschungsarbeit darauf ab, die Nutzung und Funktion automatischer Beschattungssysteme in Büroumgebungen zu untersuchen und zu bewerten, um die Planung und den Betrieb automatischer Beschattungssysteme in bestehenden und neuen Gebäuden zu optimieren.

Um die Ziele dieser Untersuchung zu erreichen, wurden drei Phasen durchgeführt. In **Phase 01** wurde die derzeitige Praxis der Planung und des Betriebs automatisierter Beschattungssysteme in 19 Fallstudien anhand eines Fragebogens untersucht. Die am häufigsten verwendeten Beschattungssollwerte wurden ermittelt und getestet. Die Leistung von zwei im Handel erhältlichen Beschattungssteuerungen wurde in Experimenten und Feldstudien untersucht. Die Ergebnisse deuten darauf hin, dass die begrenzte Qualität und Genauigkeit kommerzieller Geräte für die automatische Beschattungssteuerung auf wirtschaftliche Zwänge oder die Position und Neigung der Sensoren zurückzuführen sein könnte. Daher sollten Planer andere Planungsstrategien in Betracht ziehen, wie z. B. eine Zwischenstellung der Jalousie oder kombinierte Innen-/Außenbeschattungssysteme.

In **Phase 02** wurde eine experimentelle Studie in einer maßstabsgetreuen Testzelle durchgeführt, um die Leistung einer automatisierten Außenjalousie in Bezug auf Benutzerverhalten und -akzeptanz sowie thermischen und visuellen Komfort in sechs Szenarien zu bewerten. Nach jedem Szenario füllten die Teilnehmer einen Fragebogen mit Selbstauskünften aus. Die Umgebungsparameter im Innen- und Außenbereich sowie die vom Nutzer und vom System ausgelösten

Einstellungen wurden aufgezeichnet. Es wurden verschiedene Leistungsindikatoren verwendet. Die wichtigsten Ergebnisse deuten darauf hin, dass ein robustes Beschattungssystem (wenige Übersteuerungsaktionen) durch folgende Maßnahmen erreicht werden kann: eine multikriterielle Steuerungsstrategie mit einer Zwischenposition für die Jalousie, ein akzeptabler Bereich von Schwellenwerten für die Bestrahlungsstärke und ein angemessenes Maß an adaptiven Steuerungsoptionen für die Arbeitsplätze.

Phase 03 wird eine Feldstudie durchgeführt, die eine Designuntersuchung, Datenüberwachung, einen Fragebogen und eine simulationsbasierte Analyse umfasst. Die Studie konzentrierte sich auf den Einsatz automatischer Beschattungssysteme in einem realen Bürogebäude, um bewohnerzentrierte Regeln für eine optimale Beschattungsplanung abzuleiten. Die Beobachtungsdaten und die Fragebogenanalyse ergaben ähnliche Ergebnisse, nämlich eine relativ geringe Interaktion zwischen den Bewohnern und den Beschattungssystemen. Die statistische Analyse der beobachteten Daten zeigte den begrenzten Ansatz des in dieser Studie verwendeten Regressionsmodells, während Data-Mining-Techniken Vorteile bei der Erforschung der Verhaltensmuster der Nutzer zeigten. Die Lehren, die sich daraus für Planer und Forscher ableiten lassen, sind unter anderem: Die Verwendung doppelter Beschattungssysteme (intern/extern) kann die Zufriedenheit der Nutzer mit automatisierten Beschattungssystemen verbessern (d. h. weniger Übersteuerungsaktionen), die Definition von Steuerungsschwellen ist von wesentlicher Bedeutung, und der Einsatz von Lichtsensoren ist von Vorteil.

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Chapter 1

Introduction

According to IEA and UNEP, the building sector accounts for 35% of the global final energy consumption (i.e., operation and construction) and 38% of energy-related CO2 emissions, as compared to other end use sectors [1]. In the European Union (EU), the building sector consumes about 40% of the total primary energy and is the main contributor to greenhouse gas (GHG) emissions [117, 66]. According to a worldwide energy evaluation, offices represent a significant part of the commercial building sector, the fastest-growing energy demand sector, with an increasing rate of 1.6% per year since 2012 extending to 2040 [116]. Energy is consumed in office buildings to maintain comfortable and healthy environments for the occupants. For instance, occupants use energy to operate computers and interact with control systems and devices.

Occupants spend 80-90% of their time inside buildings [6]. Occupants aim to maintain an acceptable and comfortable indoor environment. The perception of comfort is influenced by one's past experiences and expectations [55]. Occupants are satisfied when their expectations are met. Otherwise, they restore their desired sensation and needs by interacting with the indoor environment (e.g., adjusting the thermostat, windows and blinds, operating a fan). Consequently, their behaviours affect user comfort and building energy performance [130, 9]. Gilani and O'Brien [41] reported that the risk of neglecting occupants' needs and expectations in the building design and operation process may cause discrepancies between the predicted and actual energy performance and lead to sub-optimal decision-making in designing and operating buildings .

Modern office buildings are often designed to include a high proportion of glazing in the facade, impacting occupant comfort and building energy performance [63]. Therefore, using appropriate solar shading to control heat gain and daylighting through the transparent facade is crucial to obtain thermal and visual comfort as well as energy-saving [83, 64]. Solar shading can be static or dynamic. Dynamic solar shadings use a built-in control algorithm to determine how and when to adjust the shading device based on indoor or/and outdoor

[1] 2020 Global Status Report for Buildings and Construction: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector, https://wedocs.unep.org/20.500.11822/34572

environmental conditions [65]. Dynamic solar shadings could save energy, improve the indoor environment and occupant comfort when properly designed and used [23].

1.1 Motivation

Building automation is becoming more prevalent in modern buildings systems' design and control to improve energy efficiency while maintaining occupant comfort [121]. Automated shading systems represent a promising solution for improving indoor thermal and visual comfort as well as saving energy [23]. Whereas, automated shading systems can keep balance between various aspects of indoor environmental quality, such as discomfort glare, view to the outside, privacy, thermal comfort, and air quality [7]. However, a recent review of the literature indicates that many of the existing automated shading systems fail to improve occupants' visual comfort and reduce the energy use as intended in the design phase [93]. Several studies reported that occupants frequently override or disable these systems indicating discomfort or implying their desire for customized indoor climate [102, 84]. Nevertheless, designers often neglect or fail to understand that providing occupants more control over their environment increases their acceptance and preference for a wide range of indoor climate [12]. Thus, if designers understand what occupants desire or expect from shading systems in their offices, it would be possible to design better control strategies for automated systems.

Previous studies indicate that user acceptance and satisfaction are crucial in the development and operation of automated shading systems [7]. However, users complain about shading systems' control strategies since undesired automatic opening and closure occurred. Thus, the users expectations are not met, which impacts their productivity and well-being [77]. Moreover, a recent study found a conflict between the selected metrics, shading comfort thresholds and what occupants accepted [62]. Therefore, an integrated evaluation of user comfort and satisfaction, as well as energy use, is required while selecting an optimal solar shading control strategy with limited override actions [64, 4]. Previous studies in the area reported that limited focus was on dynamic shadings' impact on thermal comfort and user acceptance [71, 7].

Monitoring studies on occupant-shade interactions have been performed to predict occupant behaviour models, integrate them into building simulation tools, and develop shading control algorithms [41]. However, there are limited published studies on the design and post-occupancy evaluation of buildings equipped with automated shading systems [67]. A better understanding of occupants in the operation phase can enhance the robustness of building automation solutions over occupant overrides [46]. Moreover, the extracted lessons from a monitoring study can be applied in improving the design of existing and future buildings with respect to shading systems.

1.2 Research objectives

Based on the aforementioned limitations, the current research aims to explore and evaluate the use and function of automated shading systems in offices environments. This is crucial for the improvement of automated shadings' design and operation in two aspects: (a) to operate and maintain shading systems more efficient for occupants' comfort and building energy performance in existing buildings, and (b) to provide building designers and operators with recommendations for better design and control of shading systems in future buildings. To achieve the objectives of this research, three phases are implemented:

1. In **phase 01**, the current practice of automated shading systems' design and operation was investigated in commercial buildings to address the following sub-objectives:
    - **To explore** the configuration of automated shading systems and **define** the commonly-used control thresholds.
    - **To examine** the quality and accuracy of two commonly-used commercial shading control devices.
    - **To evaluate** the energy and visual performance of shade irradiance setpoints.
2. **Phase 02** introduces an experimental study, conducted in a full-scale test cell to achieve the following sub-objectives:
    - **To evaluate** the performance of automated shading systems under different scenarios in terms of user interaction and acceptance, thermal and visual comfort.
    - **To develop** a multi-objective shading control strategy based on occupant-centric parameters and test its performance.
    - **To find** optimal setpoints of solar irradiance with respect to user acceptance and comfort.
3. **Phase 03** presents an in-situ monitoring study performed in a real office building in Luxembourg. The purpose of this study is:
    - **To better understand** occupant behavioural patterns related to the use of automated shading systems and the main triggers behind that.
    - **To derive** occupant-centric rules for optimal shading design solutions.
    - **To extract** lessons and **provide** valuable insights for building designers and operators with respect to occupant-centric shading design.

1.3 Research approaches

Three main phases are conducted to achieve the main aim of the current research as previously stated. Different approaches are used to accomplish each phase. The workflow of the three main phases and the used approaches are presented in Figure 1.1.

- In **phase 01**, a survey questionnaire was conducted in 19 case studies to investigate the configuration of automated shading systems. The behaviour of commonly-used commercial shading control devices was assessed in an experimental and field studies. A simulation-based analysis using simplified tools (e.g., SimRoom and Variantas) was performed to assess the energy performance of solar irradiance setpoints.

- In **phase 02**, an experimental-based study was conducted in a full-scale test cell to evaluate the performance of automated shading systems under six scenarios (e.g., window size, cooling system, time context, and sky conditions). The test facility is a south-faced single-occupancy office located at Haspel Campus, Wuppertal, Germany. Twenty-eight participants took part in the experiments. After each scenario, a web-based questionnaire was collected. Concurrently, indoor environmental parameters, weather data, and shade deployment were recorded. Different performance indicators were used. Statistical tests analysis (e.g., paired t-test) were performed using IBM SPSS Statistics V21.0 software.

- In **phase 03**, the study included a design investigation, data monitoring statistical analysis, a questionnaire, and a simulation-based analysis. An interview with the designer was conducted to investigate the shading system design characteristics and selection criteria. The data monitoring was performed under summer conditions in 2019, and the questionnaire was conducted in 2021 under similar conditions. Finally, a simulation-based analysis was performed to evaluate the daylighting and energy performance of the established shade control strategy.

1.4 Thesis structure

The core of this dissertation consists of six chapters, structured in the following way:

- **Chapter 1** includes a brief introduction to the topic, the motivation of the current research, along with the main aims and objectives, research approaches, and the structure of the dissertation.

- **Chapter 2** reviews the recent research and the current knowledge in the field. First, a general review of occupant behaviour and its impact on building performance is presented. Second, the types of shading systems, dynamic solar shading, control strategies, and assessment methods are introduced. The third part reviews the existing research concerning occupant-related data collection (e.g., laboratory experiments

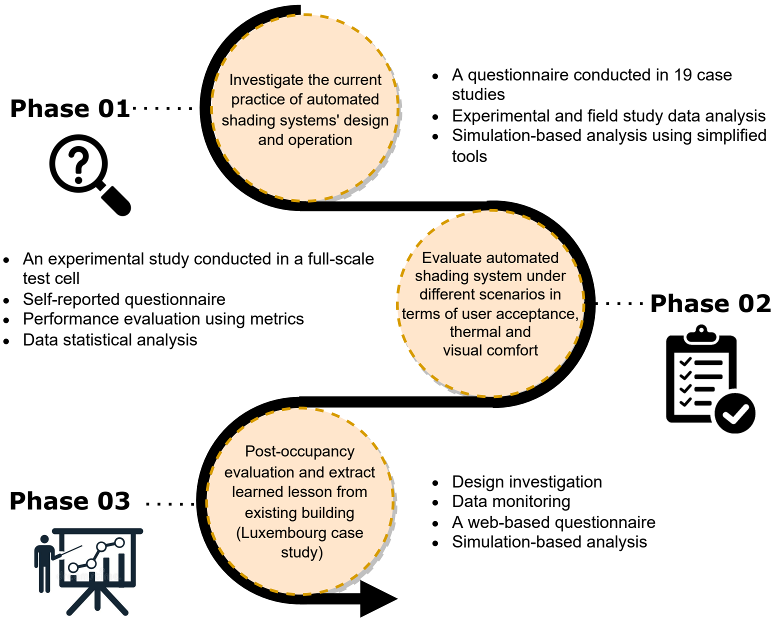


Figure 1.1: Study workflow to illustrate the three main phases in the current research and the used approaches.

and in-situ monitoring studies). Finally, recent research on occupant-centric shading design is introduced.

- **Chapter 3** presents the data collection and analysis of the automated shading systems' configuration in commercial buildings. The laboratory and monitoring-based studies to examine light sensors' quality and accuracy are reported and discussed. Finally, the tools and findings of the simulation-based analysis are introduced.

- **Chapter 4** outlines the methods used to conduct the laboratory experimental study. The performance metrics used to evaluate automated shadings are defined. The statistical analysis results of different scenarios are presented and compared. Finally, the main conclusions and limitations of the study are drawn.

- **Chapter 5** presents the methods and key findings of a comprehensive field study, including design investigation, data monitoring, a questionnaire set, and simulation-based analysis. The main conclusions and lessons learned from shading design and how occupants interact with shading are extracted for optimal shading design (i.e., few override actions).

- The last **Chapter 6** summarizes the main conclusions and recommendations obtained in each chapter and identifies their limitations. Additionally, the major contributions of this research and recommendations for future research work are outlined.

Chapter 2

Literature review

In this chapter, a high-quality journal papers, books, and conference papers are collected and reviewed to summarize the state-of-the art and main findings of previous research work related to the topics of user interaction with automated shading system and occupant-centric shading design. Related-papers over the last ten years and more were gathered in Mendeley repository from Science Direct, Scopus, and Google Scholar. The main keywords included automated shading systems, user interaction, user satisfaction with automated shading, shading control strategies, thermal and visual comfort assessment, and occupant-centric shading design. After papers were reviewed, they are summarized into the following sections.

2.1 Occupant behaviour and building automation

Occupant behaviour (OB) defined as the "presence and actions of occupants that affect building energy use, and is recognized as main source of discrepancy between simulation predictions and actual building performance" [34]. Over the last decades, occupant behaviour was found to have a significant impact on building energy consumption [130, 135, 117]. In commercial buildings, occupants' behaviour can affect annual energy use by a factor of two or more [49]. With the growing need for energy-efficient and sustainable buildings, architects, planners, designers, building operators, and researchers have started to recognize the importance of understanding occupants' presence and behaviour. On the other hand, building performance simulation (BPS) is considered one of the most effective means to evaluate building performance and design. However, the "performance gap" between the predicted and actual energy consumption can be a result of multiple sources of uncertainty, including occupant behaviour and other factors (e.g., building properties assumptions, absence of accurate weather data) [135, 54, 81]. Understanding and modeling of occupant behaviour in buildings (e.g., better representation of energy-related OB models in building energy models) are crucial to reducing these discrepancies [135, 9].

But how do occupants influence building performance? Occupants have an impact on their surroundings by simply being there. They affect the buildings' heat balance by producing water vapor and CO2 as well as emitting sensible and latent heat. Occupants respond to their surroundings in a variety of ways, ranging from physiological adaptation (e.g., sweating or shivering), to personal adaptation (e.g., changing their level of clothing, and activity level, or consuming a hot/cold beverage), to environmental adaptation (e.g., adjusting the thermostat, operating a fan, adjusting windows and blinds) [33]. The latter is called *adaptive behaviors*, while *non-adaptive behaviours* are energy-related behaviors that enable activities such as computer work in offices or cooking in dwellings [93].

Users have needs and expectations too. Sometimes, users aim to maintain acceptable indoor comfort conditions (e.g., thermal, visual, acoustic, and indoor air quality (IAQ)) in buildings. Objective and subjective aspects can affect their comfort sensation. The objective aspects are related to building properties and environmental conditions, while the latter concerns physiological and psychological attributes. Triggered by all these stimuli, occupants interact with building devices to modify their environment and restore their desired sensation and needs. Occupants have numerous options to interact with their built environment as mentioned before [130, 9]. Besides, occupant behaviour can be an interaction that result is a state change, and no interaction which leaves the current state unchanged as stated in chapter 02 of Wagner et al. [130] book. Occupants' adaptive behaviours consequently affect the indoor environment, user comfort and building energy consumption. This continuous cycle is illustrated in Figure 2.1.

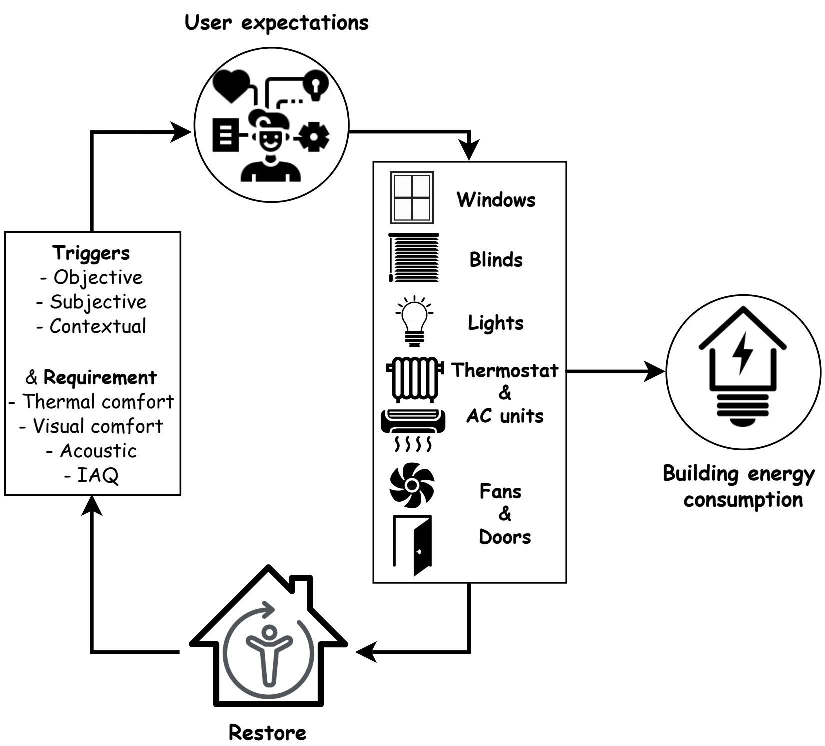


Figure 2.1: Cycle of interaction between the users and the environment [117].

The term "energy-related occupant behaviour" was defined by Schweiker [109] as "human being's unconscious and conscious actions to control the physical parameters of the surrounding built environment based on the comparison of the perceived environment to the sum of past experiences." The perception of comfort is influenced by one's past experiences and expectations [55]. Cultural expectations and context-specific expectations might influence the satisfaction with an indoor environment and confound the interaction between environment and human perception. Thus, satisfaction is achieved by matching thermal conditions in a given context and one's thermal expectations of what indoor environment should be like in the same context [11].

During the last few decades, significant research efforts have been made to evaluate the impact of occupant behaviour on building energy use. In this perspective, the IEA-EBC Annex 66 "Definition and Simulation of Occupant Behaviour in Buildings" was an important initiative to improve occupant behaviour research in terms of data collection, model representation, and evaluation, as well as the integration of OB models in building performance simulation [134]. This is followed by IEA-EBC Annex 79, "Occupant-centric Building Design and Operation," which focuses on investigating and developing occupant modeling in building design and the application and knowledge transfer to practitioners [91]. All research aimed at better understanding of occupant behavior is ultimately of great value to the building design and operation community.

Fully automated vs. personal control

Modern building systems' design and controls are shifting towards increasing building automation to improve energy efficiency while maintaining occupant comfort [121]. Ambient intelligent workplaces have clear economic motivations. For example, energy and cost savings can be gained by turning off the light while no one is in the room or reducing the electric light if there is adequate daylight. However, the energy consumption of the automation system itself may use more energy than the energy saved by the automatic control (e.g., highly efficient LED due to automatic lighting control) [68]. Therefore, fully automatic control is not the complete answer, and technology alone does not necessarily lead to low-energy buildings [29].

The consequence of reducing occupant control and increasing building automation is a topic that has been heavily investigated in the literature [121], where two main arguments emerge. First, Fanger and Toftum [30] argued that occupants with a lower degree of personal control have lower thermal comfort expectations. On the other hand, Leaman and Bordass [72] explained that occupants are "satisfiers," not "optimizers," and they tolerate deviations from ideal indoor conditions as long as they have adequate opportunities to intervene and control their environment. In terms of how occupants react to the automated control system, several studies reveal that occupants commonly override or disable the automated control systems, rendering many automation applications useless. Two different explanations have been proposed in the literature to explain occupants' dissatisfaction with the automation applications: (a) desire for the ability to control and (b) desire for a customized indoor climate [46].

Therefore, understanding the interaction between occupant behaviour and building technologies and identifying the appropriate balance between personal control and automatic strategies are crucial to improving building design and operation [135]. It is not easy to generalize the appropriate balance between personal and automatic strategy since it depends on several factors. Moreover, Day and Heschong [21] reported that there is no clear general tendency for user preferences between manual and automatic controls. The literature has identified two valid principles regarding user acceptance of building automation: automated controls are more accepted (a) if users can override them, and (b) if they meet user preferences; otherwise, they are perceived as strongly uncomfortable [80]. Another way could be to better inform occupants and train them how to interact with the building. As such, their competencies would increase and eventually their satisfaction. In addition, the whole human-building systems' resilience may increase as it is less dependent on error-prone sensors and algorithms.

2.2 Shading systems

Solar radiation and heat gain, which are transferred through the glazed envelope of a building, have a severe impact on thermal and visual comfort in the indoor environment as well as energy performance. For instance, radiant heat from the sun reduces the heating energy consumption in winter while increasing the cooling demand during the summer season. Additionally, glazed surfaces are essential for daylighting to minimize electric lighting in offices; however, excessive and uncontrolled daylight can lead to discomfort issues mainly related to glare. Control of solar gains and daylight is essential, especially in commercial buildings with large glazed surfaces [28, 71, 83]. Therefore, a suitable solar shading is required to reduce solar gains during the cooling season while keeping heat during winter, ensure sufficient and comfortable daylight while preventing glare, view access to the outside, and in some circumstances to provide privacy for the occupants [62, 83].

Shading systems can be applied externally, internally, or inside the glazing (see Figure 2.2). They can be fixed, adjustable, or retractable. Internal shading devices include Venetian blinds, roller blinds, and curtains. They can be used to control glare, provide privacy, and regulate the visible light transmission through the glazed area. External shading devices include shutters, awnings, overhangs, and louvers (horizontal, vertical, or a combination of both, named *egg-crate*). External blind is the most efficient solution for controlling incoming solar radiation. However, many architects do not like the external appearance of the blinds due to uncontrollable changes by various use of them [83]. Inter-pane shading systems are placed between the two panes of the glazing system. They can be Venetian blinds, roller shades, or pleated paper. One of the benefits of in-between-pane shading systems is that the shading device is protected from wind and rain, making it more durable than external shading devices [42]. Moreover, sun protection glass and fixed shading systems work independently from user behaviour, making the building more robust in this respect.

(a) (b) (c)

Figure 2.2: Various types of shading devices (a) combined (internal textile screen and external Venetian blind)[1](b) external and (c) inter-pane Venetian blind [2].

In terms of shade control methods, blinds can be classified as manual, motorized, and automated. A manual blind is the simplest type of blind that can be operated manually and does not incorporate a motorized device. Motorized blinds are operated by a motor and controlled manually using a remote or central operation. Movable blinds, though commonly used, have limitations in reducing energy consumption since occupants tend to operate the blind only when glare makes conditions uncomfortable. On the contrary, sensors can automatically control shades based on indoor and outdoor environmental conditions. Therefore, excessive energy use and glare discomfort can be significantly reduced [65, 14]. Moreover, automated shading systems can play an essential role in balancing various aspects of indoor environmental quality, such as discomfort glare, view to the outside, privacy, thermal comfort, and air quality [7].

From an energy point of view, automatic control of solar shading should be applied in office buildings. Considering that occupants do not tend to change the blind position for short-term events in the external weather conditions, and the blind rate of change is commonly relatively low [95, 124, 20]. Besides, automation is also needed to secure a suitable blind position during summer weekends and other periods without utilization (absence period). A research study confirmed that the building performance was improved by applying dynamic solar shadings on different buildings, and they claimed that dynamic facades are essential in achieving high-performance building [132]. In another study, the potential energy-saving and comfort enhancement when using an automated blind, compared to the employment of a manual one, was experimentally confirmed in an open office building in Korea [65]. Thus, the automated shading system could save energy and improve the indoor environment when properly designed and used. Moreover, simulation results indicated that

[1]https://www.golav.lu/, by Jürgen MÜLLER.
[2]https://www.archiexpo.com

the estimated daily average energy consumption for heating and cooling was considerably higher for manual users than for occupants using the automatic mode [85]. Keeping in mind that all simulation studies depend on context and assumptions in their analysis. A body of research was developed in the area of dynamic solar shading, including the properties and position, the control strategy development, performance testing methods, and measured metrics. A comprehensive review and discussion of methodologies and findings from the recent research effort are presented in the following sections of this chapter.

2.2.1 Automated shading and their control

Automated shading systems utilize a built-in control algorithm to maintain comfortable indoor conditions since the dynamically changing weather conditions are checked continually [65]. The shade control strategy is the logic used to determine how and when to adjust the shading device to improve occupant comfort, lighting levels, glare, energy use, or combination. Besides weather data and indoor environment, recent efforts have used system building performance as input parameter into a control strategy [71]. Usually, the shading device is lowered completely when a chosen parameter exceeds the setpoint and is retracted when the parameter is below another limit value [14]. In general, control modes and threshold values must be carefully selected, considering the facade orientation, use of the building, local weather data, season of the year, and activity of the occupants [127].

In the early 2000s, shading controls were either based on outdoor environmental variations (e.g., direct sunlight, sun position, outdoor irradiation) using "open-loop" controls or "closed-loop" based on feedback from an indoor environment. "Open-loop" controls require low initial cost and don't allow direct user interactions or external inputs; therefore, a feedback loop is absent in its logic. While "closed-loop" controls allow feedback signals and user interventions which increases the initial costs [120].

The shading control strategies can also be deterministic or stochastic. The deterministic control strategies are based on measured or model-predicted quantities. Measurement-based strategies using a simple parameter or multiple criteria are easier to implement. Various shading control algorithms have been used in literature, where some are based on transmitted or incident solar radiation [100, 113], others based on incident radiation and indoor temperature [127]. Among these parameters, solar irradiance or illuminance is the most common parameter used in the solar shading control strategy. The literature suggests a wide disparity among the irradiance values to use, ranging from 100-450 W/m^2, and a variety of locations and orientations to detect the irradiance [64]. Model-based sensors read external real-time information and process it in simulation software (e.g., predicted energy performance, comfort metrics, and potential glare) to adjust the shading position. A good example of implementing real-time, model-based roller shade controls, with multiple visual comfort criteria, intermediate shade positions, and lighting energy use considerations, is presented by Xiong and Tzempelikos [133]. The model-based algorithm can effectively reduce lighting energy use and improve indoor environmental conditions.

Besides deterministic models, stochastic models based on OB can be incorporated within building simulation programs to implement shading operation [69, 43]. For instance, Gunay et al. [44] developed an adaptive model which was based on lab-collected data on occupants interaction with shading devices. According to the findings, the developed adaptive lighting and blinds control algorithm can significantly reduce the lighting loads in office buildings while maintaining the occupant comfort.

2.2.2 Assessing automated shading performance

Different performance metrics and testing methods were used to assess the performance of automated shading devices and associated control strategies. Table 2.1 summarizes previous experimental and simulation-based studies focus on performance assessment of automated shading control strategies.

Many research efforts have focused on shading control evaluation in terms of visual comfort. For instance, Karlsen et al. [64] used vertical illuminance, solar irradiance, and cooling demand measurement as criteria to control shading devices of a combined external and internal Venetian blinds. In the same study, the researchers investigated the Venetian blind with a cut-off strategy of the slats to achieve balance in preventing glare and providing daylight as well as view to the outside. However, they reported that cut-off strategy might be insufficient to avoid glare [62]. In another study, a comprehensive assessment of Venetian blind control strategy were presented by Chan and Tzempelikos [15] considering daylight provision, lighting energy use and visual comfort. The researchers suggest controlling the solar shading according to Daylight Glare Probability (DGP) for providing sufficient glare-free daylight. However, they conclude that this metric is impractical for calculating in real scenes when sunlight falls directly on the occupant. Other researchers suggest vertical illuminance as a successful control for achieving visual comfort since it is a parameter that may dramatically decrease glare without significantly affecting daylight availability [126, 70]. A recent study developed an artificial intelligence algorithm that detects subjective glare discomfort from the image analysis of the videotape of an office occupant's face to achieve glare-free daylight solutions [60].

Alongside the visual comfort, less effort has been placed on evaluation of thermal comfort impacts from automated shading. In a laboratory experimental study, Carletti et al. [14] controlled external Venetian blinds at four predetermined configurations based on external illuminance and temperature in two different periods (spring and summer) for residential buildings in Mediterranean climate to study the impact on indoor thermal conditions. The results showed that the different configuration of the Venetian blind hugely affect indoor thermal and lighting performance. In another study, Van Moeseke et al. [127] investigated the impact on thermal conditions in naturally-ventilated office building using two simulation sets under six different shading and natural ventilation control modes. Simulations have been carried out for a typical year in Belgium. Combined criteria (indoor temperature and solar irradiation) was found to allow more efficient solar gains for heating in winter, limiting the shade operation closure time and increasing daylight inlet. Other studies focused on the impact of shading controls on the thermal environment and air-conditioning energy use. For example, Liu et al. [76] evaluated different control strategies for intelligent facades to optimize comfort performance and minimize HVAC energy demand for an office building.

A number of researchers state the importance of integrating daylight, thermal comfort and energy consumption assessment when selecting a solar shading system and their control strategies, since an appropriate solution might be a combination between these aspects. For instance, a control strategy based on a combination of internal and external shading was evaluated in terms of energy use and indoor environmental conditions using a full-scale experiments [64]. Vertical illuminance at the eye level was used as closure criterion to reduce glare discomfort and a modified cut-off strategy for the slat angle to provide sufficient daylight and view to the outside. The study demonstrated the importance of doing integrated evaluation of energy use, thermal and visual comfort when deciding on solar shading control strategies. Similarly, Atzeri et al. [4] analyzed the impact of the shading systems on visual and thermal comfort as well as total energy consumption using two movable shading systems. Roller shades and Venetian blinds were controlled by two setpoint: glare index and incident solar radiation on the facades. The researchers concluded that external shading application only reduced the PMV values variations since the temperature was controlled with mechanical system.

Recently, simulation-based methods and experimental-based testing methods have been improved and increased, however experimental test methods are still limited in comparison to simulation-based research [71]. Many simulation efforts have focused mostly on visual comfort evaluation and/or energy performance. For instance, Atzeri et al. [3] investigated the performance of different glazing systems coupled with three control strategies for roller shades in a typical office space. The first control strategy was developed using a fully open/closed operation, the other two allowing intermediate positions depending on the sun's position or indoor illuminances. The overall impact of the considered variables (shading controls, window size, glazing properties, and orientation) on comfort metrics and primary energy demand showed that it is possible to balance daylighting, thermal and visual comfort, and energy use. This can be achieved by selecting a control strategy that allow adequate daylight without glare and glazing properties with good thermal and visual performance. Another detailed simulation-based analysis of four shading control strategies based on constant and variable setpoints including the intermediate shade positions was reported in Tzempelikos and Shen [122]. The results showed that it is critical to understand how shading control strategies affect the interaction of daylight provision, lighting energy use, thermal loads and the role of internal heat gains. Recently, a comprehensive simulation-based comparison among different shading control strategies, thresholds and climates was conducted by Tabadkani et al. [120] to study their impact on user comfort and energy load. Results showed that climatic conditions and initial design objectives impact significantly the shading control optimum scenario.

Concerning experimental studies, some have focused on the use of illuminance-based shading control and others on glare-based controls in a full-scale test setup. For instance, Karlsen et al. [64, 62] conducted an experimental study to investigate occupant satisfaction in terms of visual comfort in a controlled chamber in Aalborg, Denmark (latitude 57.02^{o}N, longitude 10.0^{o}E) [64]. Two blind control strategies were used: one simple control strategy with closed slats and one more detailed control strategy with the cut-off angle of the slats. The results revealed that the detailed control strategy was significantly more popular among the participants than the simple one. According to the findings, more effort should be made into finding optimal setpoints for solar shading activation to obtain a more robust control strategy with limited override actions.

Some research have used a combination of experimental and simulation testing methods. For instance, Shen and Tzempelikos [115] tested a simplified shading control-based on the transmitted illuminance from the window- using a full-scale experimental test combined with simulation. Two identical side-by-side offices with adjustable facade and lighting systems, located in West Lafayette, Indiana, were used for the experiments. To maximize daylight utilization while reducing glare, shades move to intermediate position. In another study, real-time tests and computer simulations were performed to study how the shading devices work in controlling air temperature and improving illuminance. Indoor air temperature, visual environment and users' interaction were monitored, and the results were compared to a non-shaded environment in a Jordanian office building, located in sub-tropical area [32].

Another recent study investigated the importance of occupant behaviour (OB) modelling when evaluating the daylight and energy performance of an automated blind control strategies using experimental and simulation-based methods. The preliminary results showed that the energy performance of automated blind control strategies could be overestimated by non-considering occupant overrides. The researcher confirms the need for new OB models to estimate the impact of user override actions while evaluating the performance of automated shading control strategies [78]. Based on the author review, a recent study utilized a Bayesian modeling approach to investigate human interactions with automated shading and lighting systems in terms of override actions [104].

2.3 Occupant interaction with automated shading system

User interaction and satisfaction are two primary factors that cannot be neglected in the development and operation of automated building systems [7]. Occupant satisfaction with automated shading system is influenced by their visual and thermal comfort as well as their ability to control the conditions of their working environment. Their response to automated shading system affects building energy performance [67].

Table 2.1: Selected findings from the literature focused on the performance assessment of automated shading control strategies

Reference	Building type	Location/climatic zone	Season	shading type	Control strategy	Testing methods	Performance assessment
Carletti et al. [14]	Residential building	Italy/ Mediterranean climate	Spring and summer	Venetian blind, two control systems: motorized, and operated by a built-in control algorithm	O: completely packed blind. Open, C-H: closed sheets in horizontal position, C-I45: closed sheets tilted 45, C-V: closed sheets in vertical position.	Full-scale experiment in a test room	Thermal and lighting effects
Karlsen et al. [62, 64]	test facility "the Cube"	Aalborg, Denmark/ temperate climate	May-June 2014 (46 participants)	internal and external Venetian blind	simple control strategy: fully closed, detailed control strategy: cut-off angle of the slats	Experimental-based test	Visual comfort
Atzeri et al. [4, 3]	Open office module	Rome, Italy/ Mediterranean climate	Winter and summer	Three different movable shading system (two types of Venetian blind and roller shade	glare index and solar radiation incident on the window	Simulation-based analysis	Thermal and visual comfort, total building energy (heating, cooling and artificial lighting)
Van Moeseke et al. [127]	South-oriented office room	Belgium /temperate maritime climate	Typical year	External blind in the first set of simulation, an overhang in the second set	Indoor temperature and solar irradiation set	Simulation-based analysis	comfort and cooling demand
Shen and Tzempelikos [115]	Two identical side by side offices	West Lafayette, Indiana / Humid Continental Hot Summers	different sky conditions, sun angles (several months)	Automated interior roller shades	a simplified model-based shading control using as a variable criterion the "effective daylight" transmitted into the space;	Full-scale experiment	daylight metrics, lighting energy use and visual comfort performance
Tabadkani et al. [120]	South-facing office	nine different cities	Annual analysis	Venetian blind	five control variables including direct and incident radiation on window , Workplane illuminance, transmitted solar radiation from window, and view luminance	Simulation-based analysis	User comfort and energy load

2.3.1 Perceived control and comfort of automated shading systems

User acceptance is essential for effective building automation technology adoption, but it is difficult to achieve. It is necessary to find a balance between energy efficiency and occupant comfort, ensuring that people feel comfortable and productive at their workplace while still keeping the energy-saving potential of building automation technology [86]. Perceived control is often included as a factor in technology acceptance models and users satisfaction measures [84]. A recent literature review indicates that many of the existing blinds automation systems fail to improve occupants' visual comfort and reduce the lighting energy use as intended in the design phase [93]. Gunay et al. [45] reported that occupants frequently override or disable these systems, either indicating discomfort or implying their desire for a customized indoor climate or view-to-the outside. Another study found that occupants disabled the automatic mode because they did not understand why the blinds were moving up or down. They felt this was often occurring at the wrong moments [86].

Occupants' perceived comfort is highly affected by the degree of interaction between buildings' users and the shading system. For instance, Sadeghi et al. [105] conducted a comparison study on occupant interactions with shading and lighting systems using four different control interfaces, including a fully automated system, an automated system with manual overrides (via remote control), and manual control (via a wall switch or a web interface). The fully automatic system had the lowest comfort ratings. When manual override was possible or manual control via the web interface or wall switch was available, comfort votes were increased. Similarly, Bakker et al. [7] showed that having the ability to override the automated shading systems manually leads to higher user satisfaction with light levels in the work environment and view to the outside. Additionally, they found that limiting the number of facade movement and associated noise, as these are perceived as a disturbance even when occupants that this intervention is for their benefit, are considered to be more acceptable. Vine et al. [128] found that users prefer manual blind systems to automatic systems and complain about the low level of indoor illuminance caused by automatic closure. These findings were confirmed by Reinhart and Voss [102], demonstrating that occupants accept an automated shading systems when they can raise the blind and increase the view. In general, Tamas et al. [121] indicated that the availability of adaptive opportunities (e.g., movable blinds, operable windows, thermostats) significantly improved occupants' perceived comfort.

One of the studies suggested that an integrated multi-domain approach is required to evaluate occupant satisfaction with the performance of automated shading systems. The authors conducted an exploratory experimental study in a test cell. They found that occupant are satisfied not only if a comfort thermal and visual conditions are reached, but also how it is achieved (i.e., if users perceive the blind actuation as disruptive or not) [79]. While other studies indicated the importance of considering user-accepted solar shading control strategies during building design to ensure realistic building performance predictions [62]. However, there is still limited effort on evaluating shading control strategies in terms of user interaction and acceptance (i.e., few override actions) combined with thermal and visual comfort assessment in an experimental study due to the high cost of sensors and data acquisition.

2.3.2 Triggering parameters

The majority of the research work on occupants' response to shading systems is related to the manual use control, while a limited number of studies related to the use of automated systems [68]. However, findings of studies on manually operated blinds may help conclude automated ones as indicated by Galasiu and Veitch [36]. Many factors trigger occupants to interact with shading devices such as solar intensity and sun position, sky conditions, season, time of the day, view-to-the outside, cooling system, user expectations and preferences, etc. However, a general result on trigger parameters for blind use is still missing because of the various studies on monitored and correlated factors. Nevertheless, some stimuli seem to recur more frequently [118]. In general, previous studies found that occupants may use shading devices to mitigate both visual and thermal discomfort and the need for view and/or privacy. Several authors reported that occupants in offices operate blinds to achieve better visual comfort than thermal comfort [55, 48]. However, it is arguable whether visual or thermal comfort influences more blind operation. Based on previous studies, the primary triggers behind blind use include but are not limited to (see Figure 2.3):

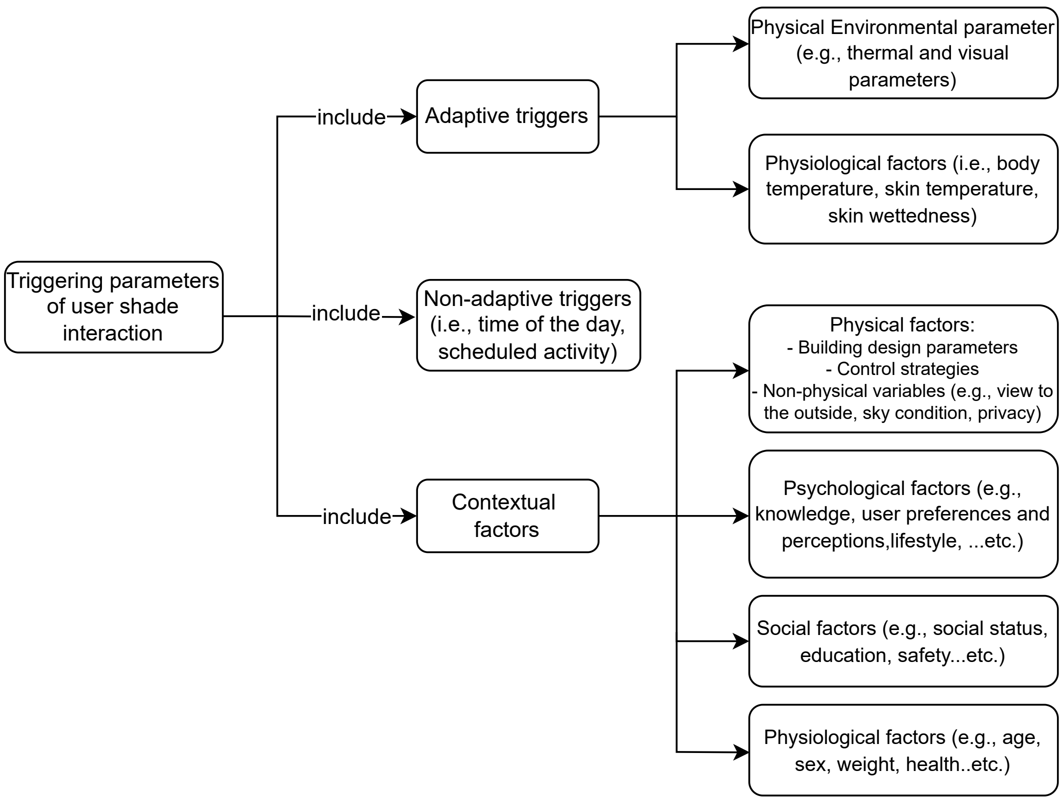


Figure 2.3: Potential triggers and contextual factors influencing user shade interaction

- **Physical/environmental parameters**: A wide range of indoor and outdoor physical parameters was monitored in various campaigns to investigate the triggers of interaction with shadings. Indoor variables include indoor air temperature [82, 136, 55, 56], workplane illuminance [119, 82, 48], vertical illuminance on Visual Display Units (VDU) screens [119], daylight glare index and probability [20], transmitted solar radiation [58, 119], solar penetration depth [58, 102]. Solar irradiance (e.g. direct, global, incident) [82, 119], outdoor temperature [47, 101], solar altitude [136] are among the outdoor parameters which were investigated and found to influence blind adjustments. O'Brien et al. [95] suggested for studies to investigate the nature of transmitted solar radiation rather than exterior one because it is the interior conditions that trigger occupants to control their shades. Other studies described the solar conditions as quantitative metrics (e.g., sunny and cloudy, sunshine index) [31, 57, 75]. Inkarojrit [55] found a significant difference in the frequency and shade position on sunny days versus cloudy days.

  Significant variations between the main drivers behind blind use was found in literature. A reasonable explanation for this contradictions is that occupants use blinds to mitigate both visual and thermal discomfort (excluding the non-physical factors such as view or privacy), which can be caused by temperature, solar radiation, glare, etc. For instance, indoor temperature and incident solar radiation were reported in Mahdavi et al. [82] study to be significant for occupant interaction with shading. In contrast, Foster and Oreszczyn [31] claimed that both variables cannot be a predictor variable for shade deployment. Illuminance (e.g. external, horizontal, global) was found as major driving to modify the blind position. However, more recent studies found significant correlations especially with workplane illuminance [118]. In another study, Zhang and Barrett [136] found a higher probability of shade lowering when incident solar radiation increases, while the one proposed by Gunay et al. [44] presents a decreasing trend. These differences suggest that users' behaviours can be very different for similar physical quantities. These findings suggest that boundary factors (e.g. building exposure, desks position...etc.) have a significant impact on user-shade interaction.

- **Seasonal effect**: Long-term observational studies found significant differences in occupant adaptive behaviors between cooling and heating seasons. Some authors found seasonal effect as a key driver of user-shade interaction when taking the building orientation into account. Zhang and Barrett [136], for example, found the non-north blinds to vary seasonally. On the contrary, Haldi and Robinson [48] reported that the effects of seasonable changes are dependent on other physical parameters such as indoor temperature or daylight level, thus they were found statistically non-significant.

- **Non-physical parameters**: Personal characteristics and human attributes (non-physical parameters) can influence occupant interaction with shading devices. These variables are not measurable with typical sensors, such as view to the outside, privacy, and daylight-health perception. Previous studies found that occupants may tolerate a certain degree of glare as long as the view-connection to the outside was maintained [58, 62]. They discovered that an outdoor view is critical for building occupants' satisfaction. Similarly, Gunay et al. [45] reported that one of the primary reasons for occupants to open their blinds is to increase their view connection to the outdoors. In addition, Rubin et al. [103] stated that the view of the other office buildings could conflict with the preference to maintain privacy. Other researchers [55, 31, 102] reported that occupants' desire to maintain privacy is a secondary reason for choosing blind positions.

- **Contextual factors (facade orientation, floor level, desk-shade position, and control interface)**: Facade orientation was reported as one of the most significant factors that affect blind occlusion [124, 125]. Facade orientation affects the magnitude and temporal distribution of the solar gains. For instance, the south facades receive the most useful solar radiation during the winter, while the north facades receive the least solar gains. Several studies reported that mean shade occlusion was the lowest on north facades and highest on south facades [82, 103, 31]. Additionally, Mahdavi et al. [82] observed a correlation between shade use frequency and facade orientation during a survey in three office buildings in Austria. They found a higher variability of the shade adjustment in east and west-facing offices compared to south and north ones. Regarding floor level, O'Brien et al. [95] suggested a correlation between shade use and office floor level, considering that occupants in higher offices tend to have better views. However, few studies distinguished offices' height, and they did not find any significant conclusions.

  Desk-shade position could affect the shade pattern; for example, the different distances of sitting far from the facade could result in a different behavioural patterns [95]. Escuyer and Fontoynont [27] noticed a high correlation between the position of the computer screen related to the window and the frequency of user-shade interaction [67]. Moreover, the orientation of desks and VDUs is known to significantly affect visual comfort [95]. In terms of control interface, O'Brien et al. [95] reported that providing occupants with easy-to-use shade controls makes them more likely to control them since the effort required to improve the indoor environment is reduced. Moreover, Sadeghi et al. [105] observed a significantly higher number of shade interactions where ease of control accessibility was high (manual control with web interface). Similarly, Sutter et al. [119] observed that remotely-controlled motorized shades were adjusted three times more often than manually operated shades.

- **Social constraints**: The likelihood of adaptive behavior was influenced by sharing the same controlled device with many occupants. According to Day et al. [23], interfaces often affect many people, imposing implicit or spoken social constraints on the degree to which an occupant can adjust an interface for their benefit. For instance, O'Brien et al. [95] reported that office workers are less engaged in their interaction with shades due to perceived or real social constraints (i.e., concerns of annoying office mates). Similarly, Haldi and Robinson [48] found that the shades of single-occupancy offices were adapted more frequently to changing indoor illuminance levels than shared offices.

- **Time of the day**: Occupants tend to occupy offices during the daytime, where the solar geometry varies cyclically over the day, thus affecting the daily patterns of shade use. Moreover, the frequency of shade interactions was significantly different between arrival, intermediate, and departure in relevant studies [48, 20]. Inoue et al. [58] reported that shades on east facades are usually closed by occupants upon arrival but gradually raised during the day, while the opposite occurs for the west-facing offices. On the contrary, Rea [99] reported that time of day had minimal effect on shade position since occupants make little effort to change it during the day.

- **HVAC system and lighting control**: Most studies have found that occupants rely less on adaptive behaviors -either by choice or necessity- when HVAC and dimming lighting systems are available. The presence of an HVAC system may affect the adaptive behaviours since occupants do not need to take as many if comfort conditions are automatically provided [46]. For instance, Inkarojrit [55] observed that occupants in mechanically air-conditioned spaces tend to use the blinds less than in buildings with natural or hybrid ventilation systems. In contrast, the occupants are more likely to use blinds to achieve thermal comfort. In terms of automated lighting control, Eilers et al. [26] found that occupants without automatic lighting control were much more likely to leave their shades closed, while those with automatic lighting control were much more active shade users.

- **Physiological factors**: such as individual ability to adapt to the changing physical environment, thermal and visual preferences, age, and gender [55]. Findings from previous studies suggest that age affects the visual performance. For example, Bennett [10] reported that old people were more sensitive to discomfort from overall bright lighting systems than young people. Moreover, several studies indicate that ideal thermal conditions for the elderly people are different from those of young people [108]. In addition, gender plays a role in perceiving the thermal environment. In general, females are more sensitive for cold conditions and deviations from the individual ideal conditions than males [107]. However, studies in ASHRAE Handbook [51] revealed that the thermal conditions preferred by old people and females do not differ from those preferred by young adults and males.

2.4 Findings based on data collection methods

There are numerous methods of collecting occupant-related data to understand occupants' behaviour in buildings, such as in-situ monitoring studies, laboratory studies, surveys, and virtual reality [130]. In the current research, a laboratory experimental study and an in-situ monitoring study are deployed to investigate occupant behaviour related to the use of automated shading systems. Virtual reality[3]approach is not in the scope of this research. This section introduces an overview of each approach, followed by the state-of-the-art.

2.4.1 Findings from laboratory experimental studies

Overview

One of the approaches used to investigate the relationship between occupant interaction with automated shading systems is using controlled chambers to conduct experiments. A laboratory experiment is a full-scale environment that resembles typical spaces of interest. A number of occupants participate in the study by spending time in laboratory spaces and interacting with the indoor climate designed for scientific research purposes (e.g., building performance, occupant behaviour, and comfort). The Technical University of Denmark (DTU), btga-box of Wuppertal University, and LOBSTER of the Karlsruhe Institute of Technology are examples of climatic chambers for occupant behavior studies [41].

Laboratories are flexible to manipulate layout, material, control systems, indoor environmental conditions, and orientation (some test facilities are rotatable). In laboratories, indoor environmental conditions are often tightly controlled, particularly to study adaptive opportunities. It is easy to quantify skin temperature, mean radiant temperature, and air velocity, which is impractical or costly to measure in in-situ monitoring studies. Moreover, the social constraints (presence of other colleagues) that influence adaptive behaviours can be measured efficiently. However, the construction and operation of laboratories as well as the recruitment of volunteers are both expensive [41, 130]. Despite the significance of findings reported from these controlled experiments, they are not necessarily applicable for broader usage due to inherent limitations. For instance, participants usually know in advance that they only have to use these spaces for a short predefined period, which may alter their comfort perceptions and interactions with building controls due to the "Hawthorne effect"[4][121]. Schweiker and Wagner [112] reported that the generalizability of the inferences and mathematical OB models in laboratory studies is not well-established.

State-of-the-art

Several efforts have been made to evaluate user satisfaction and interaction with controlled shading using experimental testing [64, 62, 105, 86, 44, 104]. Table 2.2 summarizes related

[3]Virtual environments use computer-based 3D special effects to mimic the actual world by giving users a sensation of presence as if they were in a real space [41].

[4]Hawthorne effect is the notion that knowledge of being studied affects occupants' behavior.

previous studies in controlled laboratories. One of the earliest studies is the experiment conducted by Kim et al. [65] in two mock-up test rooms in the summer season to determine whether occupant comfort and environmental performance can be improved by applying an automated Venetian blind compared to a manual or motorized one. The pattern used with motorized blinds was established based on a survey, conducted over four days at a high-rise building in Seoul, Korea under a temperate climate. The potential energy savings and the comfort enhancement when using the automated blind were confirmed, and the insufficiency of the automatic control algorithm was found out. Another experimental study was conducted by Lolli et al. [77] in two cell offices to investigate occupants' satisfaction with indoor brightness under two control strategies (fully automatic and manual) for blind and ceiling lights use. 11 participants took part in the experiments over 36 days under a Nordic climate and high latitude sky conditions. Results show that the use of the automatic control strategy led to a higher visual and thermal discomfort, although a high average operative temperature did not cause the latter.

A new interface was assessed by Meerbeek et al. [86] in terms of user satisfaction and use of automated blinds at various levels of automation and types of system expressiveness (via interface). The experiment was conducted in the ExperienceLab of Philips Research, which mimicked an office environment with a virtual window. The results revealed that using expressive interfaces -providing information to the end-user about the intentions and actions of the automated systems- could increase users' acceptance of automated blinds and so achieve the predicted energy savings. Gunay et al. [44] developed an adaptive lighting and blinds control algorithm based on the occupants' illuminance preferences learned from their light switch-on and blinds closing behaviors in ten private offices. The developed algorithm was first tested inside a controlled laboratory of shared office space, then implemented inside controllers serving five private offices. The results indicated that the developed adaptive control algorithm could substantially reduce the lighting loads in office buildings without compromising occupant comfort [44].

During another experiment, 26 participants were subjected to multiple test scenarios in a daylight laboratory at Eindhoven University of Technology, Netherlands. Varied time intervals and discrete steps with pre-determined positions for roller shades was used to examine user satisfaction and distraction caused by shade movement. They found that less frequent façade configuration was significantly better appreciated than smooth transition at a higher frequency. They showed that manual override is required for the operation of dynamic facades [7]. Another experimental study in a south-oriented test room in Denmark was conducted with the use of self-reported surveys of 40 participants combined with physical measurements under Nordic climate. The authors found that building occupants emphasized the view-to-the outside as a critical factor for satisfaction, and they could tolerate a certain degree of glare as long as the view was maintained [62, 64].

Table 2.2: Summary of related previous studies from controlled laboratory experiments

Study reference	Facility/Location	shading system	Study period	participants number	methods	Experiments setups	IEQ/comfort parameters
Kim et al. [65]	mock-up test rooms located on the top floor of a building at Seoul National University in Seoul, Korea	Internal Venetian blinds	August, 2006	24 subjects	Monitoring, self-reported questionnaire	6 cases were tested: a combination of automatic mode vs. manual mode with and without cooling.	thermal and visual comfort, energy consumption
Karlsen et al. [62]	the Cube, Aalborg University, Denmark	internal and external Venetian blinds	May–June 2014	40 subjects	physical measurements and occupants surveys	(1) a simple control strategy. (2) a more detailed control strategy.	visual comfort and user satisfaction
Lolli et al. [77]	ZEB Test Cell Laboratory, Trondheim, Norway.			11 participants	measurements, computer-based questionnaire	two different control strategies (fully automatic and manual) for blind and ceiling lights	thermal and visual comfort.
Bakker et al. [7]	daylight laboratory at Eindhoven University, Netherlands	Interior roller shades	April and May	26 test subjects (10 male, 16 female)	Monitoring, questionnaire	Eight different test scenarios	daylight aspects and visual performance.
Gunay et al. [44]	10 offices to develop an adaptive lighting and blinds control algorithm, five private offices and a controls laboratory to test the algorithm.	Interior roller blinds	1 year	N/A	Monitoring	(1) the adaptive occupant learning blinds and lighting control algorithm developed in this paper and (2) a more traditional control method whereby the blinds and lighting were operated by the occupants.	blind operation, user satisfaction
Meerbeek et al. [86]	ExperienceLab of Philips. Eindhoven, Netherlands	motorized blinds system with manual override via a tablet	N/A	48 participants	questionnaire, semi-structured interview	C0:high automation C1: low automation (gradual) C2: medium automation (gradual) C3: low automation (pulsating) C4: medium automation (pulsating)	user interaction and satisfaction with the blinds.
Sadeghi et al. [105]	Four identical private offices, West Lafayette, Indiana	motorized roller shades	40 days, April 1st and June 15th 2015	147 office occupants	monitoring, web-based questionnaire	Four setups ranging from fully automated to fully manual and interfaces with low or high level of accessibility (wall switch, remote controller and web interface)	visual comfort and satisfaction.

2.4.2 Findings from in-situ monitoring studies

Overview

In-situ studies involve monitoring occupants in their typical workplace environment during a short or long data collection period (weeks or years). In-situ monitoring techniques for data collection include observations and surveys. Monitored data are acquired through built-in sensors as part of building automation systems (BAS), or stand-alone sensors operate independently from other systems for data acquisition, storage, and maintenance. Survey studies actively involve occupants in the monitoring study by self-reporting personal behaviours, either by filling out a questionnaire or through interviews and focus groups. Surveys can show the logic and explanation behind user habits and behaviours in ways that sensor-based methods do not. However, misinterpretations of questions may cause occupants to misreport things [41]. Both built-in sensors and surveys are cost-effective methods for collecting data. In general, in-situ studies are preferable for replicating reality and reducing the *"Hawthorne effect"*. However, existing occupied spaces limit the flexibility of experiments and sensor replacement, reducing accuracy and introducing errors. Ethics, participants' recruitment, and informed consent are crucial challenges for this approach as well as for laboratory experiments [130].

State-of-the-art

In-situ monitoring of occupant behavior is one of the most effective and widely used research methods. However, there are limited published design and post-occupancy evaluation (POE) studies on buildings equipped with dynamic facades [67]. Table 2.3 summarizes in-situ monitoring related case studies.

Reinhart and Voss [101] investigated the use of automated shading systems with the possibility to override the system in 10 south-west facing offices in Germany. The shade lowering threshold was set above 28 klux (vertical illuminance on the facade). The participants were informed that their blind use was monitored. Based on 174 weekdays observations, the authors reported a mean of 3.7 blind movements per day per office. They attributed the high rate adjustments to user corrections to the automated system (48% of the automated blind adjustments). Moreover, they found that people are more likely to accept automatic retracting than lowering blinds, where 88% of user corrections were reopening the blinds after an automated closure occurred. This was explained due to the electric dimming lighting that provides a minimum of 400 lux on the workplane. Lowering of the blinds was only accepted if incident radiation was higher than 450 W/m^2 or if direct sunlight on the workplane was above 50 W/m^2.

On the contrary, Lee et al. [73] found that 70% of all actions were taken to lower the blind in a post-occupancy evaluation of the automated interior roller shades in the New York times company. A year-long monitored study was carried out to verify energy efficiency, evaluate occupant comfort and satisfaction with the indoor environment, including the automated shading operations. They reported that 80% of shade motors were overridden on average of

18 times per year for a total of 38 hours per year (4.7 adjustments per day). The motors were overridden on average of 199 times each year for the remaining 20% of the same motor groups, for a total of 757 hours per year (2.6 adjustments per day).

In another monitoring field study, Sutter et al. [119] reported a survey on how occupants operate the remote-controlled motorized blinds in 8 individual southeast-facing offices in France over 30 weeks. Concurrently, seven offices equipped with manually controlled fabric blinds during the same period were monitored. A total of 832 blind adjustments with an average of 2.1 per day per office was observed. They found that remotely-controlled blinds were used three times more than manually-controlled fabric blinds. Similarly, Meerbeek et al. [84] performed a field study on motorized exterior blinds in 40 shared offices over 100 working days in the Netherlands. A total number of 3433 (average of 0.63 per office per day) external blind adjustments were recorded, where the users triggered 73.6%. They explained the high rate of user adjustments that the majority of the users switched off the automatic mode and did not use it during the study period.

Sadeghi et al. [105] conducted a field study on human interactions with motorized rollers shades and dimmable electric lights in four identical south-facing private offices of a high-performance building over 40 days (9:00 am - 4:00 pm), covering a wide range of sky conditions. Four different control setups were considered, ranging from fully-automated to fully manual, and interfaces with a low or high level of accessibility (wall switch, remote controller, and web interface). The authors found significantly higher interactions when easy control accessibility was high (manual control with web interface). The results showed a strong preference for customized indoor climates instead of automatic operations.

Grynning et al. [42] investigated the visual comfort and quality of daylight in three modern office buildings in a Nordic cold climate using a combination of quantitative and qualitative methods. These buildings were selected to represent different solar shading solutions or combinations (e.g., fixed exterior shading, external Venetian blind, and internal roller shades). The authors found that automatic shading can be regarded as a source of discomfort due to the lack of manual override control possibilities and disturbances caused by the system moving up and down. According to the users, the external fixed shading is a good and satisfactory system for south-facing offices when interior roller shades can solve local glare issues.

Gunay et al. [44] conducted a monitoring study in ten west-facing private offices from an academic office building in Ottawa, Canada. The light switch, internal blind position, occupancy, indoor illuminance, and solar irradiance data were analyzed to develop an adaptive lighting and blind control algorithm using discrete-time Markov logistic regression models. The algorithm was applied inside controllers serving five offices and a controlled laboratory to assess energy performance and occupant comfort.

To summarize, most of the observed buildings are offices located in high latitude regions (e.g., a temperate or Nordic climatic zones). The study period was often in the summer season with limited focus on annual analysis. The majority of monitored offices are facing south or south-east direction and are located on the lower floor levels. The researchers investigated different occupancy patterns (single-occupancy offices and shared offices). Offices' windows are equipped with automated shading systems such as external Venetian blinds, inner roller shade, or a combination.

2.5 Occupant-centric shading design

Occupant-centric refers to placing occupants and their well-being as crucial throughout the building life-cycle. The integrated design process would ensure better occupant comfort and satisfaction while limiting occupants' adaptive actions that may have negative impacts on overall building performance [121]. Therefore, addressing anticipated occupants' needs and comfort should take place early in the design process. Occupant-centric building research encompasses both the design and operation phases of the buildings. The first investigates design features and strategies that maximize occupant comfort, while the latter focuses on operation strategies (e.g., post-occupancy) to achieve similar or other occupant-centric goals [5].

Studies have focused on developing statistical models for occupants' interaction with shading systems throughout the last two decades [48, 56, 104]. A research effort was made to implement OB models in BPS to improve energy predictions' accuracy and decrease the performance gap. Due to their implementation difficulties and stochasticity of results, OB models have been seldom adapted in building design practice. However, some researchers demonstrated that a building design, regardless of the accuracy of the occupant models, can be tested over different occupant users by repeating the simulations with occupants re-sampled from a generic occupant behavior model [53, 90]. A research effort is ongoing by IEA EBC Annex 79 entitled "Occupant-centric building design and operation" to promote the implementation of enhanced occupant modeling in building design and operation to improve building performance and occupant comfort [91].

The simulation-based analysis is a promising approach that can be used to support occupant-centric decision-making during design and operation. In parallel, analytical methods are developed to leverage the power of the simulation tools and extract efficient design and operation strategies [5]. These include –but are not limited to– parametric studies, sensitivity analyses, optimization, and robust building design practices [96, 98]. For instance, Buso et al. [13] investigated how different OB models impact the building performance under 15 different design options for an office building in three different climates in terms of building robustness[5]. The authors implemented stochastic models of a window opening and shading use developed by Haldi and Robinson [47] in the dynamic simulation tool (IDA ICE). They concluded that the design options with high thermal mass and smaller windows yielded the greatest robustness against OB. This is important for designers to optimize building design parameters for more accurate energy predictions. In a more focused manner, O'Brien and Gunay [94] aimed to show that increasing comfort may minimize energy consumption by reducing the number of adaptive actions. They showed that fixed exterior

Table 2.3: Summary of in-situ monitoring related studies

Study reference	Building use	Location/climatic zone	Monitoring duration	Offices' number	Type of offices	Office orientation	floor level	Type of shading	Control set-point	Daily "rate of change" per office	Ratio of over-ridden automated blinds
Reinhart and Voss [101]	Office	Germany /temperate climate	174 weekdays (Mar-Dec, 2000), almost annual study	10	private and two- person offices	South	ground and 1st floor	External Venetian blind	28 Klux	3.7 blind adjustments	48%
Lee et al. [73]	52-story office building	Manhattan, New York /humid subtropical climate	One year monitoring study (2011-2012)	10	open plans near the windows and private offices in the building core	north, east and south, west	20^th floor	upper and lower interior, motorized roller shades	N/A	80% of shade motors:4.7 adjustments per day, 20% of the same motor groups: 2.6 adjustments per day	25%
Meerbeek et al. [84]	Office	Netherlands/ temperate climate	21 working weeks (July-Dec, 2011), Summer and Autumn	40	two- and three person offices	south	3^rd to 7^th floor	individual manual indoor roller shades and external blinds	16 Klux	0.63 blind adjustments	73.6%
Sutter et al. [119]	Office	Lyon, France/ humid subtropical climate	30 weeks (Jan-Sep, 2002), Winter, spring and summer	8	single offices	south-east	six in GF and two in 1^st	motorized remote-controlled black louver blinds	N/A	2.1 blind adjustments	N/A
Gunay et al. [44]	Office	Ottawa, Canada/semi-continental climate	seven months-one year	10	private offices	west	N/A	manually controlled top-down roller shades	N/A	N/A	N/A
Inkarojrit [55]	Office	N/A	seven months-one year	10	private offices	west	N/A	interior Venetian blinds	N/A	N/A	N/A

shading might reduce the frequency of daytime glare and so prevent occupants from closing blinds using a formal robust design method. This improves daylight availability and reduces dependence on electric lighting.

Shen and Tzempelikos [114] conducted a sensitivity analysis for private offices with automated interior roller shades to identify the most critical factors in terms of daylighting and energy performance (e.g., glazing size and properties, shading properties, and control, climate, and orientation). Using an integrated thermal and lighting building simulation model, four different automated shading control strategies with constant and variable setpoints were developed and analyzed. The results showed that (a) controlling shades based on illuminance thresholds are more appropriate than the commonly used solar radiation threshold, (b) different ranges of energy consumption between control strategies depending on glazing and shading properties, and (c) different strategies should be used in a different orientation. In another study, Karjalainen [61] focused on understanding the role of Venetian blinds as a part of a building energy system. Annual simulation-based analyses were performed to evaluate different solar shading control strategies, including a new control strategy developed in the study to minimize energy consumption. The heating, cooling, and lighting demand in four European climates in three single-family houses with two window sizes were calculated. The results showed that the new control strategy leads to the lowest total energy consumption in all simulation cases. This is valuable for designing automatic control of blinds and advising occupants towards energy-efficient use of manual blinds.

Some studies focused on developing methods to improve OB modeling during building design. For instance, Gaetani et al. [33] conducted a simulation-based study to combine OB modeling and the adaptive facade design process. The authors applied the fit-for-purpose OB method (FFP-OBm) for six solar shading control strategies. Based on irradiance lowering thresholds and energy-saving modes, these control strategies were evaluated to select the best-performing shading control strategy. Two additional strategies: fully open and fully closed, were added to the analysis for benchmarking. The results show that an advanced occupancy model is needed to select and evaluate the best-performing shading strategy. The authors consider it a step towards developing robust methods to assess the performance of adaptive behaviours such as occupancy presence.

2.6 Concluding remarks

Based on the aforementioned literature review of automated shading systems, their control strategies, common used thresholds, and testing methods, user interaction and satisfaction, the following key research gaps can be summarized:

[5] Robustness is “the sensitivity of identified performance indicators of a building design for errors in the design assumptions” [52]

Shading system control strategies and their assessment

- Previous studies state the significance of making integrated evaluations of daylight, thermal comfort and energy use when selecting an optimal solar shading control strategies in terms of user comfort and energy efficiency. However, limited focus was on the impact of automated shading controls on thermal comfort and user acceptance.

- Both simulation-based methods and experimental-based testing methods have been used to assess the performance of automated shading controls; however, experimental studies are still limited due to the high cost of sensors and data acquisition.

- Few studies evaluated shading control systems regarding occupants' acceptance, preferences, or satisfaction. Additional research on occupants' interaction and their consistency with commonly used metrics is needed to find optimal shading control strategies with limited override actions.

- Based on the researcher review, non of the previous studies examine the quality and performance of shading control hardware devices.

User interaction with automated shading systems

- Most of the reviewed experimental and field studies are conducted in high latitude regions (e.g., temperate and Nordic climates), while few studies address shading control and operation in tropical and Mediterranean areas where high solar radiation and long sunshine duration on the facades.

- As outlined by previous studies, different methods are used to increase users' acceptance and achieve the predicted energy savings (e.g., expressive interfaces and adaptive control models). Moreover, less frequent facade operation, ability of manual override, and maintaining view-to-the outside are critical factors for occupants' satisfactions and less override actions.

- Monitoring studies in the literature are mostly focused on predicting occupant behaviour models from empirical data, rather than extracting useful lessons for both design and operation[40]. Moreover, there are limited published design and post occupancy evaluation studies on buildings equipped with dynamic elements in their facades with the possibility to override these systems [67]

- Parametric studies, sensitivity analyses, optimization, and robust building design practices are simulation-based approaches to support occupant-centric design. However, there is still a need to test new methods in different design and operation phases of buildings to transfer valuable feedback to the practitioners and researchers.

Chapter 3

Current practice of automated shading systems and their behaviour

This chapter presents the common practice of designing and operating automated shading systems in commercial buildings. First, the configuration of automated shading systems was investigated in nineteen case studies using a short questionnaire. Then, the shading system behaviour was evaluated in one of the case studies, the Luxembourg building. Additionally, two commercial devices were examined for their quality and accuracy. Finally, this study analyzed the impact of different shading control strategies on one zone office's annual heating and cooling demand and hours of undisturbed views to the outside using simplified simulation tools (e.g., SimRoom and Variantas). The results show a difference between shading system behaviour in simulation (accurate) and building practice due to limited hardware quality, light sensors' location and inclination, etc. Based on these results, it is recommended for building designers and operators to consider the quality and performance of shading control devices to avoid conflict between the established shading thresholds and occupants' acceptance.

3.1 Introduction

The building sector is recognized as one of the primary energy consumers as commercial and residential buildings account for 31% of the global final energy demand [123]. The energy use of offices differs from those of residential buildings. Due to the intensive use of HVAC systems and offices equipment, commercial buildings consume more energy per occupied floor area [129]. Many modern commercial buildings are designed with highly glazed facades, which have an impact on the buildings' energy demand for more than 50-70% of the overall energy use [18]. Dynamic facades represent a promising solution for improving indoor thermal and visual conditions as well as saving energy for cooling and lighting, particularly in office buildings with large transparent facades [14].

Due to the multi-aspects of dynamic facades and the highly-individual response of occupants, designing for user interaction with dynamic facades is a challenging task since conflicts and inconsistencies often arise [21]. In the literature review, two different types of conflicts have been identified when occupants interact with dynamic facades: (a) conflicts among users concerning their control (e.g., in shared or open space offices), and (b) conflicts between users and automatic control strategies [80]. For instance, Karlsen et al. [62] found conflicting results between the established metrics and comfort thresholds of automated shading systems and what occupants have reported as acceptable [71]. This conflict could result from different users' preferences or/and the behaviour of the shading device itself. Some commercial light sensors are not suitable for sun protection control. To this end, the focus of this study is to investigate the current practice of automated shading systems in commercial buildings to address the following sub-objectives:

- To define the configuration and general characteristics of automated shading systems during the design and operation phase.
- To examine the quality and accuracy of commercial shading control devices using monitoring and experimental studies.
- To analyze the annual heating and cooling demand and visual performance of commonly used irradiance thresholds in terms of user types (i.e., passive, medium, active), space orientations, window-to-wall ratio (WWR%), and climatic zones.

3.2 Common practices of shading design and operation

This section introduces the method used to investigate the configuration of automated shading systems in 19 case studies and the main findings of the analysis.

3.2.1 Methods

A questionnaire was conducted in nineteen case studies (18 in Germany and one in Luxembourg) to investigate the configuration of automated shading systems in commercial buildings. The case studies are selected based on their types, locations and the use of automated shading systems. The case studies are Freiburg city town hall, KIT mathematics building, Luxembourg building, Kreis Mettmann, Kreishaus Siegen Building, HC Building, and 13 office buildings in Forschungszentrum Jülich. All are located in a temperate oceanic climate (cfb) zone according to Köppen-Geiger's climate classification. Table 3.1 represents the general information of some of the case studies.

The questionnaire was issued via email or paperwork for building operators or managers. The questionnaire includes two parts. The first part covers the general information about the building (e.g., location, construction year, floor area, type of solar shading system, etc.). The second part includes a set of questions about the shade operation time per day/week, brightness and wind speed upper and lower thresholds, hysteresis time, delay time, and the location of the installed weather stations (see Appendix A1.1).

Table 3.1: General information for 8 of 19 case studies.

CASE STUDY	FREIBURG CITY TOWN HALL	KIT MATHEMATICS BUILDING	LUXEMBOURG BUILDING	KREIS METTMANN
PICTURE				
BUILDING TYPE	Office Building	Educational Building	Office Building	Office Building
LOCATION	Freiburg, Germany	Karlsruhe, Germany	Niederanven, Luxembourg	Mettmann, Germany
CONSTRUCTION YEAR	2017	2015 (renovation)	2017	2017
DESIGN COMPANY	Ingenhoven Architects	Ingenhoven Architects	Goblet Lavandier & Associes ingénieurs-conseils	Eiffage Infra-Hochbau Gmbh
GROSS FLOOR AREA (GFA)	26,115.0 m^2	14,800 m^2	2,594 m^2 (Energy reference area)	5,011m^2
TYPE OF SUN PROTECTION	External vertical lamellae with blinds behind them.	External Venetian blinds	External Venetian blinds and inner glare protection	External Venetian blinds
SHADING SYSTEM				
CASE STUDY	KREISHAUS SIEGEN BUILDING	HC BUIDLING	FZJ/BUILDING NO. 4.11	FZJ/BUILDING NO. 01.30-Z
PICTURE				
BUILDING TYPE	Administration building	Educational building	Research institute	Research institute
LOCATION	Siegen, Germany	Wuppertal, Germany	Juelich, Germany	Juelich, Germany
CONSTRUCTION YEAR	2006-2010	2014-2016	2013	---
DESIGN COMPANY	Goebel Architekten Assoziierte	Kadawittfeldarchitektur Company	---	---
GROSS FLOOR AREA (GFA)	17,178.55 m^2	3,950 m^2	---	---
TYPE OF SUN PROTECTION	External Venetian blinds	Venetian Blinds (External and internal)	External Venetian blinds	External Venetian blinds

3.2.2 Case studies analysis

In 90% of the case studies, the shade operation was all days over 24 hours, while in some cases, it was limited to daily working hours. For instance, the operation hours of the automated shading system in the Luxembourg building are from 6:00 am until 8:00 pm every day. Brightness and wind speed measurements are either single permanent measurements or cyclic intervals. Figure 3.1 shows the commonly used brightness thresholds of shade lowering and raising. It is observed that the brightness lowering threshold was in the range of (25-65) klux, where the most frequent thresholds were 35 and 50 klux. The brightness raising threshold was (15-40) klux, where the most frequent thresholds were 15 and 30 klux. The delay time to lower the blind was often used as 1 min, 5 mins, or 20 mins, while 15 mins were the most often used delay time for shade raising. Brightness lowering thresholds: 300 W/m^2 (approximately 33 klux) and 450 W/m^2 (approximately 50 klux) are both evaluated in the experimental study (Chapter 4).

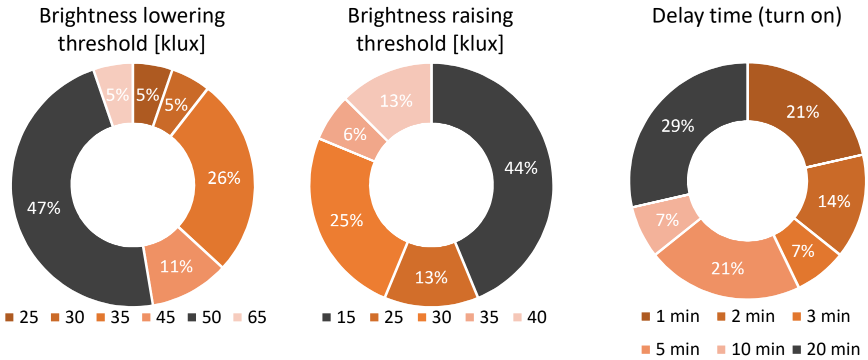


Figure 3.1: Brightness thresholds of shade operation (19 case studies).

The shade is often raised when wind speed exceeds 10 m/s as upper threshold (26% of the cases) and 0 m/s as lower threshold (58%) (see Figure 3.2). The delay time was in the range of 3 secs to 15 mins to activate the blind. Some weather sensors are installed in each facade (e.g., KIT mathematics building), while most of the weather sensors are mounted on the roof surface of the building facing different orientations.

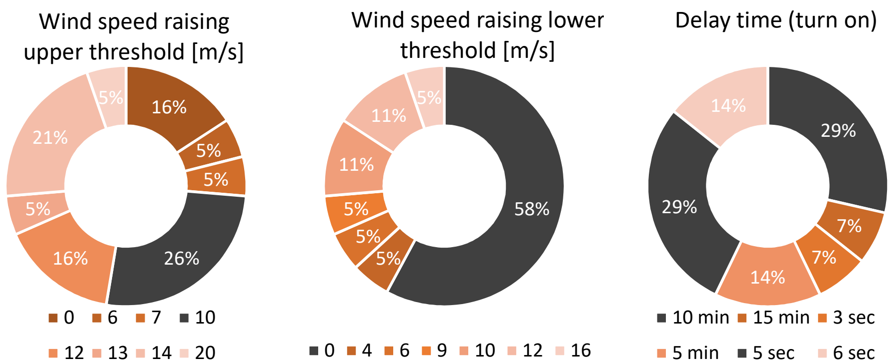


Figure 3.2: Wind speed thresholds of shade operation (19 case studies).

3.3 Shading system behaviour

The automated shading systems are activated in response to their sensors' measurements of weather conditions (e.g., outdoor air temperature, brightness, wind speed, and precipitation) or indoor parameters (e.g., indoor temperature). Weather fluctuations, the mounting position of the weather station, inclination and orientation of brightness sensors, and the shade from surrounding structures (e.g., buildings, trees) are the main reasons behind the different behaviour of shading control devices. Moreover, the quality and accuracy of the physical sensor itself could affect the behaviour of shading control devices. Consequently, occupants and buildings might behave differently due to different sensors' signals. To this end, the performance of automated shading systems was evaluated in one of the case studies, the Luxembourg building. Additionally, an experimental study was conducted to examine the quality and behaviour of two commercial shading devices.

3.3.1 System behaviour: Luxembourg case study

This study evaluates three commercial light sensors: the Elsner KNX pyranometer, Warema multi-sense weather station, and MWG pyranometer. These sensors are mounted on two masts in the middle of the building rooftop (see Figure 3.3). Elsner KNX and MWG pyranometer measure global irradiance, perceived as heat (watts per square meter). WAREMA measures values for brightness, wind speed, precipitation, and temperature. Both Elsner KNX and MWG pyranometer are mounted to measure parallel to the façade. WAREMA weather station had four photodiodes placed at the right angles to the building facades. The photodiode 1 is used for the dawn/dusk control, facing northward. For more technical information, see Table 3.4. Elsner KNX is used to activate the external Venetian blind on each facade of the building. The analysis of shading system-triggered actions are presented in Chapter 5, Section 5.4.2.1.

Table 3.2: Technical information about the shading control devices.

Device	Measurements	Range	Accuracy	Orientation/angles
Elsner KNX pyranometer	Global irradiance	0-2500 W/m^2	± 15% of the measured value at above 150 W/m^2	Parallel to the building facade
WAREMA multi-sense	Brightness using photo sensors	0-100 klux	± 1 klux	The four photo-diodes directed to the building facades, photodiode 1 face northward to measure dusk
	Wind speed	0-25 m/s	± 1 m/s	
	Temperature	(-30 to +60) °C	± 2 °C	
	Precipitation	yes/no		
MWG pyranometer	Global irradiance	0–1400 W/m^2	± 2 %	Parallel to the building facade

Figure 3.4 indicates that the hourly profile of solar irradiance -measured by the three commercial devices- was different during a reference day. This behavior may result from (a) different position and inclination angles of each light sensor and (b) the quality and accuracy of the sensor itself. One sample t-test was performed on the monitored datasets

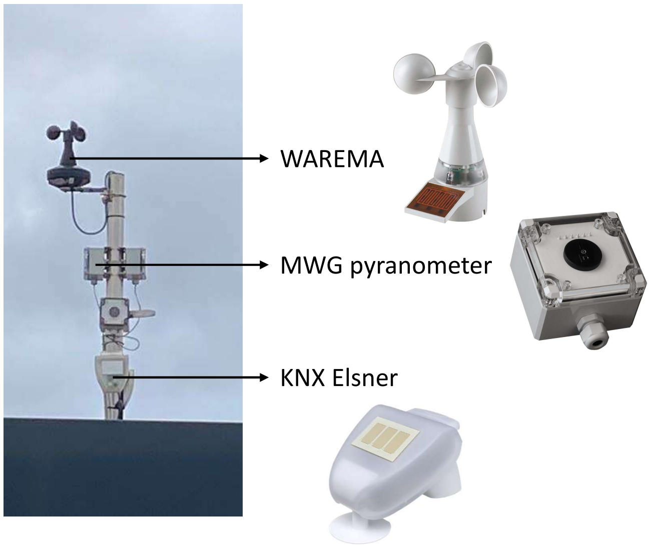


Figure 3.3: WAREMA, pyranometer, and KNX Elsner weather stations.

to examine the accuracy of the three light sensors using SPSS software. Briefly, one sample t-test compares the mean of your sample data to a known value to determine whether the two means are significantly different. The following hypotheses were tested:

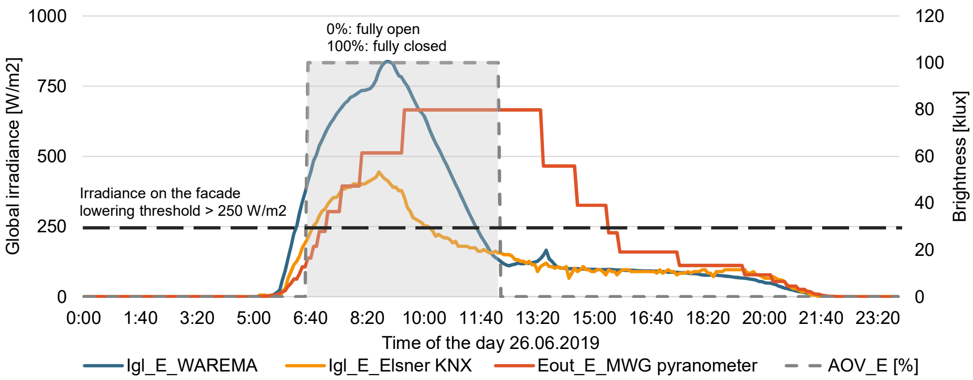


Figure 3.4: Hourly profile of signals measured by Elsner, Warema, and pyranometer during a reference day in east elevation.

- **Hypothesis 01**: Irradiance threshold on the facade of shade raising

  Null hypothesis: irradiance threshold of shade raising [AOV=0%] is higher than 250 W/m^2 (27.5 klux).

  Alternative hypothesis: irradiance threshold of shade raising [AOV=0%] is below 250 W/m^2.

- **Hypothesis 02**: Irradiance threshold on the facade of shade lowering

Null hypothesis: irradiance threshold of shade lowering [AOV=100%] is below 250 W/m^2 (27.5 klux).

Alternative hypothesis: irradiance threshold of shade lowering [AOV=100%] is higher than 250 W/m^2.

Table 3.3 summarizes the results of one sample t-test. It is concluded that null hypothesis 01 was rejected in all cases (p-value < 0.05). This result indicated that the mean of solar irradiance on the facade -at the moment of shade raising- was significantly below 250 W/m^2. Similarly, null hypothesis 02 was rejected in all cases (p-value < 0.05). This result indicated that the mean of solar irradiance measurements -at the moment of shade lowering- was significantly higher than 250 W/m^2.

Table 3.3: Summary of one sample t-test results.

Parameters	Mean	SD	t_value	P-value	test mean value
I_{gl}_Elsner KNX if AOV_S = 0%.	147.69	134.75	-54.46	<0.05	<250 W/m^2
I_{gl}_WAREMA if AOV_S = 0%.	114.19	147.9	-75.25	<0.05	<250 W/m^2
E_{out}_Pyranometer if AOV_S = 0%	16015	23711	-38.5	<0.05	<27.5 klux.
I_{gl}_Elsner KNX if AOV_S = 100%.	441.12	206.13	69.16	<0.05	>250 W/m^2
I_{gl}_WAREMA if AOV_S = 100%.	442.78	258.99	56.09	<0.05	>250 W/m^2
E_{out}_Pyranometer if AOV_S = 100%	55619	26335	91.9	<0.05	>27.5 klux.

Figure 3.5 (a, c, and e) shows that a high frequency of shade raising actions occurred when the irradiance on the facade was below 250 W/m^2 in each of the three devices. Meanwhile, the shade lowering actions occurred when the solar irradiance exceeded 250 W/m^2. Similar behaviour was observed in the measurements of the three devices. These findings indicate that high-quality and accurate shading light sensors were considered during the operation phase of this building. Therefore, system behaviour is another factor should be considered while developing shading control strategies to avoid the conflict between the established thresholds and what occupants accepted. A field study was conducted in Luxembourg case study focus on occupants' interaction and satisfaction with the automated shading systems, presented in Chapter 5.

3.3.2 System behaviour: an experimental study

Experimental procedure

The quality and accuracy of two commercial shading devices (SOLEXA II and WAREMA) were examined in an experimental test cell, "btga-box," located in Haspel Campus, Wuppertal University.

- SOLEXA II : SOLEXA control system was developed for automatic control of blinds and comfortable manual operation. The basis of the system is a control display and weather station, which allows for automatic control according to the indoor and outdoor temperature, brightness, sun position, wind speed, and precipitation.

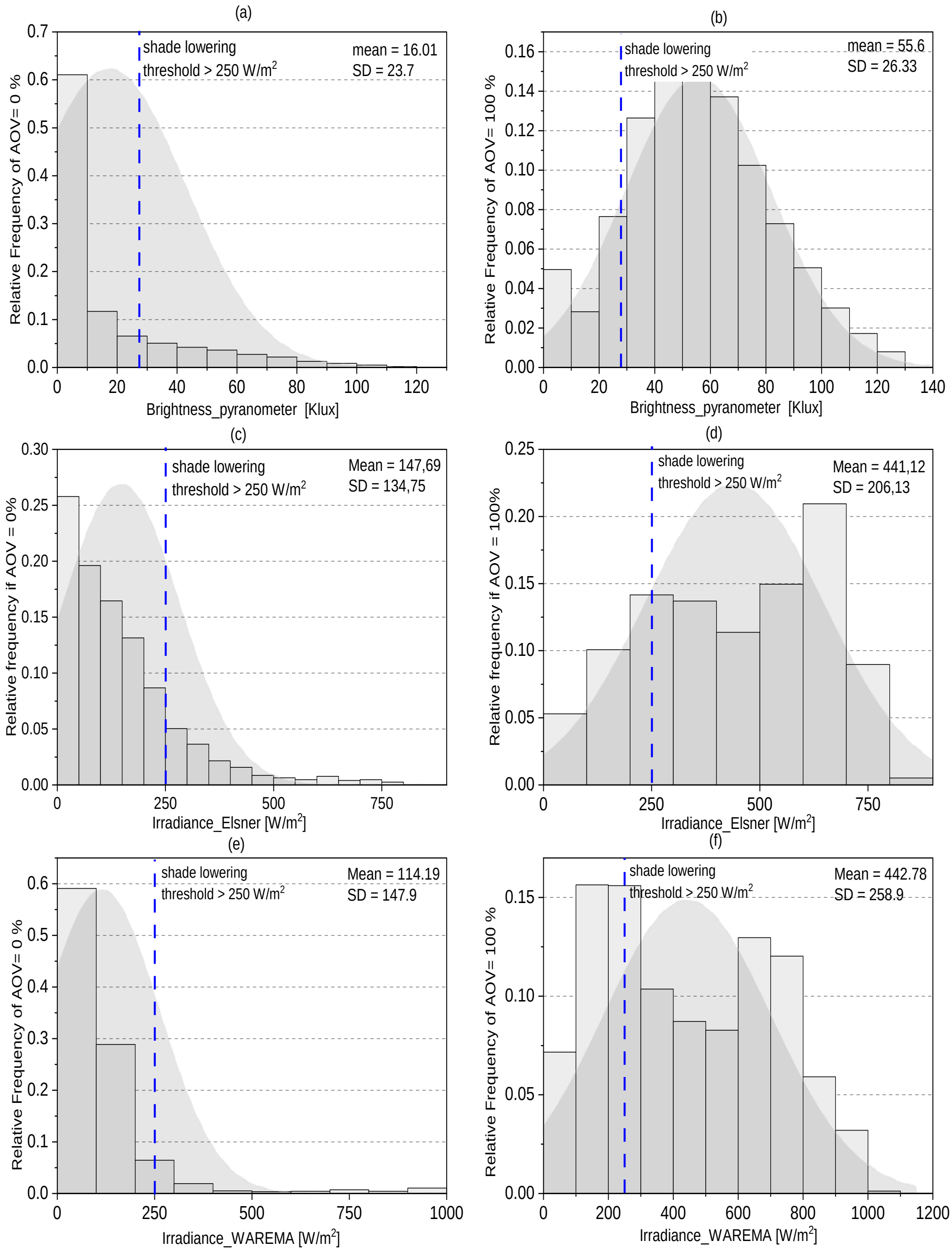


Figure 3.5: Relative frequency of irradiance measured by (a, b) Pyranometer (c,d) Elsner (e,f) WAREMA at the moment of shade raising and lowering respectively in south elevation.

- WAREMA: it consists of a multi-sense weather station that measures the brightness, wind speed, precipitation, and temperature values. The measuring values are transferred to the WAREMA Wistronic to control the connected sun shading as a function of this weather information.

Table 3.4 shows the measurement range and resolution of the environmental parameters quoted by the manufacturer of both devices. Table 3.5 shows the accuracy of WAREMA environmental parameters, while the manufacturer does not provide SOLEXA II accuracy specification. Figure 3.6 (a) shows the installation requirements of the SOLEXA II weather station. The sun sensor is located beneath the glass cover of the weather station. There must be at least 60 cm of free space around the weather station to ensure correct wind speed and temperature measurements. Additionally, the weather station must be mounted horizontally and aligned in the shading operation direction.

Figure 3.6 (b) shows the position of photodiodes in the WAREMA weather station. The four photodiodes must be arranged at the right angles to the building facades to record ambient brightness. The weather station must be mounted in an upright position and on the highest point of the roof structure. The precipitation sensor is the inclined surface which can be heated to measure the outside temperature.

Table 3.4: SOLEXA II and WAREMA environmental parameters range of measurements and resolution quoted by manufacturer.

Type	Indoor Temperature range	Outdoor temperature range	Resolution temperature	Wind range	Resolution wind	Brightness range	Resolution brightness	Brightness sensor inclination/orientation
SOLEXA II	-40 - +80 °C	-40 - +80 °C	0.6 °C	0-120 km/h	I km/h	0-150 klux	1 klux	Surface inclination is 60 degree towards vertical surface, oriented to the south.
WAREMA	0-50 °C	-30 - +60 °C	0.5 °C	0-25 m/s	1 m/s	0-100 klux	1 klux	four photodiodes are arranged at the building facades.

Table 3.5: WAREMA environmental parameters accuracy quoted by manufacturer.

Environmental parameters	Outdoor temperature	Wind speed	Brightness during daytime	Brightness at dawn/dusk
Accuracy	± 2 °C	± 1 m/s	± 1 klux	± 10 klux

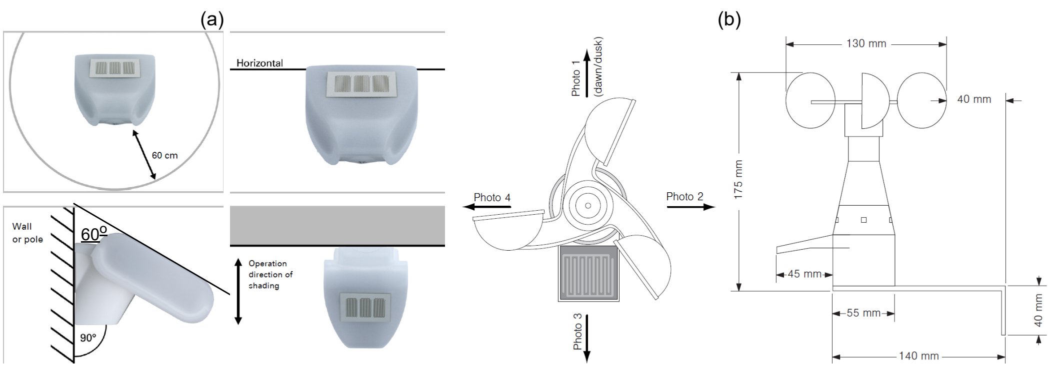


Figure 3.6: Weather station position of (a) SOLEXA II (b) WAREMA devices.

Installation of shading control devices

The weather stations of both devices were mounted on the aluminum structure on the rooftop of the test cell "btga-box" (see Figure 3.7 (a)). Both were aligned with the south façade, where the shading system is equipped. SOLEXA II and WAREMA devices were placed at 1.2 m height from roof level and 1 m away from each other to ensure the same surrounding context for both devices (see Figure 3.8). The control panels were installed inside the test cell next to each other (see Figure 3.7 (b)).

(a) (left) SOLEXA II and (right) WAREMA weather stations.

(b) (left) SOLEXA II and (right) WAREMA control panels.

Figure 3.7: SOLEXA II and WAREMA components.

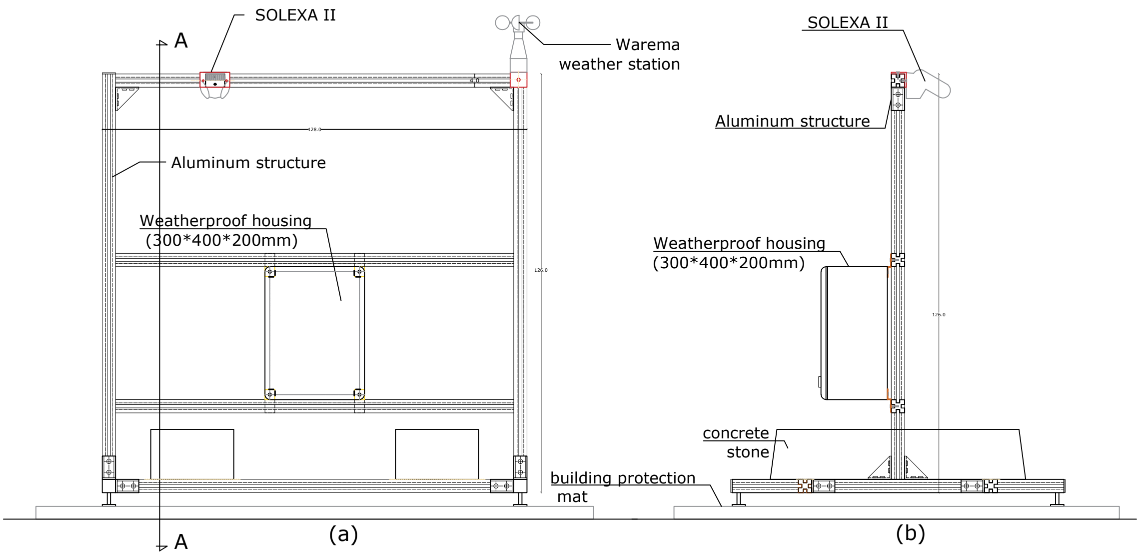


Figure 3.8: SOLEXA II and WAREMA aluminum structure installation (a) Elevation (b) Section A-A.

Experimental setups

SOLEXA II and WAREMA control devices were connected to the same shading system. The same settings of automatic operations were adjusted for both control devices for comparison purposes. Three different brightness thresholds were tested in three different monitoring periods. Setup (01) was between 9:00 am and 12:00 pm, where the shade lowering threshold was above 35 klux (approximately 320 W/m^2). Setup (02) was between 12:00 pm and 4:00 pm, where the shade lowering threshold was above 50 klux (approximately 450 W/m^2). Setup 01&02 experiments were carried on from 26th of August until the 23rd of October 2019. Setup (03) was conducted during the summertime in 2020 over 26 monitoring days from 8:00 am until 8:00 pm. Table 3.6 and 3.7 shows the operation settings of both devices under the three different setups.

Table 3.6: WAREMA automatic operation settings.

WAREMA settings parameters	Setup (01)	Setup (02)	Setup (03)
Brightness limit value SUN	50 klux(approx. 450 W/m^2)	35 klux(approx. 320 W/m^2)	300 W/m^2
Delay time of SUN	5 min	5 min	5 min
Brightness limit value CLEAR	40 klux	25 klux	25 klux
Delay time of CLEAR	10 min	10 min	10 min
Brightness limit value CLOUD	30 klux	15 klux	100 W/m^2
Delay time of CLOUD	15 mins	15 mins	15 mins
Wind speed	12 m/s	12 m/s	12 m/s
Delay time of wind speed	5 sec	5 sec	5 sec
Warm limit value /Indoor temperature	25 °C	25 °C	25 °C
Cold limit value Indoor/ temperature	21 °C	21 °C	21 °C
Operating mode for temp. control	On	On	On
Precipitation (rain or snow)	On	On	On

Table 3.7: SOLEXA II automatic operation settings.

SOLEXA II settings parameters	Setup (01)	Setup (02)	Setup (03)
Brightness	50 klux	35 klux	300 W/m^2
Wind speed	12 m/s	12 m/s	12 m/s
Delay time of brightness	5 min	5 min	5 min
Delay time of wind speed	5 sec	5 sec	5 sec
Indoor temperature Block	25 °C	25 °C	25 °C
Hysteresis of indoor temperature	3 °C	3 °C	3 °C
Outdoor temperature block	5 °C	5 °C	5 °C
Rain alarm	On	On	On

Electrical installation

SOLEXA II and WAREMA output signals were not connected directly to the motor of the shading device. First, both devices' signal output (230 V) was recorded as a digital input in DASYLab 2016 v14 software (i.e., data acquisition system laboratory). The DASYLab worksheet output was used to control the shade motor. To convert the analog signals to digital ones and vice versa, ADC (analog to digital converter) system was applied as illustrated in Figure 3.9. For detailed electrical plan see Appendix A1.4.

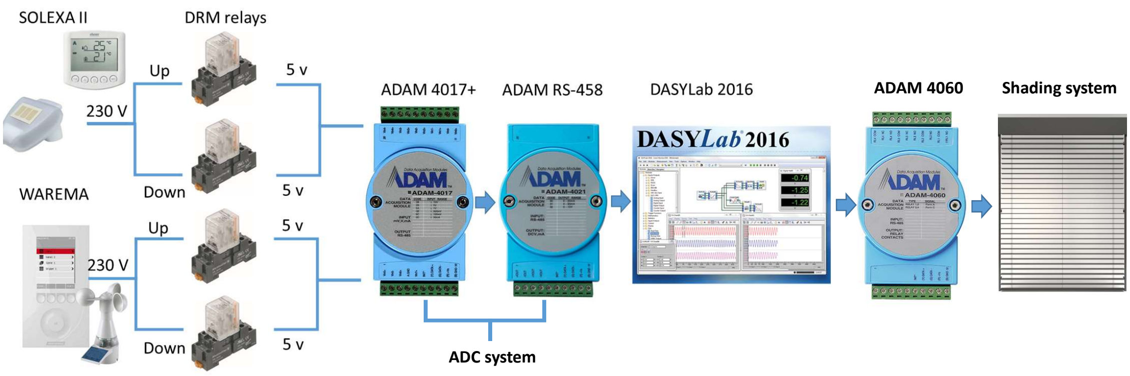


Figure 3.9: Electrical installation

Scientific reference instruments

SOLEXA II and WAREMA are black box devices. Their weather stations' measurements were not recorded. Alternatively, three scientific instruments were used as a reference for comparison during the same study period (see Figure 3.10). Reference 01 is a pyranometer mounted on the south façade of the test cell, measuring the solar irradiance on the facade (W/m^2). Reference 02 is a local weather station (HB) located on the rooftop of a nearby building at the Haspel Campus, recording a minute-averaged measurement of global and diffuse solar irradiance, outdoor temperature, wind speed, and humidity . The third reference is the thermometer located next to the shading devices control panel inside the test cell measuring the indoor temperature. A simulation-based algorithm was developed in the DASYLab 2016 v14 virtual environment to control the blind based on solar irradiance on the facade, representing a simple control strategy and an accurate reference. The shade-triggered signals were then compared in terms of SOLEXA II, WAREMA, and the algorithm.

Data analysis approach

The accuracy of experimental measurements is best determined by comparing the average of the measured values with a reference value. The precision of a set of measurements can be determined by calculating the standard deviation of the datasets (see Figure 3.11). Accordingly, one sample t-test was used to determine whether the population mean is statistically different from a reference value, the shade triggering threshold in this study.

[1] https://en.wikipedia.org/wiki/Accuracy_and_precision

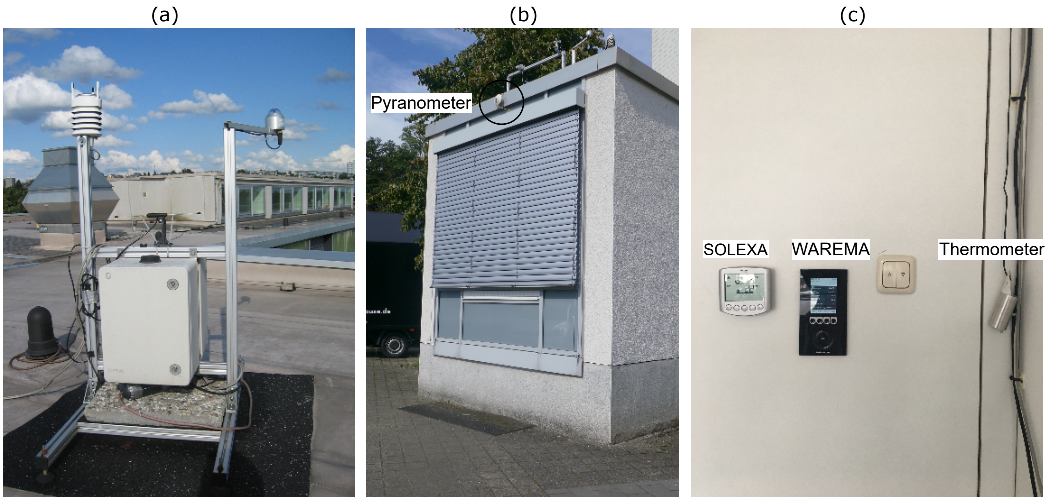


Figure 3.10: Scientific reference instruments (a) HB weather station (b) pyranomter (c) Thermometer.

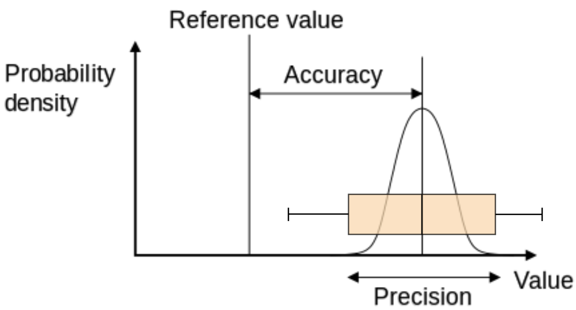


Figure 3.11: Accuracy and precision of measurements related to a reference value [1].

Results analysis

In setup 01&02, SOLEXA II recorded 26 shade lowering events and 105 raising events during 31 monitoring days. WAREMA recorded 179 closure events and 120 raising ones during 19 days. The results revealed that the blind rate of change per day of WAREMA lowering and raising events (9.42, 6.3 respectively) was higher than SOLEXA II, where the rate of change was 0.83 and 3.38 for lowering and raising events, respectively. Table 3.8 illustrates that 38% (Ref.01) and 15% (Ref.02) of SOLEXA II lowering triggered actions occurred when the irradiance threshold was below 320 and 450 W/m^2 (lowering threshold). Regarding WAREMA lowering triggered actions, 64% (Ref.01) and 40% (Ref.02) occurred below the irradiance lowering threshold. These results indicate that many shade lowering actions occurred before the irradiance threshold was met. Moreover, Figure 3.12 shows that SOLEXA II and WAREMA's behavior differed regarding the occurrence of lowering events, considering that both devices have the same control settings. This behaviour is explained due to (a) different positions of the weather stations (1 m distance), (b) different light sensors' inclination, and (c) the quality and accuracy of the device itself.

Table 3.8: Percentage of shade lowering actions in terms of SOLEXA II and WAREMA devices (setup 01&02).

	Percentage of shade lowering actions when irradiance is				
Shading devices	<320 W/m2	>320 W/m2	<450 W/m2	>450 W/m2	<320 or 450 W/m2
SOLEXA II (Ref.01)	60%	40%	0%	100%	38%
SOLEXA II (Ref.02)	19%	81%	22%	78%	15%
WAREMA (Ref.01)	61%	39%	59%	41%	64%
WAREMA (Ref.02)	20%	80%	48%	52%	40%

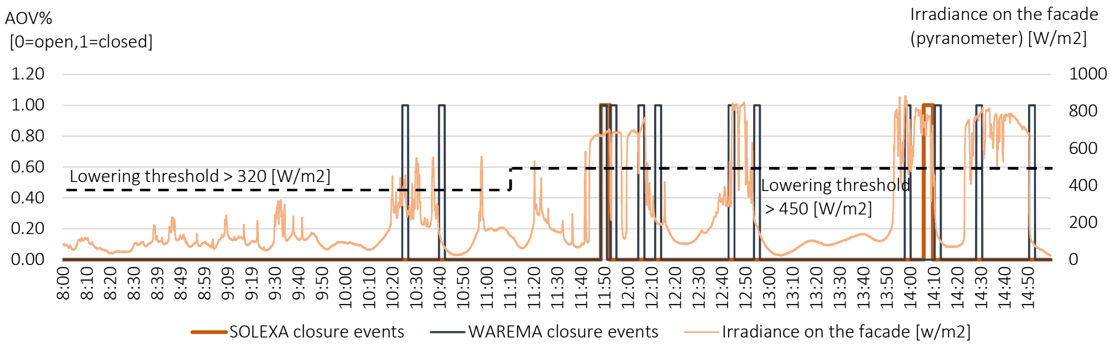


Figure 3.12: SOLEXA II and WAREMA closure events and hourly profile of irradiance on the facade in a reference day [05.09.2019].

To examine the quality and accuracy of the light sensors, the current study analyzed the lowering actions of the shading control devices (SOLEXA II and WAREMA) and the simulation-based algorithm related to three scientific instruments' measurements: pyranometer (Ref.01), HB weather station (Ref.02) and thermometer (Ref.03). Figure 3.13 shows the hourly profile of solar irradiance on the facade measured by the pyranometer and the global irradiance measured by HB weather station during a reference day. The difference is due that HB weather station measures diffuse and direct solar radiation incident on a horizontal surface.

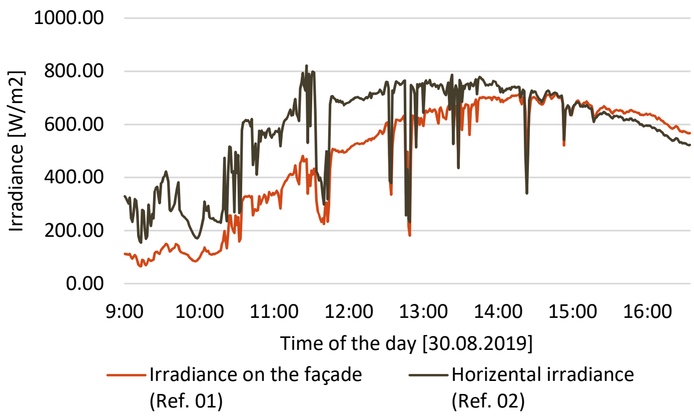


Figure 3.13: Hourly profile of solar irradiance measured by Ref.01 and 02.

Results of Setup 01

Figure 3.14 shows the box-plot distribution of irradiance measurements (Ref. 01 and 02) at the moment of shade lowering events in terms of SOLEXA, WAREMA, and the simulation-based algorithm in setup 01. Table 3.9 summarizes the results of one-sample t-test. It is noticed that the irradiance average measured by Ref.02_I_{gl} -at the moment of SOLEXA II and WAREMA lowering actions- was significantly higher than the reference value (320 W/m^2) as well as the simulation-based algorithm. Non-significant difference was found between the irradiance average measured by Ref.01_I_r and Ref.01_I_{avg} compared to the reference value. This result is explained that Ref.01 measures the irradiance on the facade and Ref.02 measures the horizontal global irradiance, and both devices' light sensors are mounted upwards, measuring the horizontal irradiance. Overall, it is concluded that SOLEXA II and WAREMA performance were accurate related to Ref.02 measurements and not accurate related to Ref.01.

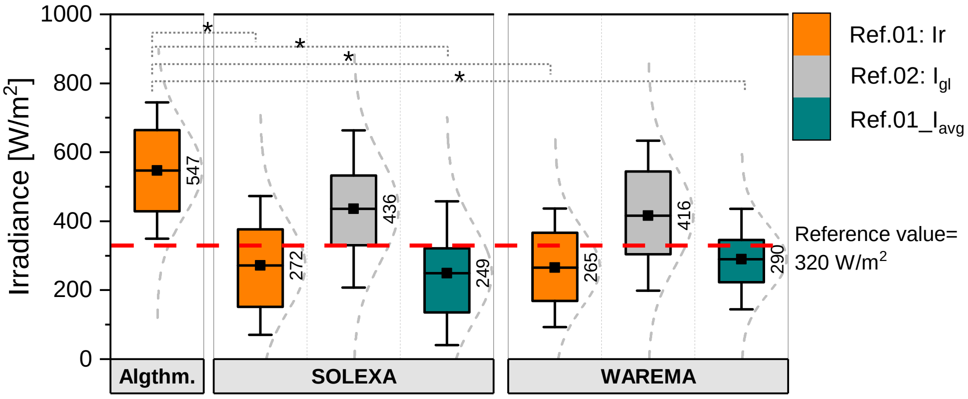


Figure 3.14: Setup 01 results: box-plot distribution of irradiance at the moment of shade lowering actions triggered by SOLEXA II and WAREMA, compared to simulation-based algorithm.

Table 3.9: One sample t-test results in setup 01.

Shading control system	Reference	t	df	Sig. (P_value)	Mean	SD	Reference value	Mean Difference
Algorithm	Ref.01_Ir	440.75	55195	0.00*	547.02	131.67	>300 W/m^2	247.02
SOLEXA	Ref.01_Ir	-1.49	16	0.92	271.53	134.27	>320 W/m^2	-48.47
	Ref.02_Igl	3.13	16	0.00*	435.57	152.13	>320 W/m^2	115.57
	Ref.01_I_{avg}	-1.84	12	0.95	249.14	139.16	>320 W/m^2	-70.86
WAREMA	Ref.01_Ir	-3.69	58	1.00	264.96	114.62	>320 W/m^2	-55.04
	Ref.02_Igl	5.10	58	0.00*	416.31	145.03	>320 W/m^2	96.31
	Ref.01_I_{avg}	-2.08	44	0.98	289.92	97.18	>320 W/m^2	-30.08

Additionally, paired t-test analysis was used to compare the performance of SOLEXA II and WAREMA with the simulation-based algorithm. A significant difference was found between the irradiance average (algorithm) and the data triggered by SOLEXA II and WAREMA (Ref.01_I_r and Ref.01_I_{avg}) (p-value < 0.05) (see Figure 3.14).

Results of Setup 02

Similarly, in setup 02, the irradiance measurements (Ref.01& 02) were analyzed as a function of SOLEXA II and WAREMA compared to the simulation-based algorithm for shade lowering actions. The same settings were used in setup 02 except the irradiance lowering threshold (450 W/m^2). The results in Figure 3.15 indicate that the irradiance average -at the moment of SOLEXA II lowering actions- was significantly higher than the reference value (450 W/m^2) with regards to Ref.01 and 02. Regarding WAREMA lowering actions, the irradiance average was significantly higher than the reference value only in Ref.02 and Ref.01, averaging values every 5 minutes. According to one sample t-test analysis (see Table 3.10), the results indicate that SOLEXA II performance was inaccurate in setup 02 since the mean difference between the measurements' average and the reference value was significantly high different from algorithm performance. WAREMA performance was accurate in Ref.02_I_{gl} and Ref.01_I_{avg}, similar to the simulation-based algorithm performance.

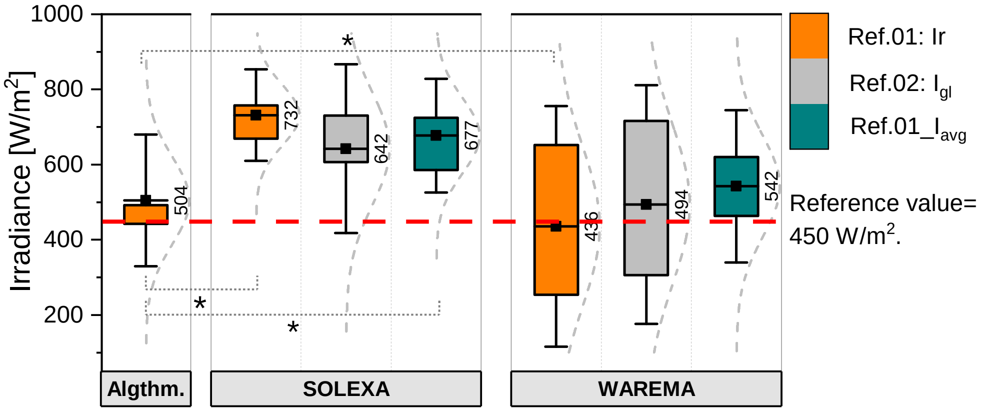


Figure 3.15: Setup 02 results:box-plot distribution of irradiance at the moment of shade lowering actions triggered by SOLEXA II and WAREMA, compared to simulation-based algorithm.

Table 3.10: One sample t-test results in setup 02.

Shading control system	Reference	t	df	Sig. (p_value)	Mean	SD	Reference value	Mean Difference
Algorithm	Ref.01_I_r	3.5185	56	0.00*	504.44	116.81	>450 W/m^2	54.44
SOLEXA II	Ref.01_Ir	10.404	8	0.00*	731.51	81.17	>450 W/m^2	281.51
	Ref.02_Igl	3.8538	8	0.00*	642.36	149.74	>450 W/m^2	192.36
	Ref.01_I_{avg}	6.7713	8	0.00*	677.06	100.60	>450 W/m^2	227.06
WAREMA	Ref.01_Ir	-0.73	119	0.77	435.66	213.28	>450 W/m^2	-14.34
	Ref.02_Igl	2.27	119	0.00*	493.92	211.65	>450 W/m^2	43.92
	Ref.01_I_{avg}	7.50	119	0.00*	542.48	134.91	>450 W/m^2	92.48

Figure 3.16 shows that the indoor temperature average -at the moment of shade lowering actions- was lower than the reference threshold (>25 °C) in both SOLEXA II and WAREMA devices. In contrast, the mean indoor temperature (27.12 °C) was higher than the threshold value in terms of the simulation-based algorithm. The results indicate that the commercial

devices (SOLEXA II and WAREMA) are not accurate enough to lower the blind based on the indoor temperature lowering threshold.

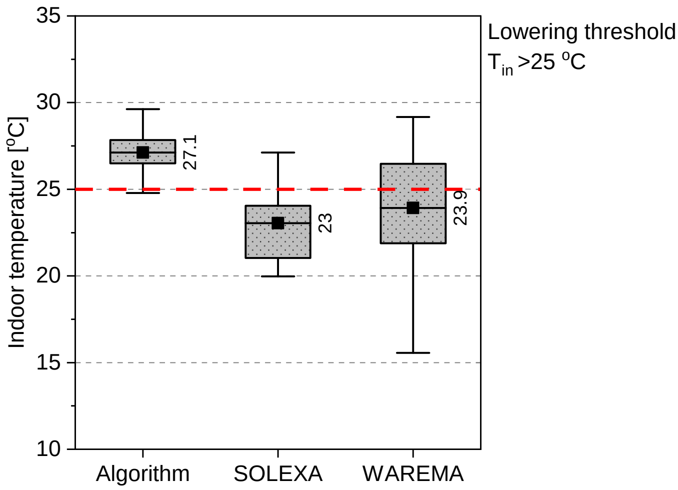


Figure 3.16: Box-plot distribution of indoor temperature at the moment of shade lowering actions triggered by SOLEXA II and WAREMA, compared to simulation-based algorithm.

Results of Setup 03

Figure 3.17 (a&b) shows the box-plot distribution of irradiance measurements (Ref. 01 and 02) as a function of SOLEXA II, WAREMA compared to the simulation-based algorithm, lowering and raising actions. In setup 03, 51 shade lowering events and 100 raising events over 26 monitoring days were recorded by SOLEXA II, while WAREMA recorded 162 lowering and 125 raising events. The shade lowering threshold was when irradiance on the facade exceeded 300 W/m^2, and the raising threshold was when irradiance was below 100 W/m^2. Based on one sample t-test results (see Table 3.11), it can be noticed that the irradiance average (Ref.01&02)- at the moment of SOLEXA II and WAREMA lowering actions- was significantly higher than the reference value ($>$ 300 W/m^2) except for WAREMA (Ref.01) (p-value $>$ 0.05). In the latter, the performance of WAREMA was similar to the simulation-based algorithm (accurate).

Table 3.11: One sample t-test results of shade lowering actions in setup 03.

Shading control system	Reference	t	df	Sig (p-value)	Mean	SD	Reference value	Mean difference
Algorithm	Ref.01	2.20	236	0.01*	311.89	83.33	>300 W/m^2	11.89
SOLEXA II	Ref.01	3.12	50	0.00*	382.46	188.89	>300 W/m^2	82.46
	Ref.02	2.76	50	0.00*	401.18	262.25	>300 W/m^2	101.18
WAREMA	Ref.01	-1.50	161	0.93	280.05	169.19	>300 W/m^2	-19.95
	Ref.02	5.62	161	0.00*	438.17	312.63	>300 W/m^2	138.17

In terms of shade raising actions, significant difference was observed between the irradiance average (Ref.02) and the reference value (<100 W/m^2) in both devices based on the

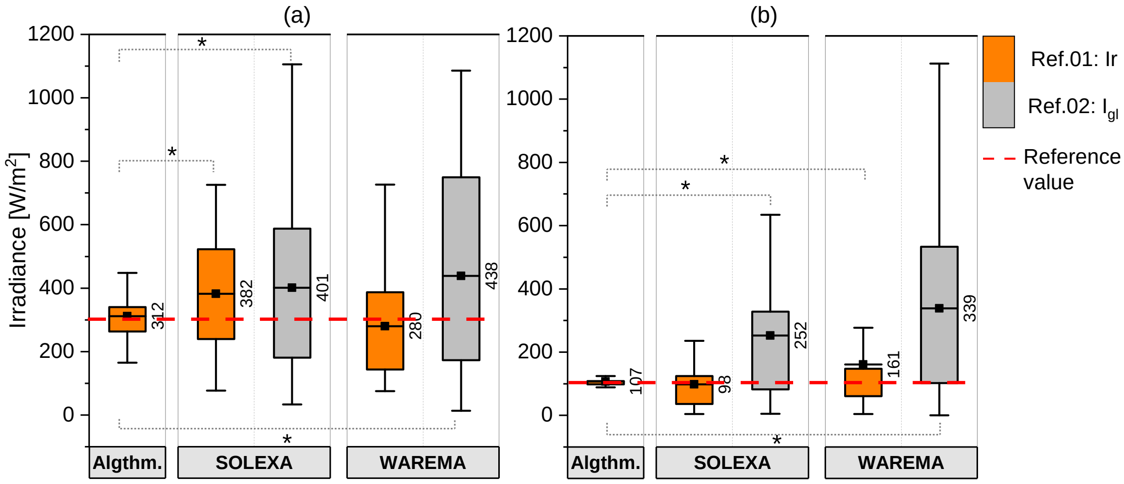


Figure 3.17: Setup 03 results: Box-plot distribution of irradiance as a function of SOLEXA II, WAREMA and simulation-based algorithm (a) lowering actions and (b) raising actions.

one sample t-test result (see Table 3.12). Non-significant difference was found in terms of SOLEXA (Ref.01), and it was similar to the simulation-based algorithm (p-value = 0.5).

Table 3.12: One sample t-test results of shade raising actions in setup 03.

Shading control system	Reference	t	df	Sig (p-value)	Mean	SD	Reference value	Mean difference
Algorithm	Ref.01	4.13	112	0.00*	106.99	17.97	<100 W/m^2	6.99
SOLEXA II	Ref.01	-0.24	99	0.81	97.96	84.34	<100 W/m^2	-2.04
	Ref.02	7.02	99	0.00*	252.28	216.90	<100 W/m^2	152.28
WAREMA	Ref.01	4.44	124	0.00*	161.04	153.72	<100 W/m^2	61.04
	Ref.02	8.61	124	0.00*	338.70	310.06	<100 W/m^2	238.70

Overall, the behaviour of commercial shading control devices was not consistent and, in most cases, differed from the simulation-based algorithm (an accurate based-control). Therefore, it is suggested that building designers and operators consider the quality and accuracy of shading control devices during the development of shading control strategies.

3.4 Evaluation of shading control strategies using simplified tools

3.4.1 Simplified tools

Shading devices play a significant role in controlling incident solar and thermal radiation for transparent elements. Their geometry, positions, and control strategies permit the control of light and heat gain entering the building. Solar irradiance is a simple and relatively common parameter used in solar shading control strategies. Moreover, a wide disparity among the irradiance values on the facade ranging from 100-450 W/m^2 was used [64].

In this study, the annual heating and cooling demands, as well as undisturbed hours to the view outside, were calculated for a single office zone, identical to the test cell "btga-box"

(2.93 m wide, 5.15 m deep, and 2.7 m height) (see Figure 4.1 in page 55). The analysis was performed under different solar shading control strategies (a range of 0-700 W/m^2) using SimRoom for zone modelling and Variantas tools for sensitivity analysis. SimRoom is an excel sheet energy calculation method developed by *Markus Lichtmeß* to simplify the optimization of building design (https://ingefo.de/Werkzeuge/SimRoom/). The input parameters of the simulation in the current study were the solar orientation of transparent and opaque components, heat protection level, thermal capacity, glazing properties, sun protection, and ventilation system. The calculations were carried out based on hourly climatic data of Wuppertal, Germany. The calculation of annual heating and cooling hours was in a free-floating temperature mode of the building. The annual heating and cooling hours were the sums of the hours where the operative temperature was below the heating limits (21 °C) and above the cooling limits (25 °C) (see Appendix A1.4).

3.4.2 Simulation analysis results

Figure 3.18 (a, b) shows the annual heating and cooling hours as a function of solar irradiance on the facade (I_r) (shade setpoint) under different window-to-wall ratio (WWR = 25%, 50%, 75%, 100%). As expected, the highest cooling hours were observed when the irradiance lowering threshold was 700 W/m^2 (approximately 77 klux) and WWR was 100%. Likewise, the cooling/heating hours varied significantly as a function of solar irradiance under different space orientations (see Figure 3.18 (c, d)). The highest cooling hours were observed in south and west facing-facades when the irradiance threshold was above 400 W/m^2.

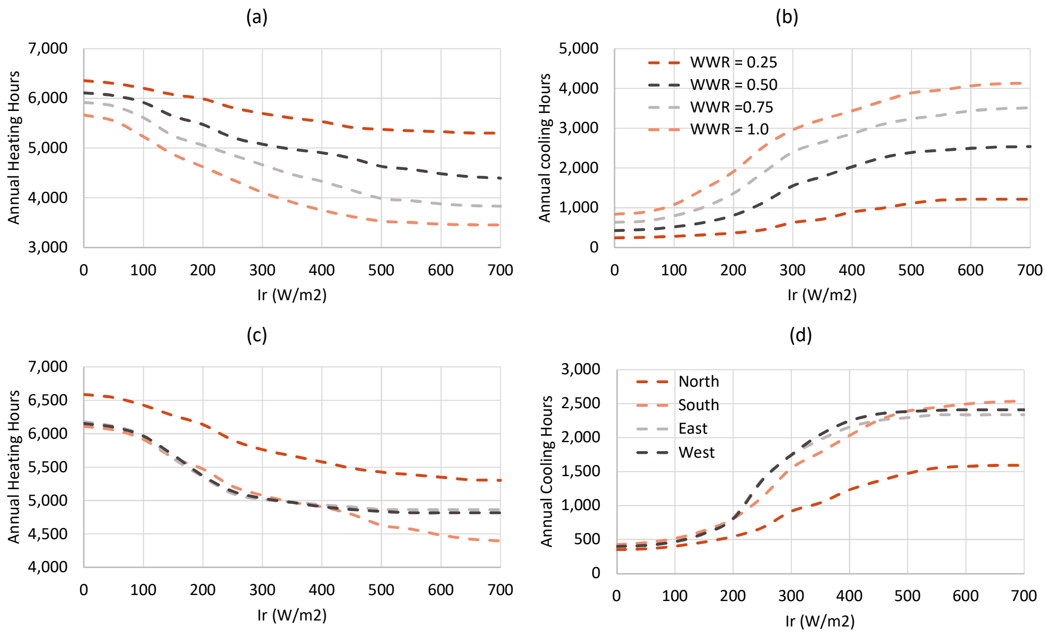


Figure 3.18: (a, b) Annual heating and cooling hours as a function of shade lowering irradiance threshold in terms of WWR%, (c, d) and space orientation, respectively.

The annual operating hours of external shade (fully closed = 1, fully open = 0) were calculated under different solar shading control strategies: (a) shade lowering threshold when irradiance on the facade exceeds 100 W/m^2, (b) 200 W/m^2, and (c) 300 W/m^2 (approximately 11 klux, 22 klux, and 33 klux, respectively). Figure 3.19 shows the hourly shade operating using three shading control strategies horizontal and per each facade. The results indicate that the maximum shade operating hours were when the irradiance lowering threshold exceeded 100 W/m^2 in west elevation, while the minimum disturbing hours to the view outside (i.e., minimum shade operating hours) were when the irradiance lowering threshold exceeded 300 W/m^2 in north elevation.

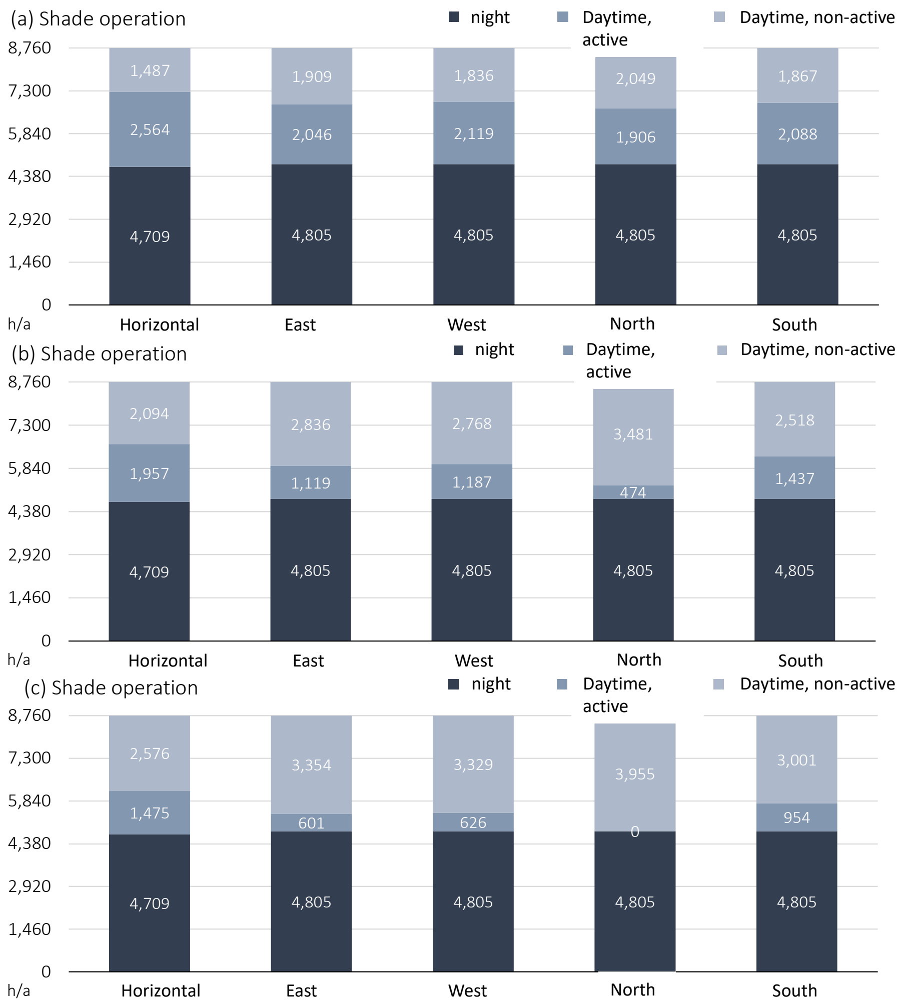


Figure 3.19: Shade operating hours using different solar shading strategies (a) 100 W/m^2, (b) 200 W/m^2, (c) 300 W/m^2 per each facade.

Figure 3.20 shows the monthly shade operating hours in terms of different facade orientation and shade control strategies. Higher shade operating hours were noticed when the irradiance lowering threshold exceeds 100 W/m^2 compared to 300 W/m^2. Higher operating hours were in the south-facing office than the north-facing office, under the same shade control strategy. Based on these results, it is recommended for the building designer to consider the space orientation while selecting the optimal shading control strategy.

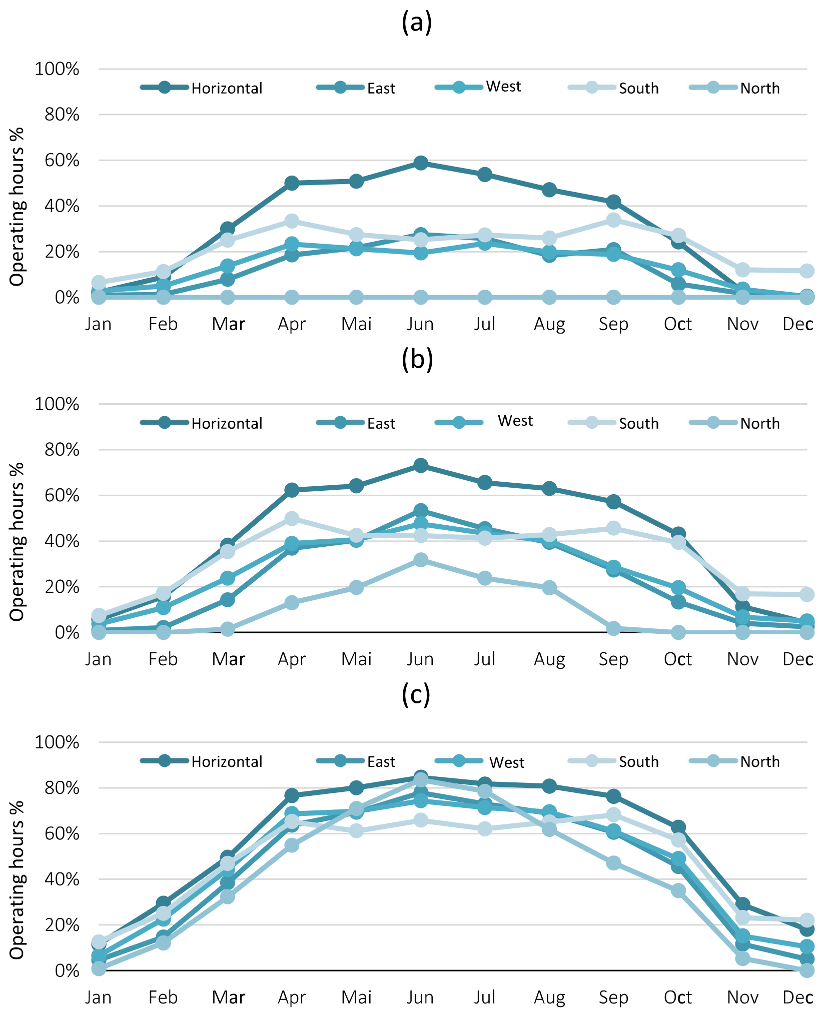


Figure 3.20: Monthly percentage of shade operating hours (closed) when irradiance threshold exceeded (a) 300 W/m^2 (b) 200 W/m^2 (c) 100 W/m^2

Shade patterns analysis

Mahdavi and Berger [81] assumed three general groups of occupants with different preference ranges. The assumptions with regard to heating, cooling, lighting, and shading setpoints for the three groups of occupants are summarized in Table 3.13. These groups are:

- Group (H): is assumed to have higher thermal expectations (narrow range of acceptance) regarding indoor environmental conditions.
- Group (M): is assumed to have moderate expectations and tolerance concerning indoor environmental conditions.

- Group (L): is assumed to have low expectations and high tolerance for the change in indoor environmental conditions.

Table 3.13: Assumptions concerning the three occupant categories (“H,” “M,” “L”) [81]

Group type	Operational scenario			
	HVAC (°C)		Light (lux)	Shading setpoints (W/m²)
	Heating	Cooling		
High (H)	22	23	700	300
Medium (M)	21	24	500	200
Low (L)	19	26	300	100

According to Mahdavi groups’ classification, the annual heating and cooling demand in terms of different building design parameters (WWR%, space orientation and climatic zone) was calculated in this study (see Figure 3.21). It is noticed that group (L) (shade lowering setpoint was 100 W/m^2) consumed the maximum annual heating demand when WWR was 25% and the window orientation was to the north. While group (H) (shade lowering set point was 300 W/m^2) consumed the maximum cooling demand when WWR was 100% and the window orientation was to the west and east. Annual cooling demand of group (M) was higher in Jerusalem compared to Luxembourg, while the opposite was observed in terms of heating demand.

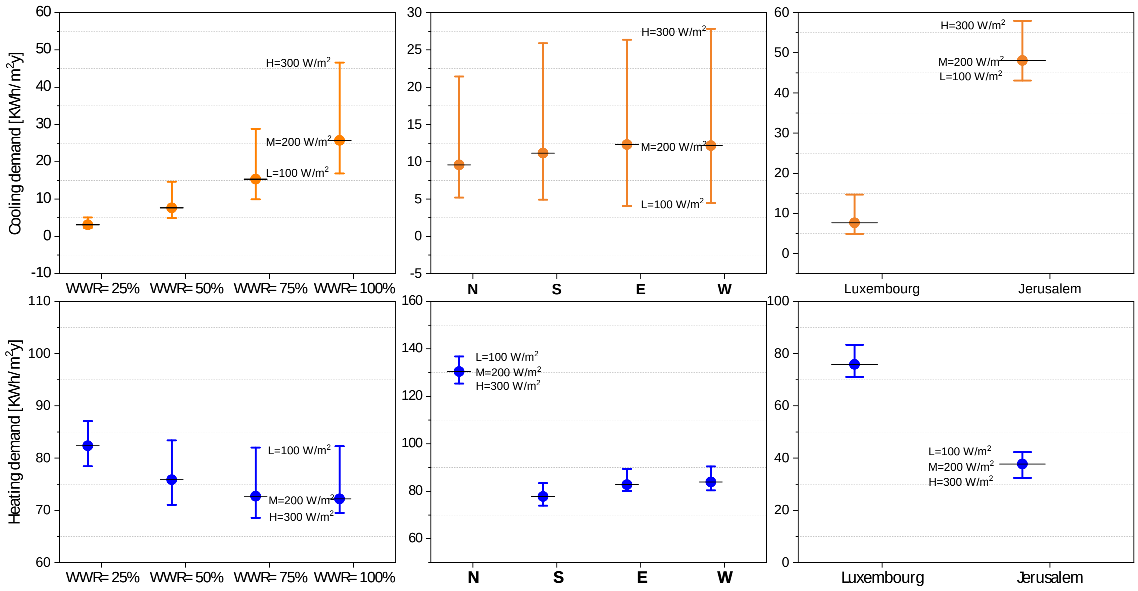


Figure 3.21: Box-plots distribution of annual heating and cooling demand considering Mahdavi groups’ classification.

To conclude, building design parameter (e.g., WWR and orientation), different behavioural patterns, climatic zone, and different user types greatly influenced the building performance in terms of heating and cooling demand as well as view access to the outside. Therefore, these parameters are crucial factors to consider while selecting the optimal solar shading control strategies. Additionally, the view-connection to the outside varied considerably with regard to the shade control irradiance setpoints.

3.5 Conclusions and lessons learned

- Different behaviour and inconsistency were observed in SOLEXA II and WAREMA performance compared to a simulation-based algorithm, representing a relatively accurate performance. Limited quality and accuracy of commercial devices for automatic shading control due to economic constraints and sensors' positions or inclinations should be considered when selecting and designing automated shading control strategies.

- In Luxembourg case study, the average of shade lowering/raising thresholds was significantly higher/lower than the established setpoint (p-value < 0.05). The results indicate that high-quality and accurate shading light sensors should be considered during the operation phase of this building. This has minimized the conflict between the established thresholds and occupants' acceptance (i.e., less override actions) as discussed later in Chapter 5.

- Space orientation and window size greatly influence the annual heating and cooling demand and undisturbed view of the outside under different solar shading control strategies and climatic zones. For instance, when WWR was 100%, the annual cooling hours were higher by 30% with high expectation users than low- expectation users. Based on these findings, it is recommended that building designers perform a parametric analysis in the early stage of building design considering building and envelope design parameters, climatic zones, and different user types while selecting the optimal shading control strategy.

3.6 Limitation of the study

- Time of the day could greatly influence the blind deployment, however, it is ignored in the experimental study analysis. It is argued that the quality of shading control devices was evaluated based on solar irradiance thresholds not the solar intensity.

Chapter 4

Optimizing automated shading's design and operation: an experimental study

An experimental study was conducted in a full-scale test cell "btga-box" from July until September 2020 at Haspel Campus in Wuppertal, Germany. This study aims to explore and evaluate the consistency of occupant interaction with automated shading systems in office spaces, and the underlying thermal and visual conditions under different scenarios (i.e., shading control strategies, window size, cooling system) for improving occupant-centric shading design and operation. Six different scenarios with repeated measures are evaluated using several performance metrics, then tested in paired groups using statistical analysis to discover the optimal shading design solutions. Twenty-eight participants of varying ages, gender, and ethnicity took part in the experiments. After each scenario, the participants were asked to fill in a web-based questionnaire to report their behaviour, perceived comfort, satisfaction, and preferences with regard to the automated shading system. Concurrently, indoor environmental parameters, weather data, system and user-triggered actions were recorded. The key findings of this study provide the building designers and operators with (a) a better understanding of user interaction with and satisfaction of automated shading systems (b) guidelines on how to design robust shading control strategies, so that override actions are mostly reduced to the minimum (c) and the selection of optimal threshold or thresholds for automated shading control. Overall, this study contributes to knowledge regarding the optimization of automated shading in office environment, considering thermal and visual comfort as well as user acceptance.

4.1 Introduction

Building automation is becoming more prevalent in modern building systems' design and control to improve energy efficiency while maintaining occupant comfort [121]. For instance, shading systems and their automation offer the potential to enhance user comfort and reduce energy consumption at the same time. Nevertheless, several studies reported that occupants frequently override or disable these systems, either indicating discomfort or implying their desire for a customized indoor climate or view-to-the outside [45, 102, 84, 105]. Occupants are more satisfied with the automated shading systems when they have the option to override them and if they meet their preferences [128, 62, 22]. Previous studies indicate that further research is needed to control shades to match occupant preferences and expectations. Moreover, the integrated evaluation of visual and thermal comfort as well as energy use is significant when selecting an optimal solar shading control strategy as stated by several studies [71, 64, 4, 120]. While others indicated the importance of considering user-accepted solar shading control strategies during building design to ensure realistic building performance predictions [62]. However, there has been limited focus on evaluating shading control strategies in terms of user interaction and acceptance (i.e., limited override actions) combined with thermal and visual comfort assessment.

To this end, the current study evaluated the performance of automated shading systems in terms of user behaviour and acceptance, thermal and visual comfort under different scenarios for optimizing occupant-centric shading design and operation. Six scenarios (S01-S06) were conducted with repeated measures (28 participants) in a full scale test cell "btga-box" under different conditions over two days for a total of 56 days. These conditions varied from the time of the day (morning, noon, and afternoon), sky conditions (sunny and cloudy), window size (WWR%), cooling systems (active cooling, non-active cooling, and ceiling fan use), and different solar shading control strategies (simple or multi-objective). Then paired groups of scenarios (cases), as summarized in Table 4.1, were analyzed and compared to provide optimal shading design solutions.

Table 4.1: Summary of paired tested groups (cases).

Cases	Scenario 01	Scenario 02
Case 01 [S01 vs. S02]	active cooling	without active cooling
Case 02 [S02 vs. S03]	simple control strategy	multi-objective control strategy
Case 03 [S02 vs. S04]	without ceiling fan control option	with ceiling fan control option
Case 04 [S02 vs. S05]	WWR% = 75%	WWR% = 40%
Case 05 [S01 vs. S04]	low degree of adaptive control options	high degree of adaptive control options
Case 06 [S05 vs. S06]	irradiance lowering threshold on the facade when exceeds 300 W/m^2	irradiance lowering threshold on the facade when exceeds 450 W/m^2

4.2 Experimental design and methods

4.2.1 Test facility

The experimental study was carried out in a full-scale test cell "btga-box" at Haspel Campus, Wuppertal University, Germany (latitude 51.2 °N, longitude 7.16 °E) (see Figure 4.1). It has a south-oriented test room that deviates by 15°to the west, with 2.93 m wide, 5.15 m deep, and 2.7 m high (inner dimensions). The entry room of the test facility, where ventilation systems, data acquisition, and the measuring PC are housed, is thermally separated from the measuring room. The test facility is based on a prefabricated concrete garage and stands on a 70 cm high base of expanded polystyrene (EPS) thermal insulation. The south facade is equipped with a double layer solar control glazing with 75% WWR (U = 1.1 W/m^2.K, g = 42%, VT = 66%) and consists of two operable windows (electrically tilt and turn) and a middle fixed large panel. The window is equipped with an automated external Venetian blind (type Schüco, with 80 mm slats) coloured in light grey. The blind is connected to a motor controlled by DASYLab 2016 v14 software (i.e., data acquisition system laboratory). The mechanical ventilation system of the test room consists of an exhaust air system using upper and lower air inlets (type Aeromat VT) in the south façade of the room. The average air change per hour was measured to be 0.67 (1/h) (7.7 L/s). Radiant heating/cooling ceiling panels are connected to a reversible heat pump. Two fluorescent tubes centered along the longitudinal axis between the ceiling panels, controlled via a switch button next to the door.

Figure 4.1: "btga-box" test facility aerial, exterior and interior views.

4.2.2 Measured parameters and physical data acquisition

This section introduces the sensors and equipment used to monitor the physical parameters during the experiments and the communication protocols for the activation of the external blind. The sensors and their positioning in the test room are illustrated in Figure 4.2 and 4.3. The indoor and outdoor monitored parameters during the experiments are:

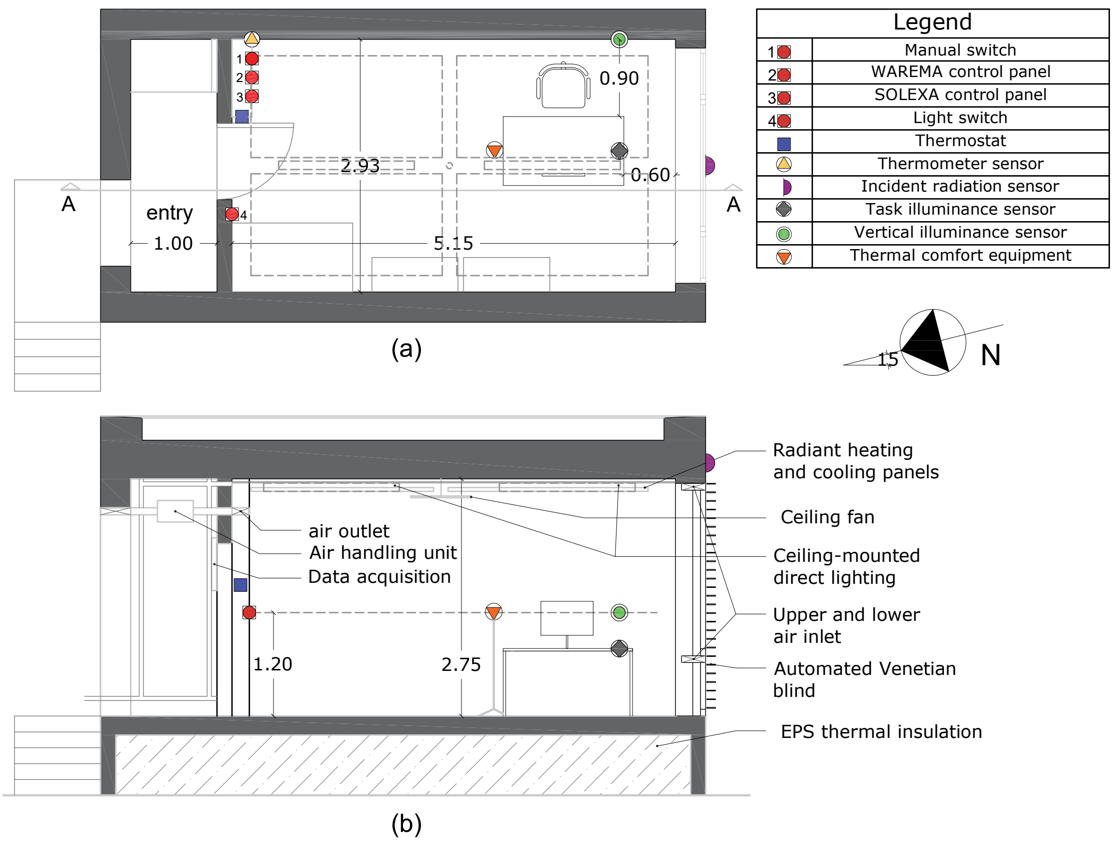


Figure 4.2: Placement of sensors in the test facility (a) plan view (b) section A-A.

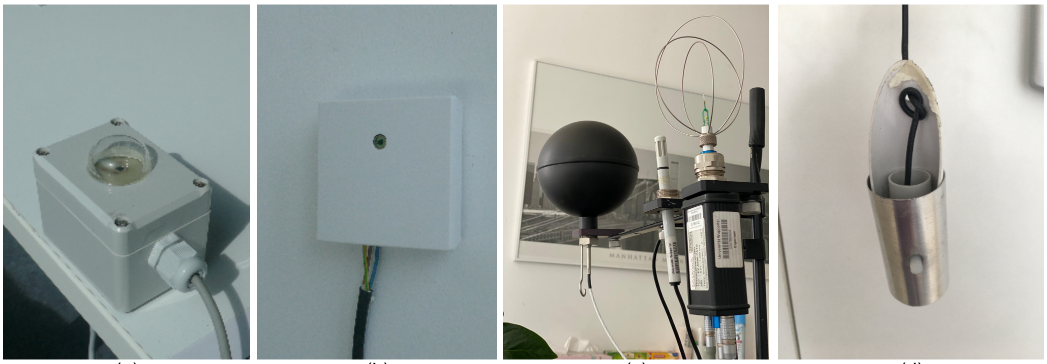
- Air and mean radiant temperature, relative humidity, and airflow were measured using thermal comfort instruments from AHLBORN. A thermal comfort stand was installed next to the workstation at 1.1 m height, according to ASHARE 55 standards, 2017 [2] (see Figure 4.4, c). Additionally, the room air temperature was measured using a radiation-protected head (type PT1000) on the north side of the test room (see Figure 4.4, d).
- Indoor horizontal illuminance was measured using light sensor (type WT-4000). The sensor was installed on the top surface of the desk workstation, a distant 0.60 m from the inner side of the window and 0.80 m above the floor level (see Figure 4.4, a). The vertical illuminance at the eye level was measured using an HFR/A brightness sensor. The sensor was mounted on the wall at 1.2 m height to the left side behind the test

subject (see Figure 4.4, b). Before the experiments, the participants were informed to keep the illuminance sensors unobstructed.

- Monitored outdoor environmental parameters included outdoor air temperature, precipitation, wind speed, global and diffuse radiation. The weather data were collected from a local weather station (HB), located on the rooftop of a four-story neighbouring building (see Figure 4.5, a). Vertical irradiance incident on the facade was measured using a pyranometer (CMP6 from Kipp & Zonen), mounted above the window on the south facade of the test room (see Figure 4.5, b).
- The external blind was actuated via DASYLab 2016 v14 software with the possibility to override the system using a wall-mounted switch (see Figure 4.3). Both system and user-triggered actions were recorded as event-based measurements.

Figure 4.3: Locations of indoor sensors in the test room.

Table 4.2 shows the main characteristics of indoor and outdoor probes used to collect data in this experimental study. Indoor environmental parameters (air temperature, vertical and horizontal illuminance) and blind adjustments were monitored using Advantech ADAM 4000 series A/D modules that collect the data for the DASYLab 2016 v14 software (see Figure 4.6, b). Thermal comfort parameters were monitored using data logger ALMEMO® 710 from AHLBORN, located on the top of the desk workstation behind indoor plant to avoid participant's attention (see Figure 4.6, a). For high resolution, the measurements of indoor and outdoor parameters as well as blind adjustments were recorded every 1 second. Thermal parameters were logged every 5 sec and weather data were recorded every 1 min.



(a) (b) (c) (d)

Figure 4.4: Indoor sensors (a) work plane illuminance sensor (b) vertical illuminance sensor (c) thermal comfort instruments (d) thermometer.

(a) (b)

Figure 4.5: Outdoor weather data using (a) Local weather station and (b) Pyranometer.

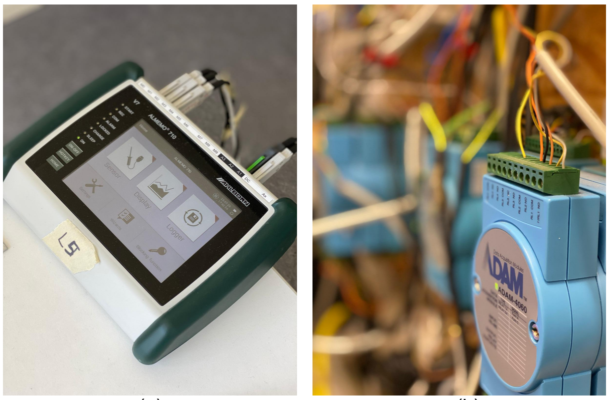
All measurements were averaged every 1 min for the analysis purpose. To reduce the measurements errors, the sensors of indoor temperature and illuminance measurements were calibrated.

4.2.3 Experimental procedure

The experimental study was conducted over 56 days between 6^{th} of July and 24^{th} of September, 2020. Each participant took part over two days for 7 hours and a half as a normal working day.

Participants

28 participants (11 males and 17 females) with different nationalities (64% German, 18% Palestinian, and 18% others) took part in the experiments. However, 43 participants were



(a) (b)

Figure 4.6: Data loggers (a) ALMEMO® 710 (b) Advantech ADAM 4000 A/D transformers.

Table 4.2: Technical characteristics of the indoor and outdoor probes.

Indoor probes sensors			
Model	Monitored parameters	Measurement range	Accuracy %
Globe thermometer	Mean radiant temperature [°C]	-40 to 200 °C	class B
Digital sensor	Dry bulb temperature [°C] Relative humidity [%]		N/A N/A
Air velocity probe	Air velocity [m/s]	up to 1 m/s	N/A
Light sensor type WT4000	Workplane illuminance [klux]	0-1 klux	± 3%
Brightness sensor with photo-diode type HFR/A	Vertical illuminance at the eye level	0-1 klux	< ± 5%
Outdoor probes sensors			
Pyranometer type CMP6 from Kipp & Zonen	Global solar irradiance on the façade [W/m^2]	0-max.2000 [W/m^2]	< 5%

estimated using G-power statistical tool to fulfill the requirements of the standard alpha (alpha = 0.05) and standard power (1 - beta = 0.8) (see Figure 4.7). The participants are students (36%) and researchers (64%) in the age range of 24-55 years old (mean of 33.21 years and median of 30 years). Participants were asked to perform regular office work during the day and interact with the test room systems as they usually do. The participants worked on their laptops during the experiment using the same monitor. The monitor is Dell P2714H with a typical luminance of 300 cd/m^2 (45% brightness and 75% contrast are display settings), fixed on the desk workstation and facing the east opaque wall of the test room. The participants took part in the experiments as volunteers without any rewards. Some of them were familiar with the general topic of the research. Participants had access to the view outside of a one-story building, distant about 20 m from the south façade.

Figure 4.7: Sample size calculation using G-power tool.

Questionnaire

A web-based questionnaire was constructed in LimeSurvey (i.e., online survey tool) to capture data that are not measurable with sensors and compare participants' subjective feedback with the monitored parameters. The design of the questionnaire was based on other related questionnaires used in previous studies [7, 62, 105, 1], and thermal comfort studies such as ASHRAE standard 55, 2017 [2]. New questions were added to achieve the aims of this study. A pilot study was conducted in 2019 with 32 participants to test their understanding of questions and the time needed to complete the survey. Participants were asked to complete the questionnaire after each scenario for 10-15 minutes, issued via e-mail 10 minutes before the end of each scenario. Depending on the setup conditions and users' responses, the questionnaire ranged from 28 to 41 questions (see Appendix A1.2). The questionnaire consists of the following sections:

- **Section 01**: General information: this section collected relevant demographic data about the participants (e.g., age, gender, current professional position, and nationality). This section was completed once time per day after the first scenario.
- **Section 02**: Adaptive control behaviors: this section asked participants how often they adjust different adaptive control options and why they do that or not (e.g., external blind, operable windows, artificial light, and ceiling fan).
- **Section 03**: Thermal comfort evaluation: this section evaluated the participants' thermal sensations using the ASHRAE 7-point scale [2], their clothing insulation level, comfort perception, and preferences.
- **Section 04**: Visual comfort evaluation: this section evaluated the lighting conditions and visual comfort perception in different scenarios. Additionally, questions about glare discomfort sources, glare magnitude using glare sensation vote scale (GSV) [16], and overall lighting satisfaction were asked.

- **Section 05**: User-blind satisfaction and preferences: participants were asked about their satisfaction with the performance of automated shading systems, the ability to override the blind position, and preferences regarding different shading control strategies.

- **Section 06**: Overall evaluation of the experiment: participants were asked to assess the workspace and the questionnaire throughout the entire measurement period.

Regarding the ethical consideration and data protection, participants were asked to proceed with the questionnaire if they agreed on the consent form shown at the beginning. This agreement states the rules or boundary conditions of this study. This form included:

- General information about the experiment, timeline and the scientific benefits of this research.

- The voluntary nature of the study and their right to withdraw their participation at any time.

- Confidentiality of their data, only the researcher can associate the responses with the identity.

Experimental sessions and scenarios

The experiments were conducted in two main sessions (Session A and B). The participants were asked to test three different scenarios in each session; each scenario endured for two hours. An introduction of 30 minutes before the experiments was meant to let the participants acclimatize[1][97] to the test room indoor environment. Besides, general information and instructions were given and explained to the participants. Participants were advised to interact with different room systems (e.g., shading systems, artificial light, ceiling fan, and operable windows) as usual as in their work offices. They test their private PC connection with the desk monitor and internet access. Participants were asked to keep the door closed during the experiment, the brightness sensors unobstructed, and the monitor fixed. The participants took an hour lunch break between the first and second scenario and a 10-minute break after the second scenario. The total session duration was 7 hours and a half, including the introduction (see Figure 4.8).

Session A included S01, S02 & S03, was carried out over 28 days from the 6^{th} of July until mid-August 2020. The experiments took place from 9:00 am until 4:40 pm over the day. Session B included S04, S05 & S06, was conducted over 28 days from the mid of August until the end of September 2020. The experiments in session B was shifted 30 minutes at the beginning of the day to ensure more direct sunlight in the first scenario. Table 4.3 summarizes the setup settings of the indoor environment in each scenario during the experiments. The main scenarios are:

[1]Acclimation is the process in which an individual organism adjusts to a change in its environment (such as a change in altitude, temperature, humidity, photo-period, or pH), allowing it to maintain performance across a range of environmental conditions. Source: Wikipedia.

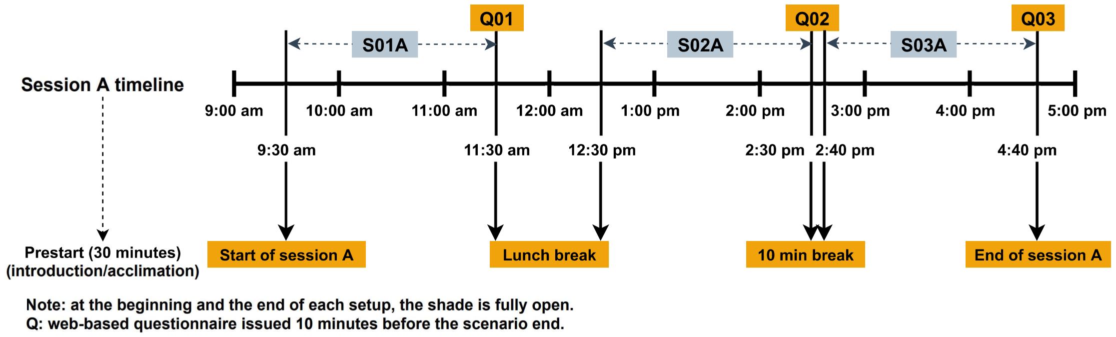


Figure 4.8: Timeline of the experimental study (Session A).

- **S01A**: In this scenario, participants were able to override the blind and turn on/off the electric light. The automated blind was activated based on a simple control strategy (shade lowering threshold was if irradiance on the facade exceeded 300 W/m^2) (see Figure 4.12). During the night and before the experiment day, the cooling system was activated in the test room to ensure a minimum indoor temperature of 21 °C. Thus, the windows were closed in this scenario and the inlet air was always on at ambient conditions.

- **S02A**: In this scenario, participants were given the control of the external blind, electric lighting, and the operable windows (left and right). Simple shade control strategy was used (300 W/m^2). The "measuring room" was in non-active cooling mode. An electric heater was used often during the lunch break to increase the room temperature as the ambient conditions.

- **S03A**: Same control systems were used as in S02A. Blind was activated based on a multi-objective control strategy (see Figure 4.13). Non-active cooling was used.

- **S04B**: Participants were able to override the blind, adjust the operable window, turn on/off the light and fan. Simple shade control strategy was used (300 W/m^2).

- **S05B**: Blind, operable window, and light switch adjustments were allowed. Simple shade control strategy was used (300 W/m^2). The window-to-wall ratio (WWR) was reduced to 40% (original design was 75%) using EPS foam insulation boards (3 cm thickness) as external cover for parts of the glazing (see Figure 4.9). Non-active cooling was used.

- **S06B**: Same control systems were used as in S04B. Irradiance threshold was set up to 450 W/m^2. WWR was 40%. Non-active cooling was used.

Table 4.3: Summary of the setup settings and control options for each scenario.

	Adaptive control options						
Scenarios	Operable windows	Artificial lighting	External blind	Ceiling fan	Shading control strategy	Ventilation strategy	WWR%
S01A	Fully closed	User operated	Fully automated with manual override	not used	Simple control strategy (shade lowered if Ir exceeded 300 W/m^2)	active cooling (minimum indoor temperature of 21 °C)	75%
S02A	User operated	User operated	Fully automated with manual override	not used	Simple control strategy (shade lowered if Ir exceeded 300 W/m^2)	non-active cooling	75%
S03A	User operated	User operated	Fully automated with manual override	not used	Multi-objective control strategy	non-active cooling	75%
S04B	User operated	User operated	Fully automated with manual override	User operated	Simple control strategy (shade lowered if Ir exceeded 300 W/m^2)	non-active cooling	75%
S05B	User operated	User operated	Fully automated with manual override	not used	Simple control strategy (shade lowered if Ir exceeded 300 W/m^2)	non-active cooling	40%
S06B	User operated	User operated	Fully automated with manual override	User operated	Simple control strategy (shade lowered if Ir exceeded 450 W/m^2)	non-active cooling	40%

(a) Exterior view (b) Interior view

Figure 4.9: WWR reduced to 40% using EPS insulation board.

4.2.4 Controlled indoor environment parameters

Based on the key findings of the experimental study conducted in 2019, limited quality and accuracy of commercial shading devices were found (see section 3.3.2). To this end, the author developed a programmed algorithm in DasyLab software based on a high-quality Pyranometer (type CMP6 from Kipp&Zonen) to control the external shading system. In all scenarios, the blind control was fully automated with the ability to override the system using a wall-mounted switch next to the test room entry (see Figure 4.10, b). After user intervention, the automatic operation was disabled for 10-15 minutes using a timer relay (type E1ZM10, 24-240 V AC/DC) from the ENYA series. The blind position was reset to a fully open position at the end of each scenario to avoid the influence of the current shade position on the next one.

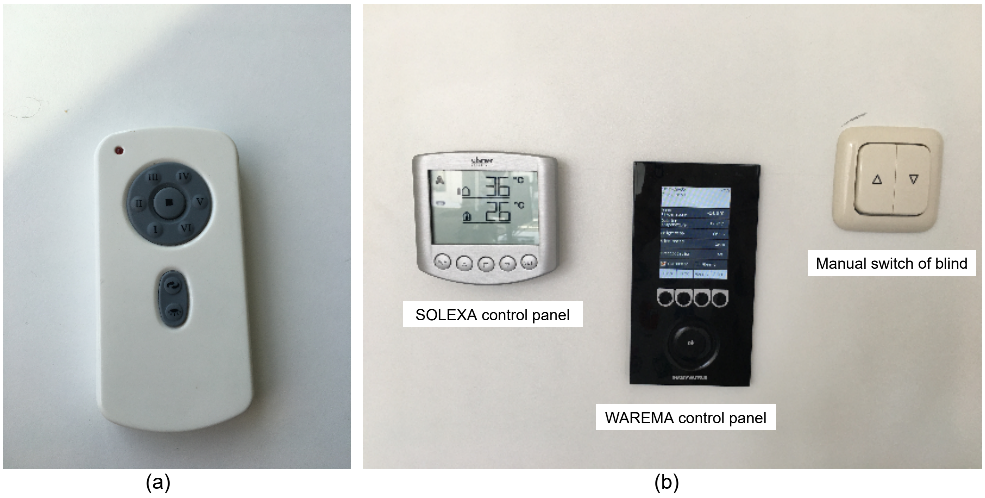


Figure 4.10: Control interfaces of devices (a) Remote control of the ceiling fan (b) Control panels of the blind, only the manual switch to the right was used in the scenarios.

The author developed two control strategies for activating the blind: (a) simple control strategy and (b) multi-objective control strategy based on occupant-centric parameters. The algorithms were created using the graphical programming of the DASYLab 2016 v14 software (see Figure 4.11).

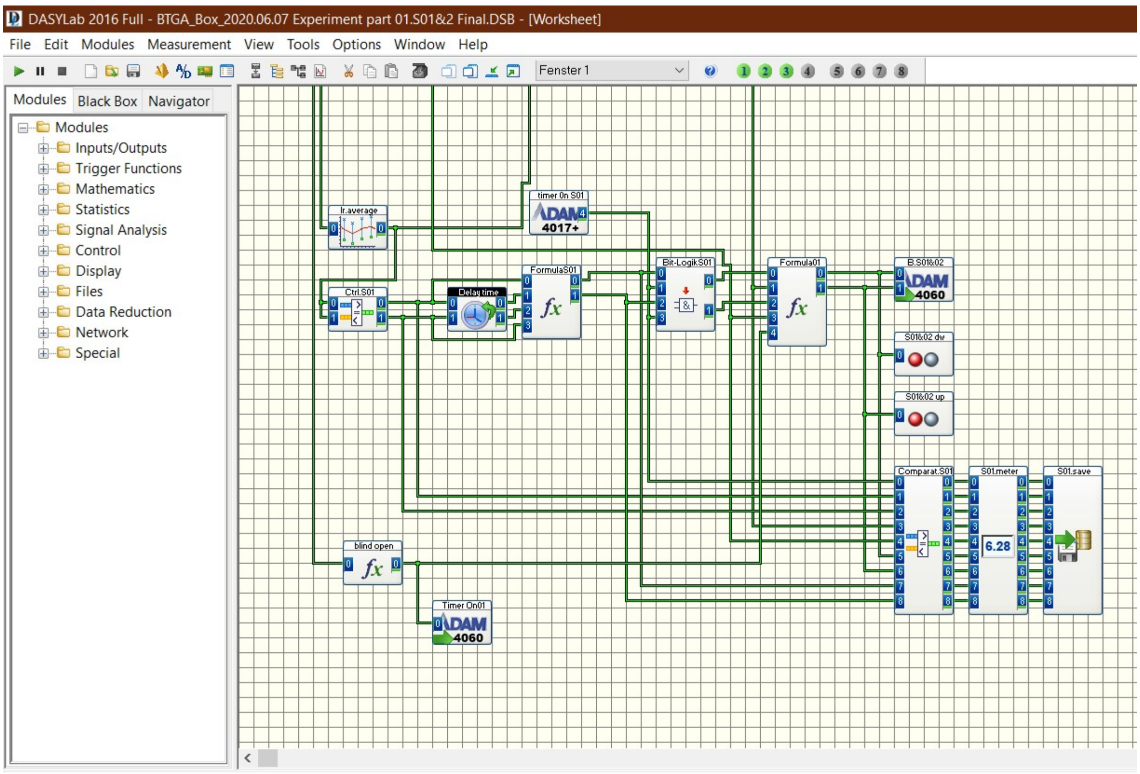


Figure 4.11: DASYLab worksheet of simple control strategy programming.

(a) Simple shade control strategy:

A simple control where the shading is fully deployed whenever a predetermined threshold is exceeded, simulating the simplified way blinds are commonly treated within building design and energy calculation. Figure 4.12 shows the flow chart of the simple control strategy. The blind was lowered if solar irradiance on the facade (Ir) exceeded 300 W/m^2 according to DIN EN ISO 52016-1 standards [59] , or 450 W/m^2 according to Reinhart and Voss [101] findings in their field study. They found that lowering of the blinds was only accepted if incident solar gains were as high as 450 W/m^2. While the blind was retracted when Ir was less than 100 W/m^2. To avoid continuous on-off of the blinds (a) the shade control system was provided with a 5-min delay when blind was lowered and a 10-min delay when blind was retracted, (b) 50 W/m^2 was used as a hysteresis threshold, and (c) irridiance measurement was averaged every 5 min.

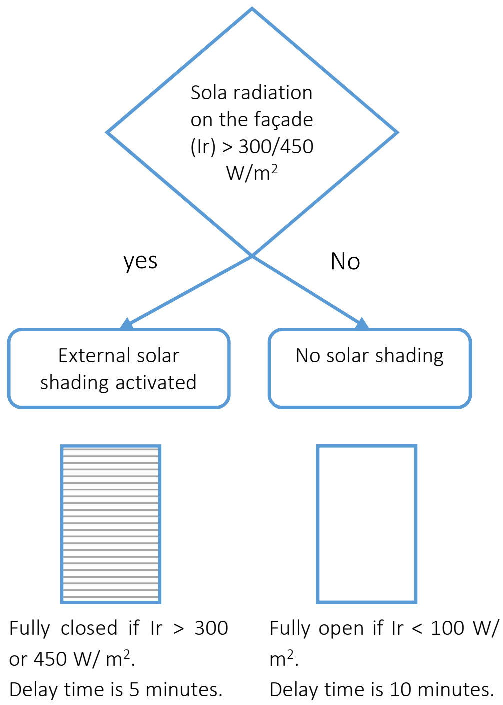


Figure 4.12: Flow chart of simple control strategy.

(b) Multi-objective control strategy:

A more detailed control strategy was developed to avoid glare and overheating as well as ensure a view to the outside by utilizing the intermediate position. Thermal comfort was controlled by fixing the indoor temperature setpoint consistent with the comfort conditions of class II of EN ISO 15251:2007 [17]. Two indices were used in the shading system control to ensure visual comfort requirements: (a) fixing a maximum limit value of glare index measured by vertical illuminance at the eye level and (b) a minimum workplane illuminance level. Accordingly, the blind was activated in three different positions (see Figure 4.13):

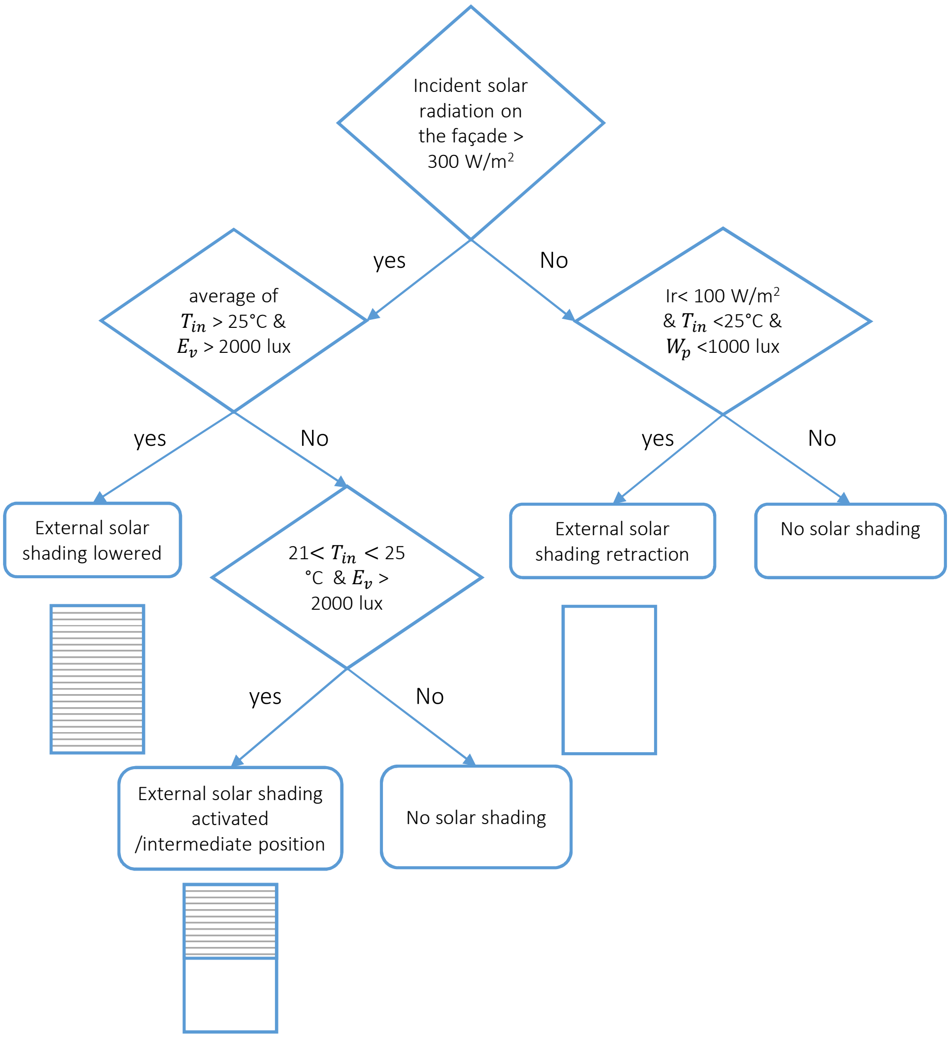


Figure 4.13: Flow chart of multi-objective control strategy.

- The blind was fully lowered if (a) the incident irradiance (I_r) on the facade exceeded 300 W/m^2 [59], and (b) the indoor vertical illuminance at the eye level exceeded 2000 lux (maximum limit value for the glare index) [63], and (c) indoor air temperature (T_{in}) was above 25 °C (consistent with the comfort conditions of class II of EN ISO 15251:2007) [127]. Vertical eye illuminance (E_v) was used as a simple indicator for discomfort glare in this study. Karlsen et al. [63] found that the threshold for E_v measured close to the occupants' eye view should be in the range of (1000-1700) lux.
- If the indoor air temperature was in the range of 21 to 25 °C and indoor vertical illuminance at the eye level was above 2000 lux; the blind was lowered to the

intermediate position.

- The blind was fully open if I_r was below 100 W/m^2 and indoor temperature was less than 25 °C. Workplane illuminance (W_p) -at the left top side of the workstation- was below 1000 lux to ensure that W_p is below 500 lux in the middle point according to EN 17037:2019.

The blind control was based on a moving average every one hour of indoor temperature measurements to consider the slow temperature changes. In the first scenario of the experiment, the test room was controlled to maintain indoor air temperature around 21 °C using the radiant cooling system in the ceiling. The heat pump cooling mode was turned on one day before the experiment and turned off after the end of the scenario. The indoor temperature was calibrated using a wall-mounted thermostat based on the thermometer measurements as a scientific reference. An electrical heater was often used during the lunch break to increase the indoor temperature to around 24 °C (see Figure 4.14).

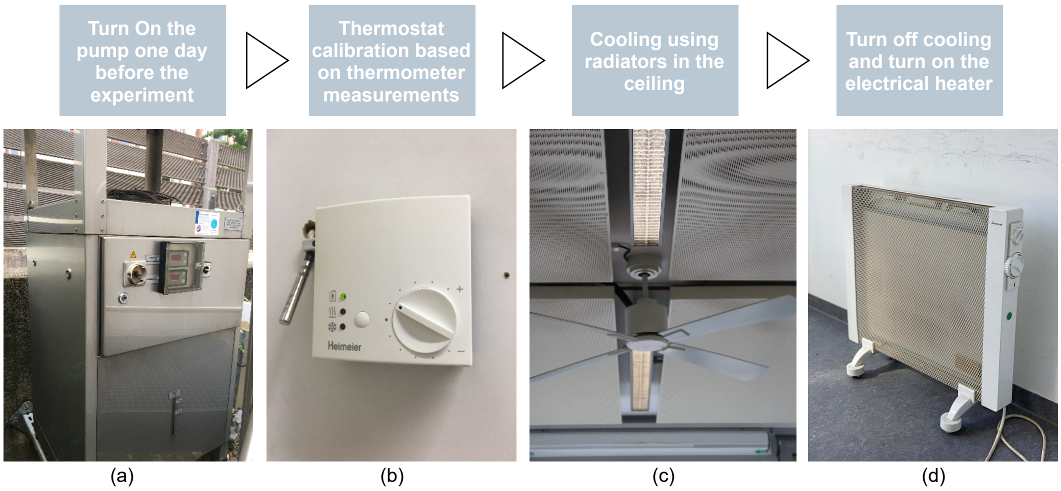


Figure 4.14: Heating and cooling control in the test room (a) Heat pump (b) Thermostat (c) Ceiling radiators (d) Electrical heater.

4.2.5 Local weather during the experiment

This study was conducted over 56 calendar days from July until September 2020. Figure 4.15 shows the minimum, maximum, and daily average of outdoor temperature and global radiation for the entire study period. The daily mean outdoor temperature was in a range of 9.6 °C and 27.3 °C. The highest daily average was 35.32 °C measured between the 8^{th}-10^{th} of August, while the lowest was 7.75 °C recorded at the 6^{th} of September. The daily mean of global radiation was in a range of 22.4-347.4 W/m^2. A total of 31 sunny, partly cloudy days and 25 cloudy days were classified based on the daytime average of global radiation[2]during the whole study period (see Table 4.4).

[2]https://de.wikipedia.org/wiki/Sonnenschein

Table 4.4: Sunny and cloudy days classifications.

Sky condition	Average of global solar irradiance	Session A	Session B
Sunny, clear sky	600-1000 W/m^2	0	0
Sunny, partly cloudy	300-600 W/m^2	19	12
Cloudy, fog	100-300 W/m^2	9	16

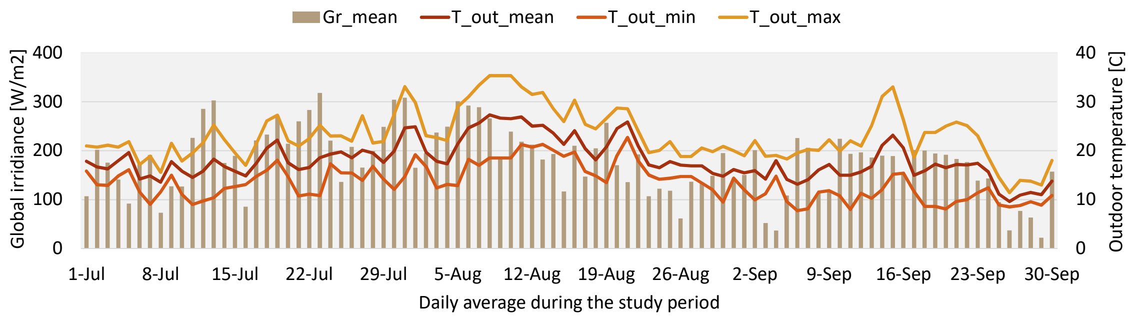


Figure 4.15: Daily average profile of max/ mean/ min outdoor temperatures and global horizontal radiation during the study period.

4.3 Data analysis and metrics for performance assessment

Different indicators and metrics were used to evaluate the performance of automated shading systems related to shade occlusion, user override actions, thermal and visual conditions in this experimental study. Statistical analysis was applied to the monitored and collected data of different scenarios in SPSS software. The results were visualized using box-plot distribution (see Figure 4.16) and stacked bar charts in OriginLab 2020. The highest and lowest average values of all scenarios (S01-S06) were analyzed and discussed. Then, paired groups of different scenarios were tested and compared using paired t-test statistical analysis to find the robust shading control strategies and optimal design solutions.

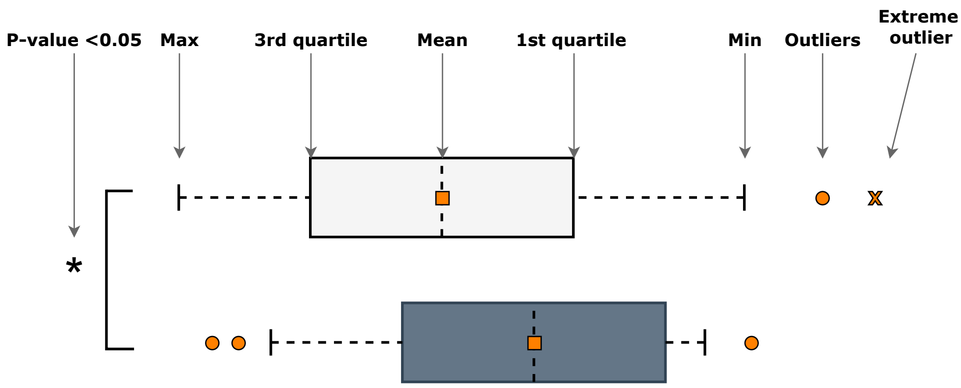


Figure 4.16: A statistical box-plot schematic diagram

4.3.1 Shade deployment metrics

There are two metrics consistently used throughout the literature: mean shade occlusion (MSO) and shade movement rate [95] or "rate of change" [124]. Mean shade occlusion is defined as the average fraction when the shades are closed. The concept of "blind occlusion value" was stated by Foster and Oreszczyn [31] and used to describe the blind position. MSO is a representative of the preferred shade position in occupant behaviour models and indicative of interior daylight level and the mean thermal properties of the facade in case of individual shade position [95]. Previous studies developed various methods to record the blind position using photographic processing or time-lapse photography [95]. In this study, a different method was used. Automatic shade adjustments and user override actions were recorded using a data acquisition system, including A/D transformer of analog signals to digital ones (off = 0 and on= 1). MSO was defined as the percentage of an occluded blind at a specific time (0%= fully open, 100% = fully closed). Figure 4.17 illustrates the five positions of blind occlusion described in this study and two positions of slat angles (0°= slat open, 90°= slat closed).

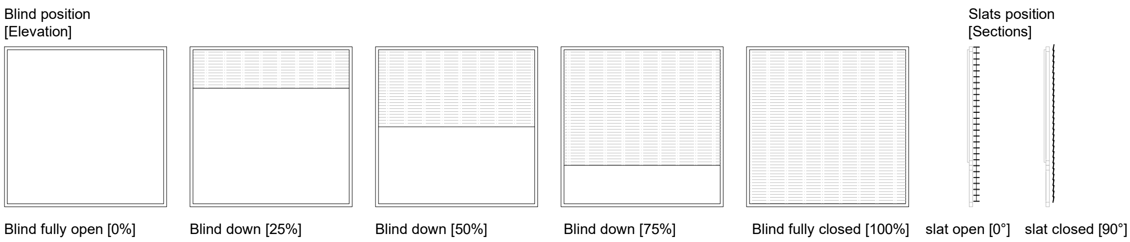


Figure 4.17: Positions of blind occlusion and slat angle used in this study.

Another critical aspect of understanding shade use patterns is shade adjustments frequency. Different terms and definitions were used to describe the blind use frequency. O'Brien et al. [95] defined the shade movement rate (SMR) as the fraction of shades that moved between two discrete times. It helps identify the triggers that may have caused occupants to adjust their shades, but it is not as useful in direct use in occupant behavior models. "Rate of change" is used to describe the shade adjustments frequency as a percentage of blinds that move per day by facade or building. However, in the case of motorized or automated systems, it was reported as the number of movements per day/window or office [125].

Meerbeek et al. [86] defined user correction as user reaction to the system's movement and involved a user-initiated adjustment of the blind position. They calculated user correction by counting the times a user corrected a system for each condition, divided by the total amount of system-triggered actions averaged over participants. In this study, the user correction (C) is defined as the number of user-shade override adjustments (UOAs) per each scenario divided by the total number of user and system-triggered actions (SA_{total}) without averaging (within-subject design)(see equation 4.1).

$$C = UOAs(perscenario)/SA_{total} \tag{4.1}$$

4.3.2 Thermal comfort metrics

Several indices were used to estimate thermal sensation and comfort in the current study under the different scenarios. Fanger's Predicted Mean Vote (PMV) model, the adaptive model according to CEN standard EN 15251, and Standard Effective Temperature (SET) by Gagge et al. [35] were applied to assess thermal comfort conditions.

Predicted mean vote (PMV)

Predicted Mean Vote (PMV) is a method to measure the level of mean occupant thermal sensation. Fanger's model (PMV) was derived from laboratory and climate chamber studies. In these studies, participants were dressed in standardized clothing and completed standardized activities while exposed to different thermal environments [1]. Fanger's model is the most widely used thermal comfort index that predicts occupants' thermal perception in the steady-state indoor environment based on the ASHRAE seven-point thermal sensation scale (see Figure 4.18). To experimentally evaluate the thermal comfort by PMV method, a combination of air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation were measured. The operative temperature (T_{op}), predicted mean vote (PMV), and predicted percentage dissatisfied (PPD) indices were calculated using the thermal comfort tool (comfort index calculator version 1.0, 2018, IEQ lab, USYI) provided from ASHRAE Standard 55-2013. Some of the calculations were repeated using CBE Thermal Comfort Tool [3], no difference was found. The satisfying thermal condition was achieved when PMV value was between -1 and +1. Table 4.5 shows predicted percentage dissatisfied (PPD) based on the predicted mean vote.

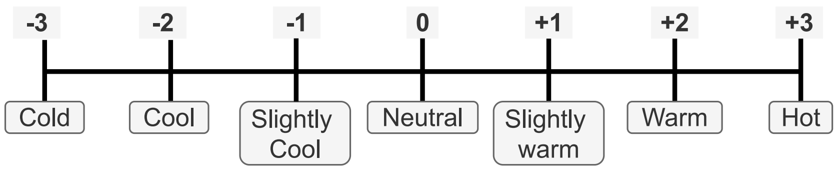


Figure 4.18: ASHRAE seven-point thermal sensation scale (ASHRAE Standard 55 2017).

Table 4.5: ASHRAE seven-point thermal sensation scale (ASHRAE Standard 55 2004, ISO 7730:2005)

Comfort	PPD%	range of PMV
Cat. A	<6	$-0.2 < PMV < 0.2$
Cat. B	<10	$-0.5 < PMV < 0.5$
Cat. C	<15	$-0.7 < PMV < 0.7$

[3]Source: https://comfort.cbe.berkeley.edu/

Clothing insulation and metabolic rate

Adding and taking off of clothing is the main adaptive mechanism used by the participants to adapt thermal comfort conditions. The clothing insulation was estimated according to ASHRAE 55-2017 standards using the following formula:

$$Icl_{tot} = \sum Iclu_I \tag{4.2}$$

Where Icl_{tot} was the insulation of the entire ensemble and $Iclu_I$ was the insulation of the individual garments listed in Appendix A1.4 [38]. After each scenario, the participants reported the clothing garments while completing the questionnaire. Metabolic rate was 1.1 met which relates to seated office activities (ASHRAE standard 2017) (see Appendix A1.4).

Actual mean vote (AMV)

Each participant's actual mean vote (AMV) was reported by a web-based questionnaire using the ASHRAE seven-point scale of thermal sensation (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot) after each scenario. The actual mean vote was then compared with the predicted thermal sensation using the PMV model.

Operative, comfort and standard effective temperature

- **Operative temperature** (T_{op}): is one of the main parameters that describe thermal comfort. It is a value of the thermal climate feeling as a function of the location in a room. A simplification is made using a surface area and averaged overall surface temperature. It was calculated as the average of air and mean radiant temperatures if occupants are engaged in near sedentary physical activity with metabolic rates between 1.0 met, and 1.3 met, not in direct sunlight, and not exposed to air velocities greater than 0.20 m/s as follows:

$$T_{op} = (T_a + T_r)/2 \tag{4.3}$$

- **Comfort temperature** (T_{com}): is the operative temperature at which either the average person will be thermally neutral or at which the largest proportion of a group of people will be comfortable. A person in comfort is taken to be "slightly cool," "neutral," or "slightly warm" on the ASHRAE scale (ASHRAE standard 55). In this study, T_{com} was calculated from the comfort votes by assuming that a comfort vote of neutral will represent an estimate of comfort using Griffiths' method. The following equation was used for the calculation:

$$T_{com} = T_{op} - (C - C_n)/G \tag{4.4}$$

Where T_{com} is the comfort temperature, T_{op} is the indoor operative temperature, C is the comfort vote, C_n is the comfort vote of neutral =0, and G is the Griffiths' slope

(K^{-1}). In this study, G value was used as 0.5 K^{-1}, it is the most likely used value in previous studies [37, 38, 88].

- **Standard effective temperature** (SET) is a comprehensive comfort metric, measuring the equivalence of any combination of environmental factors, clothing and metabolic rate, and taking skin temperature and wittedness into account [35]. According to ASHRAE standard 55-2017 [2], the SET is "the temperature of an imaginary environment at 50% relative humidity, <0.1 m/s average air speed, and mean radiant temperature equal to average air temperature, in which the total heat loss skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment". The comfortable and acceptable range of SET was assumed to be between 22.2 to 25.6 °C, which is equivalent to sensation vote range (-1 to +1) (see Table 4.6).

Table 4.6: Thermal sensation scales. Source (Rosenlund 2000) [1].

	ASHRAE	Fanger	SET [°C]
hot	7	+ 3	34.5-37.5
warm	6	+ 2	30.0-34.5
slightly warm	5	+ 1	25.6-30.0
neutral	4	0	22.2-25.6
slightly cool	3	- 1	17.5-22.2
cool	2	- 2	14.5-17.5
cold	1	- 3	10.0-14.5

Adaptive model

Adaptive models are used in several standards, including EN16798-1:2019 standards and ASHRAE Standard 55. The adaptive thermal model in the latter was derived from a global database of 21,000 measurements taken primarily in office buildings. The standard uses the relationship between indoor operative temperature and outdoor temperature. Two ranges of the acceptable operative temperature were defined according to ASHRAE standard 55, 2017. 80% acceptability for typical applications and 90% acceptability applied when higher thermal comfort standards are desired. In this study, the 80% for the acceptable range of operative temperature (22.1 to 29.1 °C) was used (see equation 4.5), AMV values equal to ± 0.85 for 80% acceptability limits.

$$Top = 0.31 * tpma(out) + 17.8 \pm 3.5 \tag{4.5}$$

where: T_{op} is the indoor operative temperature (°C), and t_{pma} (out) is the prevailing mean outdoor air temperature. The running mean temperature T_{rm} for any given day is expressed in equation 4.6 from the records of outside air temperature measured during the current experimental study [37]:

$$T_{rm} = T_{ed-1} + 0.8T_{ed-2} + 0.6T_{ed-3} + 0.5T_{ed-4} + 0.4T_{ed-5} + 0.3T_{ed-6} + 0.2T_{ed-7}/3.8 \quad (4.6)$$

where T_{rm} is the running mean temperature for today, T_{ed-1} is the daily mean external temperature for the previous day, T_{ed-2} is the daily mean external temperature for the day before and so on, and α is a constant between 0 and 1 (recommended to use 0.8) [89].

4.3.3 Visual comfort metrics

In this study, different performance metrics were used to evaluate the visual comfort conditions under different scenarios during the experiment. These metrics are described as follows:

- **Workplane illuminance** (W_p): Horizontal illuminance is commonly used as an indicator of daylight sufficiency. According to EN 12464-1 (2001) standards, sufficient daylight is insured over the workplane when the average illuminance level is at least 500 lux for office buildings. The current study assumed the useful daylighting illuminance (UDI) between 300-3000 lux for horizontal workplane illumination [87].
- **Vertical illuminance at the eye level** (E_v): It was used as a simple indicator for glare discomfort in this study. Karlsen et al. [63] found that the threshold for vertical illuminance measured close to the occupants' eye view should be in the range of 1000-2000 lux.
- **Simplified discomfort glare probability** (DGPs): It is a simplified DGP based on vertical eye illuminance (E_v) (see equation 4.7), developed and validated by Wienold [131]. Reasonable results showed from DGPs model when no peak glare sources where present. Moreover, DGPs is a simple and computationally effective measure of glare discomfort that gives a reasonable predictions of glare which can be used in the early building design decision making. DGPs has the potential of being incorporated in solar shading control strategies [63]. The current study assumed 0.35 as the upper limit of DGPs for acceptable values.

$$DGPs = 6.22 * 10 - 5.Ev + 0.184 \quad (4.7)$$

- **Glare sensation vote** (GSV): participants were asked for their subjective feedback about the glare sensation. The magnitude of glare was measured with a glare sensation vote (GSV) ordinal scale. The participants were asked to rate the perceived glare sensation according to the four-point scale (1= imperceptible, 2= noticeable, 3= disturbing, 4= intolerable) [39]. Table 4.7 shows the equivalent of GSV votes to DGPs index values.

Table 4.7: Glare discomfort indices.

Discomfort glare criteria	Glare range values GSV	DGPs
Imperceptible	1	<0.30
Noticeable	2	0.30-0.35
Disturbing	3	0.35-0.45
Intolerable	4	>0.45

- **View-to-the outside**: Access view to the outside was reported as an important contributor to the visual comfort perception in a room in several studies [18]. According to DIN EN 17037:2019-03, horizontal sight angle, outside distance of the view and the visible layers of outside environment such as sky, landscape and ground are included in the visual comfort evaluations. Additionally, the view to outside is another relevant issue when assessing the performance of a shading device [105]. Therefore, the satisfaction of view-to-the outside was assessed on a five-point scale (1: very dissatisfied, 5: very satisfied) through the web-based questionnaire.

4.4 Results and discussions

In this section, the analyses and outcomes from the experiments are presented in relation to the occupants' interaction and satisfaction with the automated shading systems and the underlying thermal and visual conditions under the different scenarios.

4.4.1 Shading patterns

This study aims to explore and quantify occupants behavioural patterns related to the use of automated shade systems and their satisfaction under different conditions. Therefore, two commonly-used metrics were used to analyze the shade behavioural patterns: (a) mean shade occlusion (MSO) and (b) frequency of shade adjustments.

Mean shade occlusion

The automatic shade operation and user override actions induce the blind position. To estimate the blind position, the author developed a python script based on the signal length. Considering that the total time of a fully blind closure was 52 seconds, the blind position ratio was calculated based on the blind movement signal length (up or down) divided by the total time of blind closure. Real position values were then rounded to one of the five shade positions (0%, 25%, 50%, 75%, 100%). Figure 4.19 illustrates the blind position real and rounded values in S05 during a reference day (02.09.2020).

Figure 4.20 demonstrates the relative frequency of the blind five positions (0%: fully open, 25%, 50%, 75%, and 100%: fully closed) for each scenario during the experiment. It is observed that the blind was fully open most of the time (90%) in S01 and 65% in S04. In S03, the blind was in intermediate position nearly half of the time (54%). More than half of

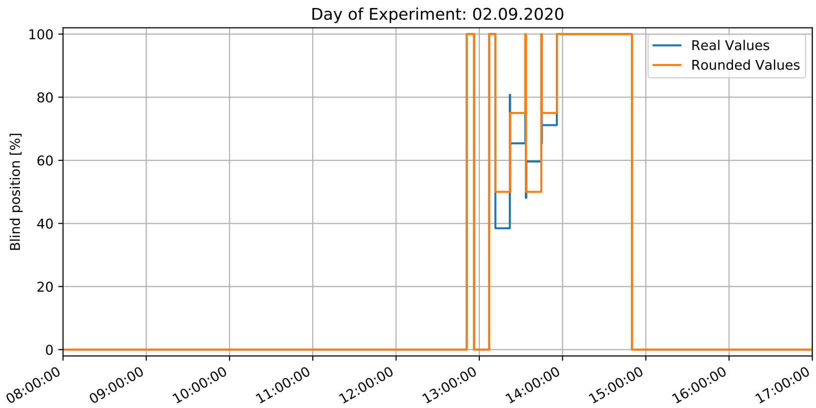


Figure 4.19: Real and rounded values of blind position during a reference day(02.09.2020).

the time, the blind was fully closed in S02, S05, and S06 (65%, 57%, and 54%, respectively). Moreover, Figure 4.21 shows that the highest average of blind occlusion values was in S02, S05, and S06 (74%, 65%, and 63%, respectively), while the lowest average was observed in S01 (7%). In S03 and S04, the mean shade occlusion was 46% and 31%, respectively. The difference in MSO is explained due to the variations of incident radiation on the facade and the time of the day. Paired t-test was used to clarify the significant difference in mean shade occlusion between the paired groups of scenarios (see Table 4.8). The results are summarized:

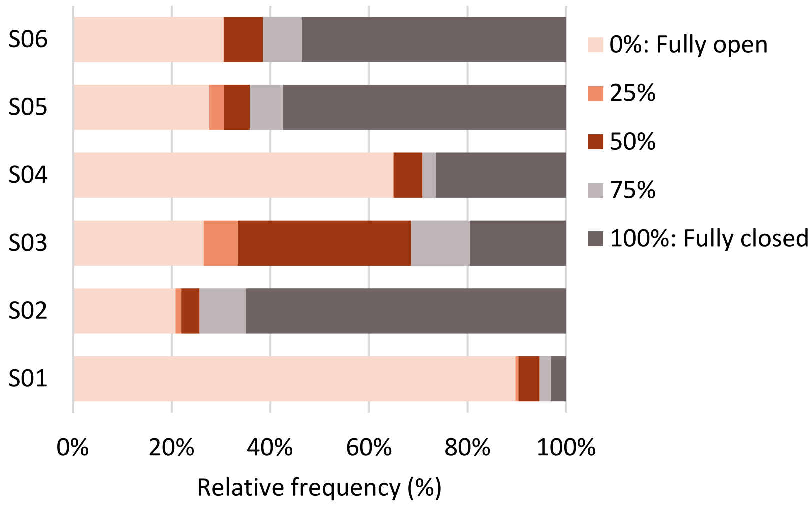


Figure 4.20: Relative frequency of the blind five positions (0%: fully open, 25%, 50%, 75%, and 100%: fully closed) for each scenario.

- Case 01 [S01 vs. S02]: A statistically significant difference (p-value < 0.05) was found between the average shade occlusion in S01 (active cooling mode) and S02 (non-active cooling). This difference can be interpreted due to high variations of incident radiation between S01 (ø= 157 W/m^2) and S02 (ø=388 W/m^2) (see Figure 4.21). In this case,

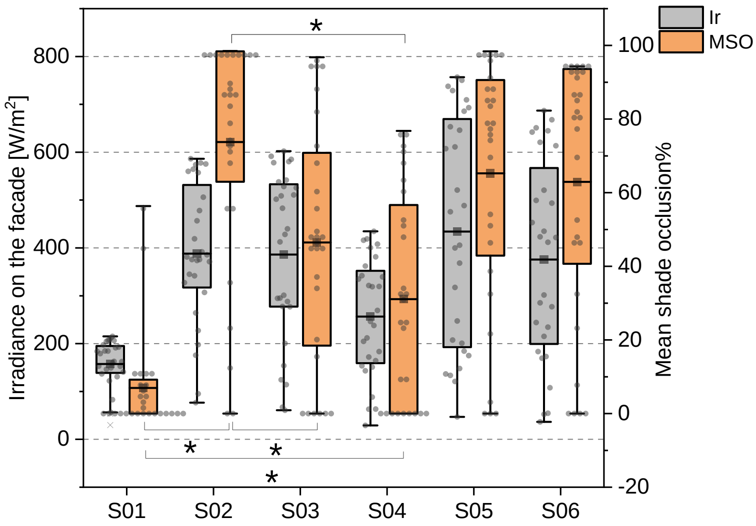


Figure 4.21: Box-plot distribution of MSO related to solar irridiance on the facade for each scenario.

it is difficult to verify the influence of cooling mode compared to free-running mode on shade deployment, since the main influence is likely to be the time of the day and not the scenario.

- Case 02 [S02 vs. S03]: Significantly, the MSO was higher in S02 compared to S03. This is explained due to using two different shade control strategies since non-significant variation was observed in incident radiation between both scenarios (p-value = 0.92). It is concluded that using the multi-objective control strategy maximized the view-to-the outside more than the simple one, keeping in mind that both were designed to prevent glare discomfort (see Figure 4.22).

- Case 03 [S02 vs. S04]: Higher shade occlusion average was observed in S02 (73.7%) compared to S04 (31%), considering that solar irradiance average was lower in S04.

- Case 04 [S02 vs. S05]: Non-significant difference was found between mean occlusion value in S02 (WWR% = 75%) and S05 (WWR%= 40%) (p-value = .383). It is expected as both have the same shade control strategy (300 W/m^2), where the main driver behind shade deployment is the outdoor solar irradiance. In this case, it is concluded that window size does not affect the mean shade occlusion value.

- Case 05 [S01 vs. S04]: A statistically significant difference was found in the mean occlusion value between S01 (7%) and S04 (31%). The cooling system was active in S01 while not in S04. However, the difference in MSO was explained because of high solar irradiance variations.

- Case 06 [S05 vs. S06]: We expected a higher occlusion value in S05 (shade lowering threshold = 300 W/m^2) compared to S06 (450 W/m^2). However, non-significant difference in blind occlusion value was observed (p-value = 0.47). 30% of user-shade lowering actions occurred in S06 compared to 9% occurred in S05. It is suggested that participants tend to lower the blind more frequently in S06 to avoid the glare occurrence.

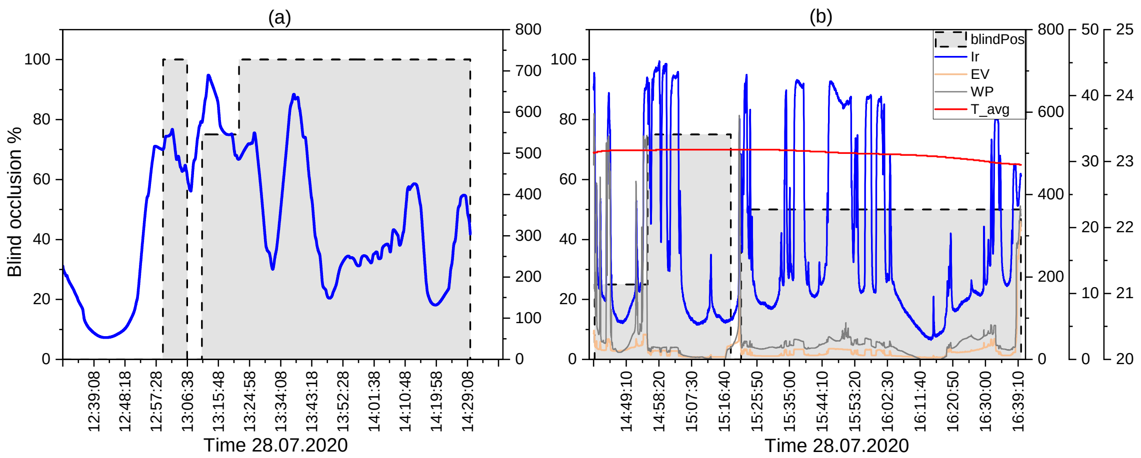


Figure 4.22: Hourly blind occlusion % during a reference day using (a) simple shade control strategy, and (b) multi-objective strategy.

Table 4.8: Paired t-test results of mean shade occlusion under different scenarios.

	MSO %		Paired t-test		
Cases	Scenario 01	Scenario 02	t	df	Sig. (2-tailed)
Case 01	S01: 7%	S02: 73.7%	-11.865	27	.000
Case 02	S02: 73.7%	S03: 46.5%	6.096	27	.000
Case 03	S02: 73.7%	S04: 31%	4.85	27	.000
Case 04	S02: 73.7%	S05: 65%	.887	27	.383
Case 05	S01: 7%	S04: 31%	-4.022	27	.000
Case 06	S05: 65%	S06: 63%	.731	27	.471

Based on the aforementioned findings, the following points are concluded:

- The mean occlusion value was highly affected by solar irradiance on the facade since each scenario has different frequency distribution during the day (see Figure 4.23). Moreover, a high correlation was observed between the incident radiation and mean shade occlusion, as illustrated in Figure 4.24. This is in line with Mahdavi et al. [82] findings as a strong evident relationship between shade deployment, and the magnitude of solar irradiance was found in their field study. Based on these findings, solar irradiance on the facade is a critical parameter that building designers should consider during the selection of optimal shading control strategy to ensure less disturbing hours of view-to-the outside.

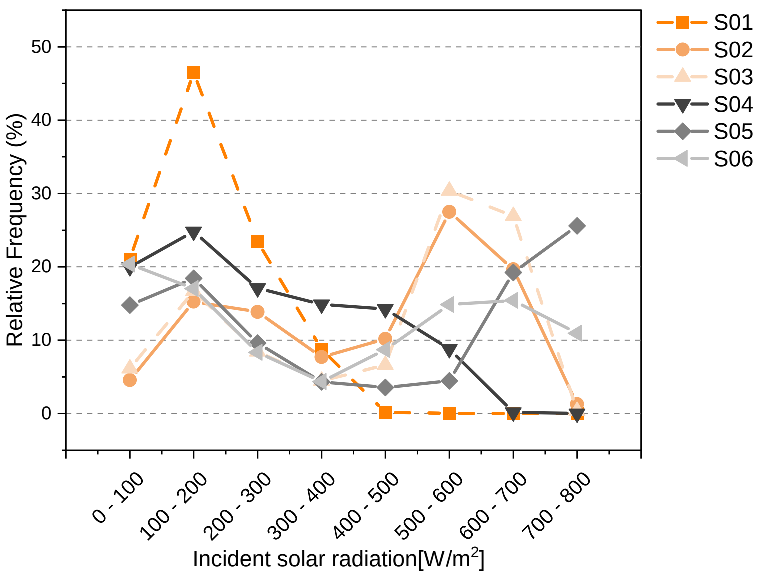


Figure 4.23: Relative frequency of solar irradiance on the facade for each scenario.

- Using the multi-objective control strategy significantly decreased the MSO compared to the simple one. However, both scenarios almost have the same frequency distribution of solar irradiance. This result underlines that the multi-objective control strategy, operating with intermediate positions, can help the occupants maintain a closer connection to the outdoor environment. Thus, it can be considered a robust shading design solution.

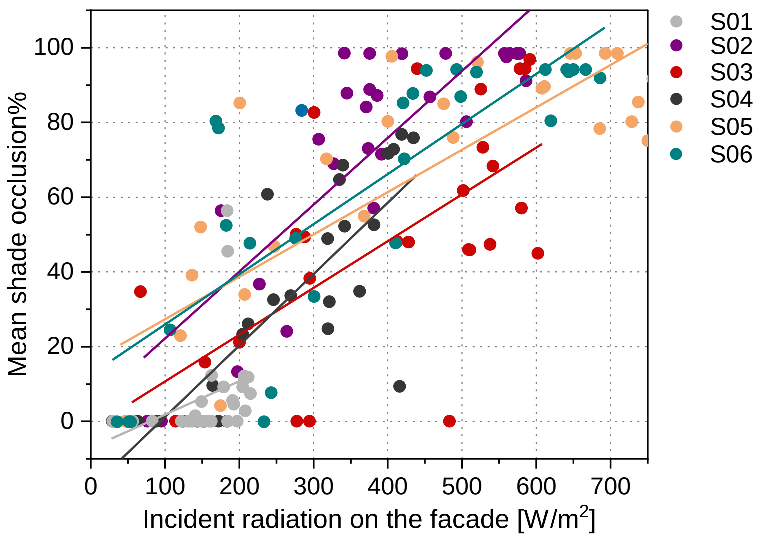


Figure 4.24: Linear regression correlation between MSO and incident irradiance for each scenario.

Shade adjustments frequency

Table 4.9 summarizes the user and system-triggered actions (lowering, raising and total adjustments) for each scenario during the entire study period. A total number of 976 blind adjustments was recorded over 56 calendar days. Approximately 30% (292) of these adjustments were triggered by the users. A sum of 67 lowering actions and 225 raising override actions.

Table 4.9: Total numbers of shade lowering and raising actions for each scenario.

	Lowering			Raising		
	system-triggered	user-triggered	Total adjustments	system-triggered	user-triggered	Total adjustments
S01	16	4	20	65	3	68
S02	113	11	124	46	56	102
S03	19	26	45	39	7	46
S04	65	0	65	45	45	90
S05	99	6	105	44	71	115
S06	72	20	92	61	43	104
Total	384	67	451	300	225	525

Figure 4.25 shows the relative frequency of shade adjustments for each scenario. In terms of user-triggered actions, the highest frequency of shade lowering was observed in S03 (39%), where 46% of these interventions were within the first 10 minutes of the scenario and the delay time for automatic blind closure was 5 minutes. More than half of the participants stayed in the test room during the short break between S02&S03 (10-minute). Probably, they faced direct sunlight during the break, and when the scenario started, they immediately lowered the blind to avoid glare. However, zero lowering actions were recorded in S04 due to low averages of outdoor weather conditions (T_{out}, I_r) (see Figure 4.26).

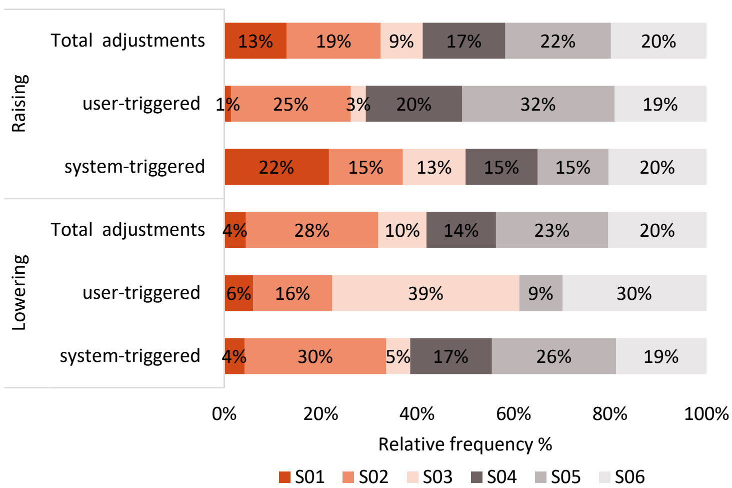


Figure 4.25: Relative frequency of user and system-triggered actions for each scenario.

A higher frequency of user-shade raising actions was observed in S02&S05 (25% and 32%, respectively) compared to other scenarios due to a high number of automatic blind closure events (30% and 26%, respectively). In fact, Reinhart and Voss [102] found in a field study that 88% of occupants' corrections were to reopen the blinds after an automated closure occurred to maximize the view to the outside and sufficient daylight. On the other hand, the lowest frequency was observed in S01&S03. It is expected as 90% of the time, the blind was fully open in S01. While in S03, the blind was either fully open or in the intermediate position more than 70% of the time. To evaluate the impact of the different conditions on the user-shade override adjustments, paired t-test statistical analysis was applied on each case. The box-plot in Figure 4.27 demonstrates the distribution of user-shade override adjustments (lowering and raising) for each scenario. The following shade patterns were observed:

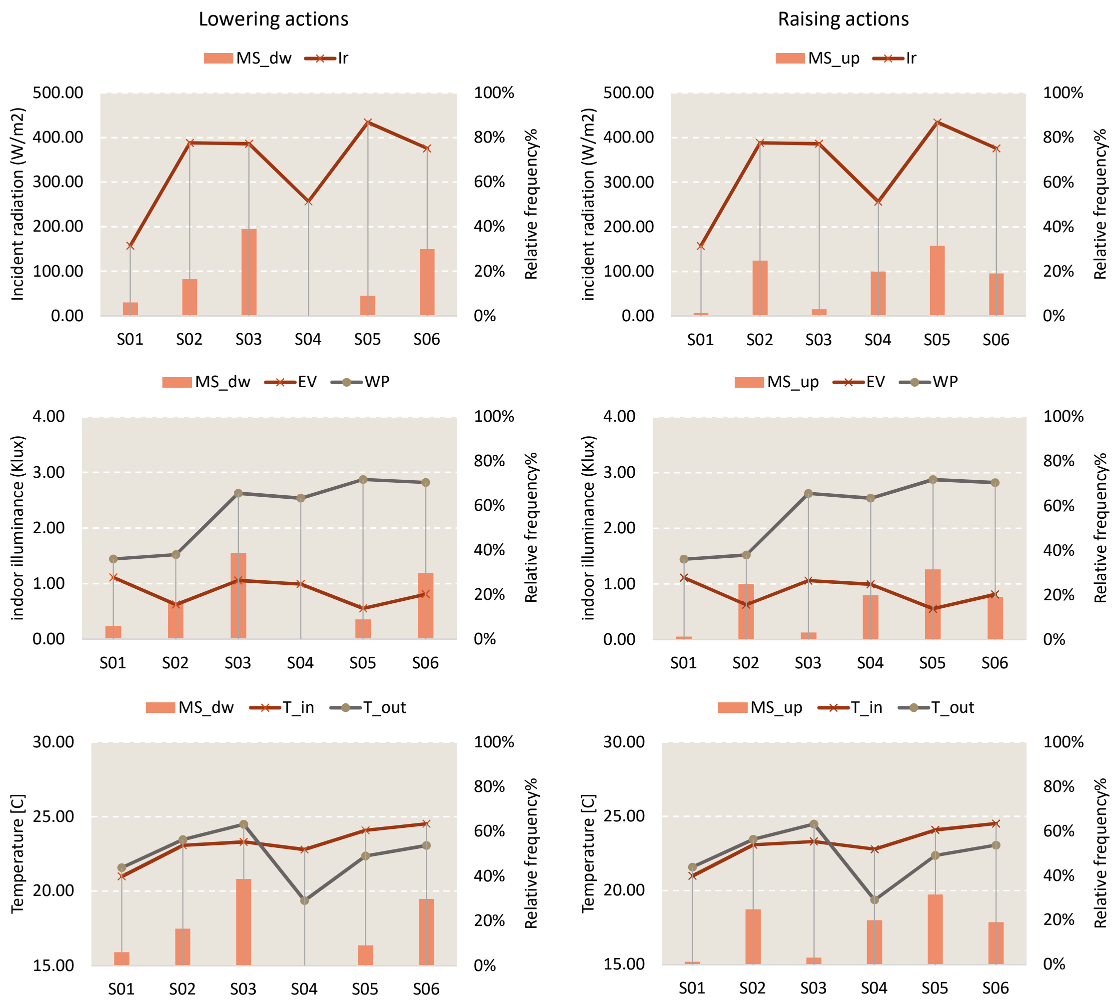


Figure 4.26: Relative frequency of USO related to the average of physical environmental parameters for each scenario.

- Case 01 [S01 vs. S02]: fewer raising and lowering override adjustments were observed in S01 (with active cooling) compared to S02 (without active cooling). The main reason might be the low average solar irradiance on the facade in S01 compared to

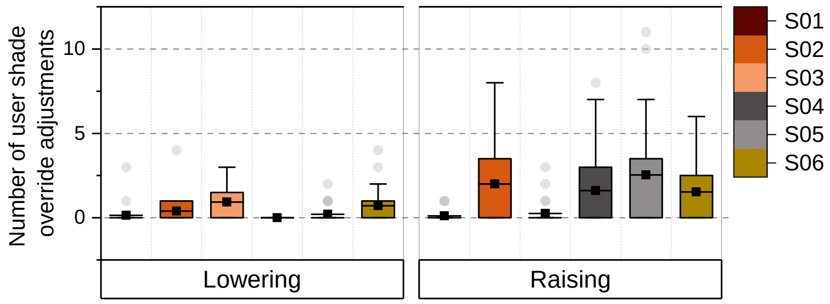


Figure 4.27: Box-plot distribution of user-shade lowering and raising adjustments for each scenario.

S02. However, this is in agreement with Inkarojrit [55] findings in their study. In mechanically air-conditioned offices, they found that the occupants use fewer blinds to adjust the indoor thermal environment. In contrast, in buildings with natural or mixed-mode systems, the occupants often use the blinds to achieve thermal comfort.

- Case 02 [S02 vs. S03]: the number of shade-raising actions was significantly less in S03 compared to S02, while the number of shade lowering actions was higher in S03. Noting that a simple control strategy (300 W/m^2) was used in S02 and a multi-objective one in S03. The results indicate that the multi-objective control strategy with an intermediate position can facilitate the balance between solar and glare protection as well as daylight availability and view-to- the outside, improving the user perception and satisfaction with the working environment. This is in agreement with Atzeri et al. [3] findings since they found that intermediate shade positions can help the occupants maintain a closer connection to the outdoor environment, improving their perception and satisfaction of the working environment.

- Case 03 [S02 vs. S04]: the average user-shade raising actions were slightly lower in S04 than in S02. A low average of outdoor solar irradiance and temperature might be the reason for zero lowering action in S04.

- Case 04 [S02 vs. S05]: Higher number of raising actions was observed in S05 (WWR% = 40%) compared to the original window design (WWR% = 70%). This observation suggests that the building designer may consider the window size while selecting the optimal solar shading control strategy from the early building design stage.

- Case 05 [S01 vs. S04]: Non-significant difference was observed in lowering actions between S01 (low degree of control options) and S04 (more control options). However, shade raising was significantly higher in S04 due to more automatic closure events occurred in S04.

- Case 06 [S05 vs. S06]: In S05, the number of raising actions was higher than in S06, while the number of lowering actions was less in S05. It is concluded that using a high irradiance lowering threshold as in S06 (450 W/m^2) decreased the raising actions compared to S05 (300 W/m^2).

The shade patterns related to the use of automated shading systems were classified into three categories as shown in Figure 4.28. Similar results can be observed. 86% of the respondents never or rarely adjusted the system (once or twice) in S03, while approximately half of them (46%) adjusted the blind three times or more in S05. More than half of the occupants didn't override the blind position in each of S01 and S04 (82% and 54%, respectively).

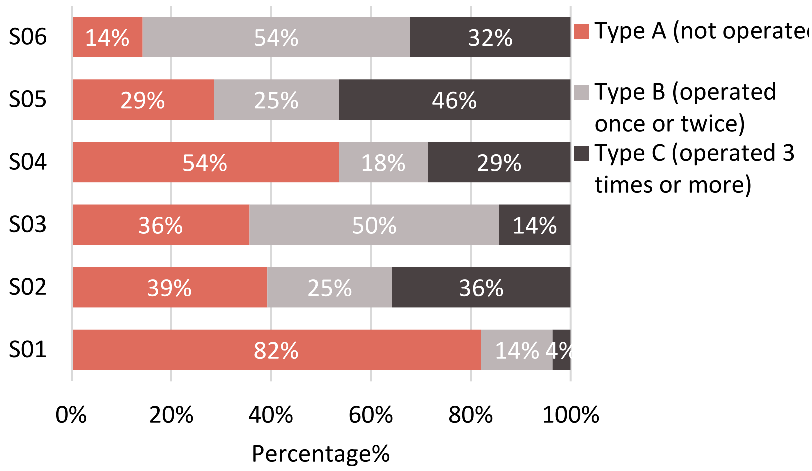


Figure 4.28: Relative frequency of user shade patterns

Overall, robust shade control strategies with a limited override action can be achieved through: (a) a multi-objective control strategy which represents a good example of keeping a balance between the different aspects of shading system design as well as fewer override actions, (b) a high irradiance lowering threshold is recommended for small windows to maximize the view-to-the outside and decrease the raising override adjustment, (c) cooled spaces are much more favorable than non-cooled spaces while using a simple control strategy since it improves the thermal comfort sensation and reduces user override adjustments.

Shade patterns on sunny and cloudy days

In total, 19 sunny days and 9 cloudy days were registered in Session A of the experiment, while 12 sunny days and 16 cloudy days were in Session B. Figure 4.29 shows a higher average of blind occlusion on sunny days than on cloudy ones for all scenarios. The overall average blind occlusion was 61.2% for sunny days and 37% for cloudy days. This seems to be consistent with Inkarojrit [56] who found that 67% of shades were fully open on cloudy days, compared to 43% on sunny days.

Moreover, Figure 4.30 shows the relative frequency of user-shade override actions on sunny and cloudy days. The results indicate that people tend to lower the blind more

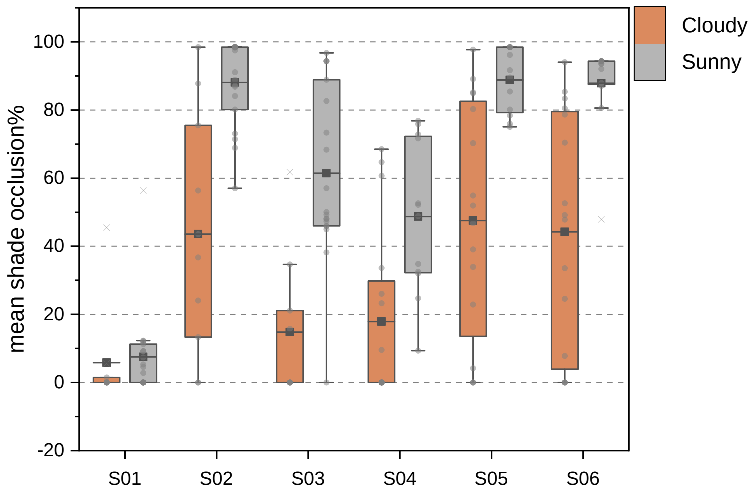


Figure 4.29: Mean shade occlusion in sunny vs. cloudy days for each scenario.

frequently on sunny days than on cloudy days, except for S05 and S06. WWR was 40% in both scenarios, decreasing direct sunlight and glare discomfort in the indoor environment. Similarly, a higher frequency of raising actions was observed on sunny days compared to cloudy days in S02, S04, S05 & S06. High shade occlusion value and more automatic closure events recorded on sunny days, provoked occupants to raise the blinds more often to achieve a better view-to-the outside and sufficient daylight.

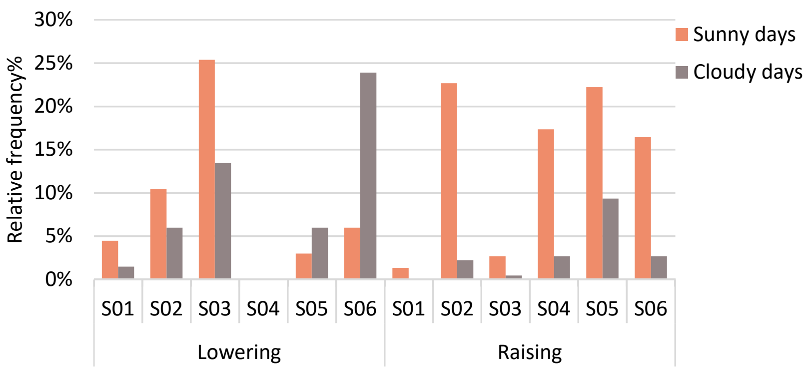


Figure 4.30: Relative frequency of user-shade override adjustments on sunny and cloudy days for each scenario.

Questionnaire results: User-shade satisfaction and preferences

Participants were asked about their interaction with the automated shading system and their reasons for each scenario (see Figure 4.31). Similar quantitative results were found in terms of blind use frequency through the questionnaire analysis compared to the quantitative findings of the monitored data analysis. For instance, the highest frequency of user-shade lowering actions was observed in S03, where 54% of the participants lowered the blind mainly to reduce the overall brightness of the workplane (33% of the respondents) and avoid glare on their computer screen (33%). The lowest frequency was observed in S01 and S04 (7%). Participants were found to raise the blind the most frequently in S05 (61%) and S06 (61%). Achieving a better view-to-the outside as well as increasing overall daylight in the workplane were reported as the primary reasons behind raising the blinds. When the users did not adjust the blind, 90% reported that it is not needed, and 10% were too busy or lazy to adjust the blind. Previous studies' findings [7, 55, 105] reported similar reasons for shade lowering and raising.

Figure 4.31: (a) User-shade override frequency (b) reasons behind no action (c) reasons behind shade raising (d) reasons behind shade lowering.

Based on the box-plot distribution of occupant satisfaction with the performance of automated shading system for each scenario in Figure 4.32, the following are concluded:

- A statistically significant difference in occupant satisfaction with the performance of the shading system was found between S01&S02. This might be explained by several reasons: (a) the cooling system was activated in S01 (21 °C setpoint) while not in S02, and (b) a higher frequency of system-triggered actions was observed in S02 than in

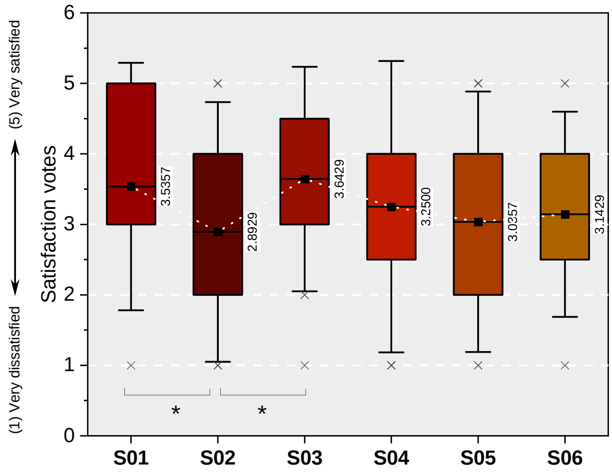


Figure 4.32: Satisfaction votes of automated shading system performance for each scenario.

S01. The high frequency could be a reason for users' discomfort and disturbance, as confirmed previously by Bakker et al. [7].

- The participants reported that the multi-objective control strategy in S03 provided sufficient daylight inside the room, prevented glare and heat gain, and maximized the view-to-the outside, as shown in Figure 4.33. Therefore, about 71.5% of participants preferred the performance of automated shading performance in S03 compared to 26.5% in S02.

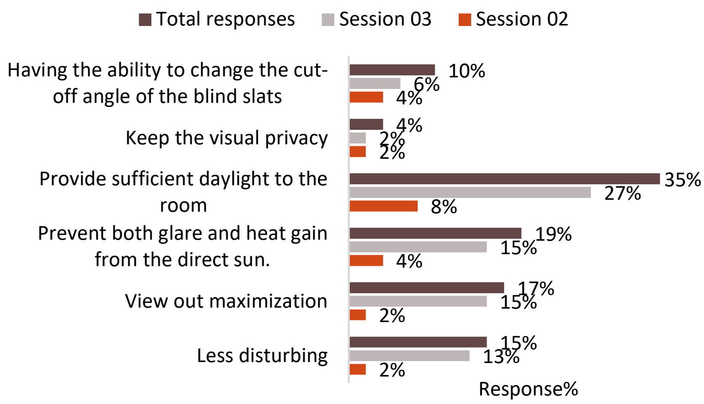


Figure 4.33: Reason behind user preference of shading performance in S02 compared to S03.

- A slight difference were found between S05 (300 W/m^2) and S06 (450 W/m^2) since 53.6% of the occupants preferred S05 and 46.4% preferred S06. They found that both control strategies were less disturbing and prevent the glare and heat gain, and few voted for view out maximization.

Figure 4.34 shows that people occasionally override the shading system when they are satisfied with the performance of automated shading systems. Therefore, the frequency of shade movement is a critical factor to consider while developing and operating the automated shading control strategies to meet occupant preferences and satisfaction. Moreover, the majority of the participants (more than 70%) were satisfied to very satisfied with having the ability to override the blind position during the sessions. More than 80% of the participants were willing to use a desk remote or a mobile application to override the blind instead of wall-mounted manual switch. This confirms previous findings [105] about considering easy-to-access control interface. In fact, providing occupants with easy-to-access controls over comfort delivery systems would make them more eager to act for improving their comfort.

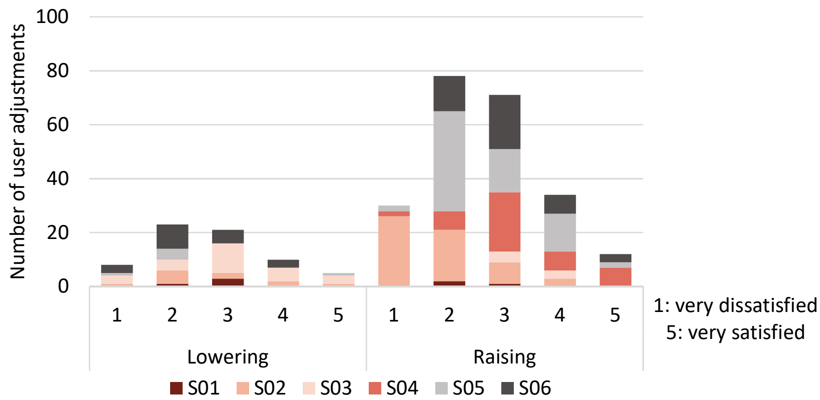


Figure 4.34: User shade adjustments in relation to satisfaction votes with automated shading performance.

4.4.2 Thermal comfort results

To understand the indoor thermal conditions that participants had experienced during the first and second sessions of the experiment, the hourly profile of outdoor and indoor operative temperature during the daytime (9:00 am- 5:00 pm) was analyzed in Figure 4.35. The blue dashed lines show the upper and lower comfort indoor operative temperature limits according to EN 15251:2006 standards (category II). The operative temperature average was within the recommended comfort range for all scenarios except S06, which was higher by a half-degree.

Clothing insulation and metabolic rate

Figure 4.36 shows the box-plot distribution of clothing insulation for male and female participants for each scenario. Females were observed to have a higher average of clothing insulation (0.62-0.80 clo) than the male participants (0.45-0.65 clo). Overall, the mean of clothing insulation was in the range of (0.62-0.70 clo). The closing insulation rate (I_{cl}) used to estimate the PMV values was 0.66 clo. Figure 4.37 shows the distribution of the actual mean vote related to the clothing insulation level. The results indicate that people adapted to the warm conditions by taking off some clothes. Participants were engaged in different office work activities during the experiment. 43.3% of the respondents reported that they work on their PC, 30% spent time reading, writing, and filing activities, and 26.6% for

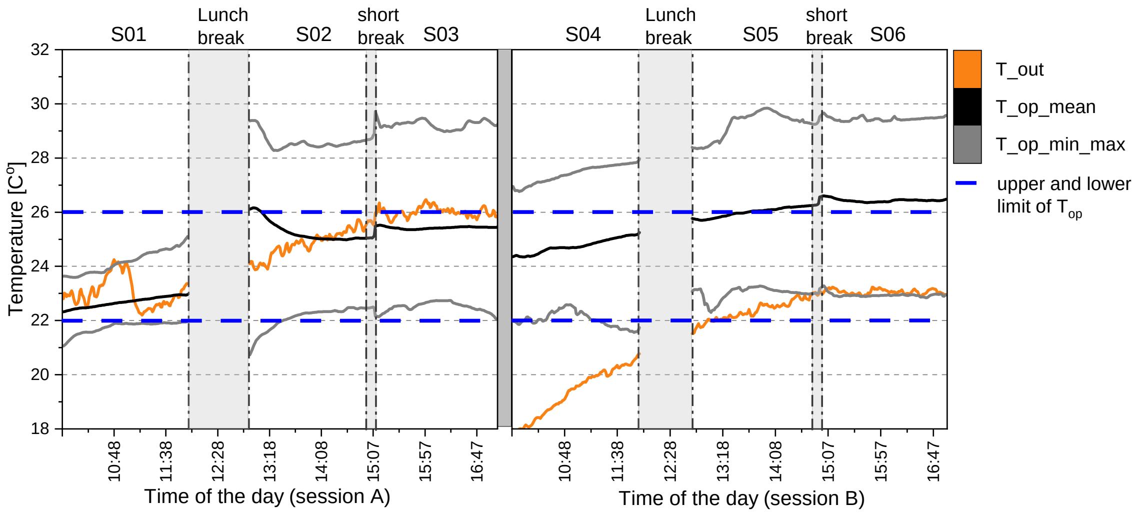


Figure 4.35: Hourly profile of outdoor temperature and indoor operative mean, max, and min during daytime in Session A and B.

meetings. However, the metabolic rate was assumed to be 1.1 met for all scenarios, as a typical seated office activity according to ASHRAE 55-2017 standards.

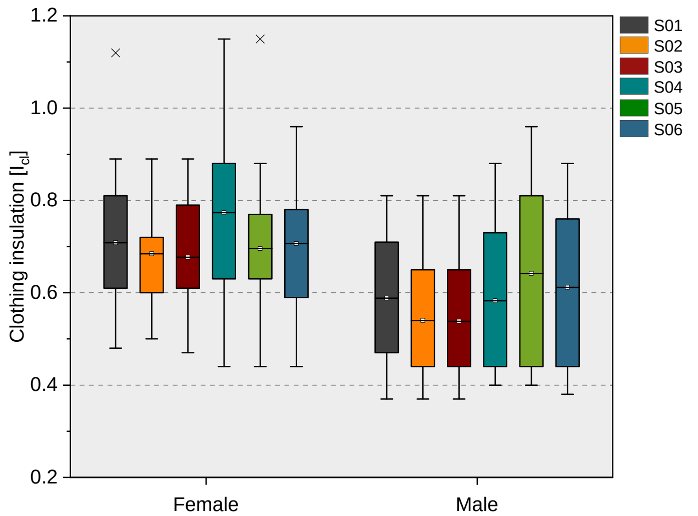


Figure 4.36: Box-plot distribution of clothing insulation: gender as index

Operative, comfort and standard effective temperatures

Table 4.10 summarizes the descriptive statistics of indoor operative, comfort, standard effective temperature, and outdoor temperature during each scenario. The relative frequency of indoor operative temperature was analyzed per each scenario to evaluate the performance of the automated shading system in terms of indoor thermal conditions (see Figure 4.38). The histogram of operative temperatures clearly expressed the range of indoor thermal conditions experienced by the occupants in each scenario. A similar distribution of indoor operative

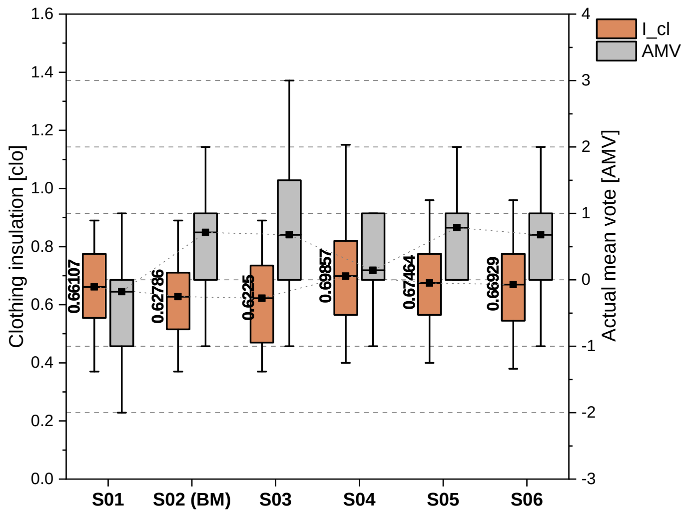


Figure 4.37: Box-plot distribution of actual mean vote and clothing insulation for each session.

temperature was noticed in S02, S03, and S04, while S05 and S06 showed a higher average operative temperature. S01 was the lowest since the cooling system was active.

Table 4.10: Descriptive statistics of indoor operative, comfort, standard effective temperature and outdoor temperature for each scenario

	S01		S02		S03		S04		S05		S06	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
T_{op} [°C]	22.68	0.65	25.27	1.64	25.43	1.96	24.76	1.41	26.01	1.64	26.44	1.67
T_{comf} [°C]	23.04	2.10	23.84	1.42	24.07	1.46	24.47	1.47	24.44	1.79	25.08	1.98
SET [°C]	23.15	1.14	25.76	1.78	25.84	2.02	25.48	1.63	26.69	1.66	26.52	1.79
T_{out} [°C]	21.58	5.46	23.46	5.94	24.48	5.75	19.36	3.44	22.37	4.54	23.06	4.66

Figure 4.39 shows the box-plot distribution of operative temperature related to the mean shade occlusion for each scenario. These results indicate that the mechanical exhaust air ventilation and active cooling could improve indoor thermal comfort in S01, as the average operative temperature was about 22.68 °C. In S06, the operative temperature was significantly higher than in S05. However, a non-significant difference in shade occlusion was observed. It can be explained due to the high average outdoor temperature. In S02, S03, and S04, the average operative temperature varied between 25-26 °C. However, the mean occlusion value was 46.5%, 73.8% in S03 and S02, respectively.

Overall, the operative temperature was highly correlated with the mean shade occlusion in both sessions (Pearson correlation was 0.72, 0.57 in sessions A&B, respectively) (see Figure 4.40). Figure 4.41 shows that the distribution of indoor operative temperature was slightly influenced in terms of different types of users (i.e., type A: did not adjust the blind, type B: adjusted once or twice, type C: adjusted more than twice). Based on these results, it is concluded that thermal stimuli affected the blind position more than shade adjustment. Similarly, few participants (20%) reported that they lower the blind to reduce the heat from

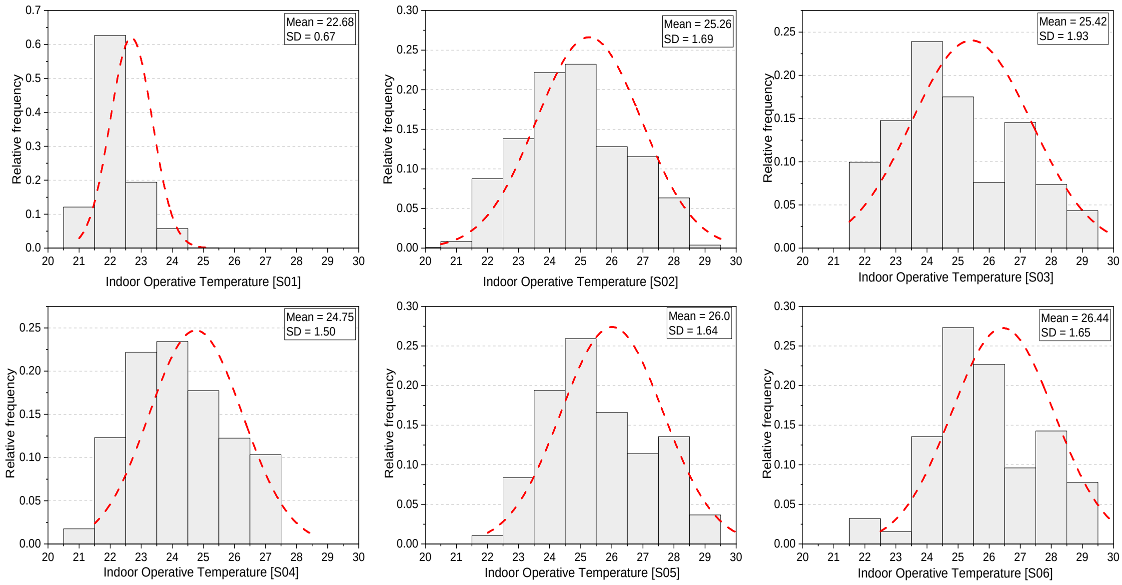


Figure 4.38: Histograms of indoor operative temperature, mean and standard deviation for each session.

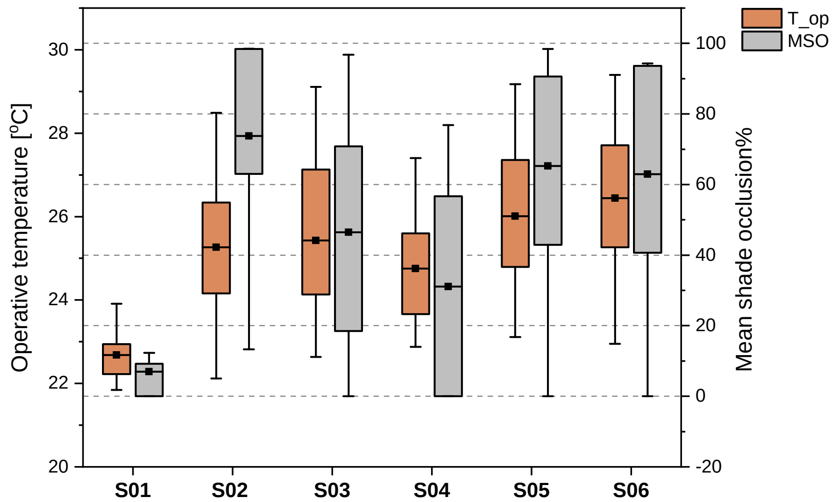


Figure 4.39: Box-plot distribution of indoor operative temperature vs. MSO.

the sun. This is in line with O'Brien et al. [95] findings. They reported that few studies indicate that occupants change their shades in an attempt to control the indoor thermal comfort.

Figure 4.42 presents the box-plot distribution of operative temperature related to the estimated comfort temperature using Griffiths' method. The highest average comfort temperature was observed in S06 (25.1 °C), while the lowest was in S01 (23 °C). A statistically significant difference was found in the mean comfort temperature between S01&S02 and S01&S04. User expectation could also play an important role since people were informed about the active cooling in S01. Overall, the occupants' comfort perception of the indoor

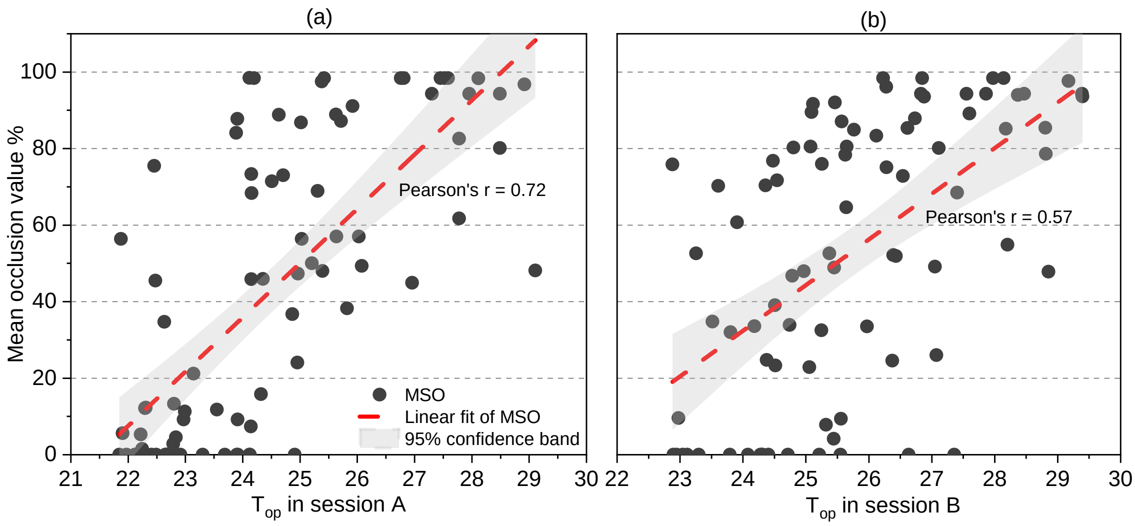


Figure 4.40: Correlation of operative temperature with mean occlusion value for each session.

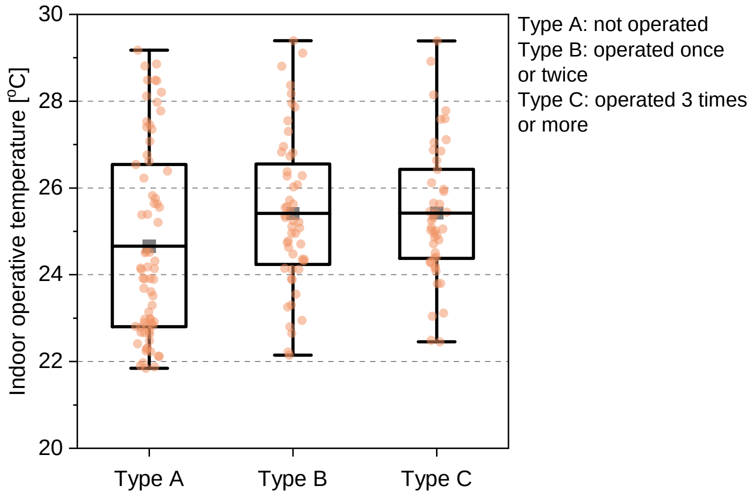


Figure 4.41: Box-plot distribution of indoor operative temperature in terms of three types of users A, B, &C .

temperature was lower than the actual measured values. Figure 4.43 shows that comfort temperature was slightly correlated with the mean operative temperature in both experiment sessions. This result indicates that the participants could barely match their comfort temperature with their typical environment, which is not in agreement with Gallardo et al. [37] findings (high correlation). It can be explained due to (a) users' expectations since they were informed about active and non-active cooling scenarios in the thematic introduction, and (b) the non-steady state conditions during this experiment compared to steady state conditions during the old PMV research.

Figure 4.42 shows that the lowest average of standard effective temperature (SET) was observed in S01 (23.15 °C), where the highest was in S05 (26.69 °C). Moreover, the average of SET was above the upper comfort value (25.6 °C) in each of S02, S03, S05 and S06. A statistically significant difference was found in the SET average between S01&S02, S02&S05, and S01&S04 (p-value <0.05). Overall, SET prediction model overestimated the human sensation to the thermal environment except in S01, where the cooling system was active.

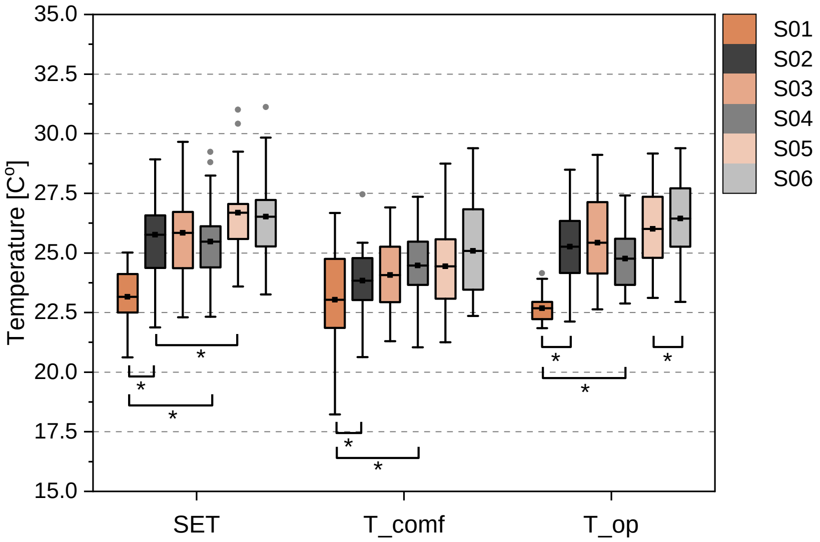


Figure 4.42: Box-plot distribution of operative temperature related to comfort and standard effective temperature

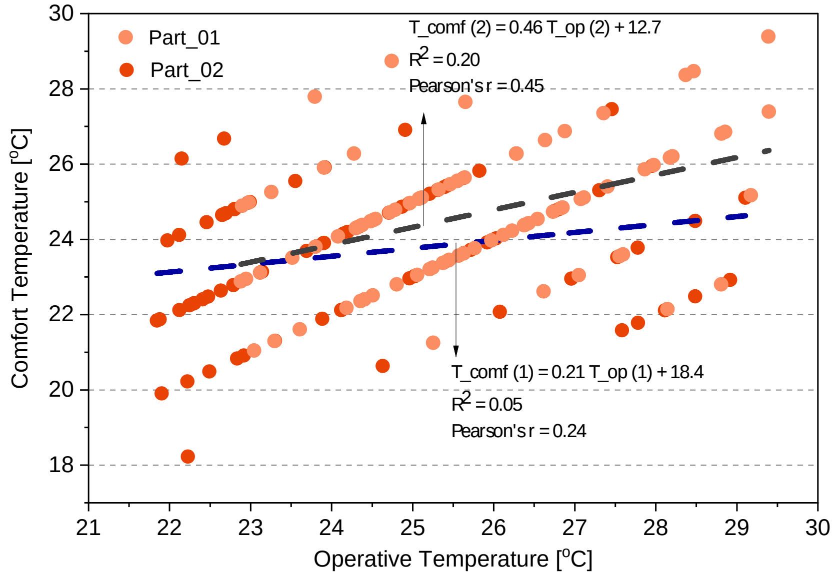


Figure 4.43: Correlation of comfort temperature with the mean operative temperature.

PMV, AMV and PPD comfort indices

The participants expressed their thermal sensation through an actual mean vote (AMV), while the predicted thermal sensation was estimated using the PMV model. Table 4.11

presents the standard deviation and the average of PMV, AMV, and PPD metrics for each scenario. Figure 4.44 demonstrates that the relative frequency of AMV was normally distributed around neutral comfort temperature in S01, S02, S03, and S04, where the distribution was skewed to slightly warm in S05 and S06. However, the frequency of PMV was normally distributed around neutral comfort for all scenarios except S01, where the PMV distribution shifted toward slightly cool.

Table 4.11: Descriptive statistics of AMV, PMV, and PPD indices for each scenario

Scenarios	S01		S02		S03		S04		S05		S06	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
AMV	-0.18	0.94	0.71	1.05	0.68	1.22	0.14	0.71	0.79	1.13	0.68	0.72
PMV	-0.58	0.36	0.21	0.52	0.24	0.61	0.10	0.46	0.48	0.46	0.47	0.51
PPD%	14.8	11.1	12.0	8.7	13.8	12.0	10.1	6.0	14.1	13.0	15.3	12.9

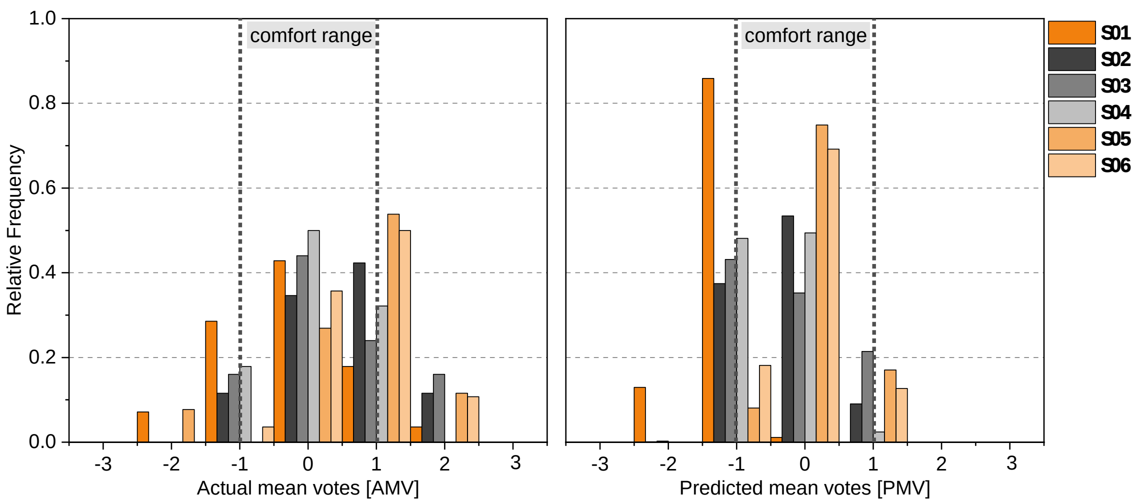


Figure 4.44: Relative frequency of AMV and PMV indices fro each scenario.

In Figure 4.45, it is noticed that participants perceived the indoor environment close to neutral comfort in S01 and S04 (the morning scenarios), while they felt slightly warm (close to +1) in S02, S03, S05, and S06. A statistically significant difference was found between S01&S02 and S02&S04. Instead, the PMV index predicted that occupants perceived the thermal environment close to neutral in all scenarios except in S01 since it was around slightly cool. It is expected since the indoor temperature was kept around 22 °C in S01, while non-active cooling was in the other scenarios. Overall, the PMV model underestimated the actual thermal sensation reported by the participants. T_{op} is the thermal climate feeling as a function of the location in a room. Therefore, occupants may feel warmer because of direct solar heat gain close to the window, while the thermal comfort equipment stand was deeper in the test room. This result is consistent with García et al. [38] findings, which reported the PMV model does not predict the thermal sensation of the occupants in naturally ventilated buildings.

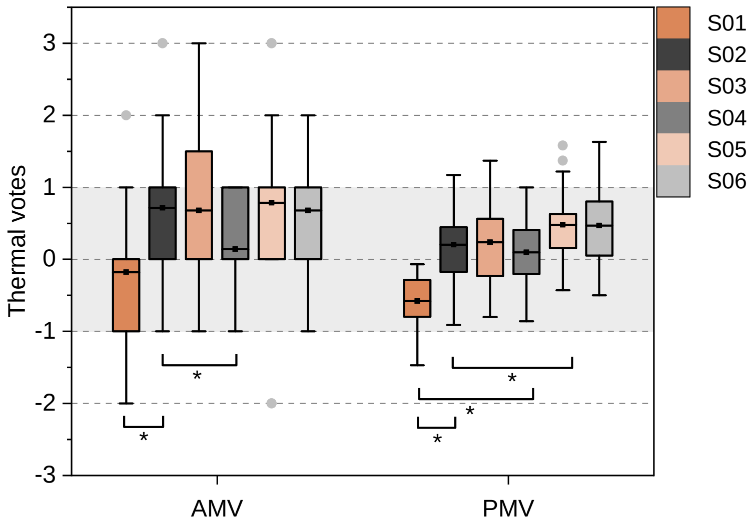


Figure 4.45: Box-plot distribution of AMV related to PMV for each scenario.

Thermal perception votes and operative temperature

The range of indoor operative temperature was between (22-30 °C) during the study period, between the average of slightly cool and slightly warm, as predicted by the PMV model. Figure 4.46 shows that participants perceived their thermal environment as slightly warm since the average operative temperature increased up to the range (25-26.5 °C) in each of S02, S03, S05, and S06. Figure 4.47 presents the linear regression of thermal sensation votes as a function of indoor operative temperature. Surprisingly, a high correlation between thermal perception -obtained with the actual user votes- and measured operative temperature in S02 and S03 (R-squared values are 0.54, 0.64), and a weak correlation in S04 and S05 (0.20, 0.38), with almost no correlation in S01 and S06.

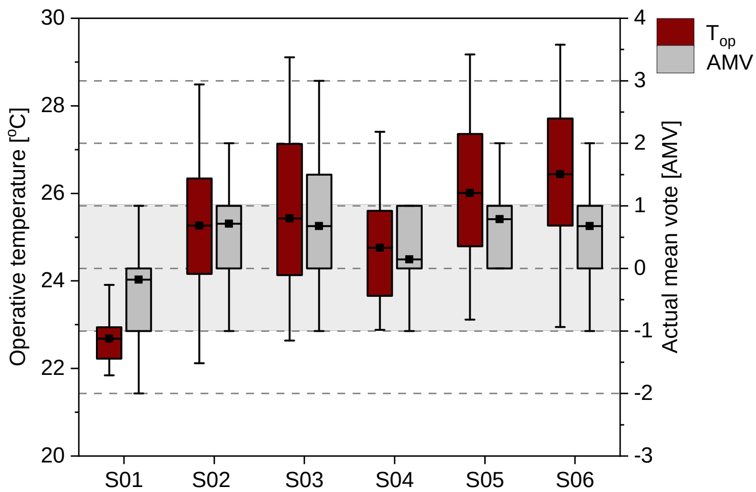


Figure 4.46: Box-plot distribution of operative temperature and AMV for each scenario.

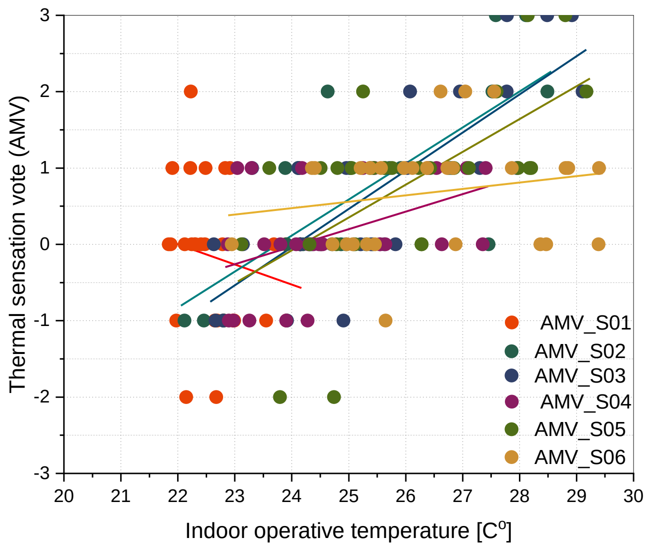


Figure 4.47: Thermal perception in relation to operative temperature for all scenarios.

Adaptive model

S01 was excluded from the analysis since it was actively cooled and had no open windows. As shown in Figure 4.48, most dots in S02, S03, and S04 lay in the acceptable range of operative temperature (80% upper and lower limits). In S05 and S06, a few dots apply above the upper limit of acceptable operative temperature. The latter result is consistent with the thermal sensation votes of the participants since the AMV average was close to slightly warm (+1) in both scenarios, while not in S02 and S03 as the AMV average was close to slightly warm. However, various studies have shown large individual preferences not supporting this assumption as reported by Schweiker et al. [110].

Questionnaire results: thermal comfort perception and sensation

The occupant's satisfaction votes of indoor temperature, relative humidity, and air movement on a scale of 1–5 (1= very uncomfortable and 5= very comfortable) measured the thermal perception of the work environment for each scenario (see Figure 4.49). People perceived the thermal comfort parameters as more comfortable in S01 compared to other scenarios, while they perceived least comfortable in S06. The latter is explained due to the high average operative temperature (26.44°C) recorded in that scenario.

Thermal preference vote was measured on a scale of 1–5 (1= much cooler, a bit cooler, no change, a bit warmer, and 5= much warmer). In Figure 4.50, 43% of the participants preferred no change in air temperature in S01, while a bit cooler temperature was preferred in S02-S06 with an average of (2.4, 2.57, 2.6, 2.32, 2.39, respectively). It is expected that people feel comfortable in spaces with active cooling (S01) compared to non-active cooling in the other scenarios. Moreover, people was informed in the thematic introduction before the experiment that the cooling system will be active in S01, while not in other scenarios.

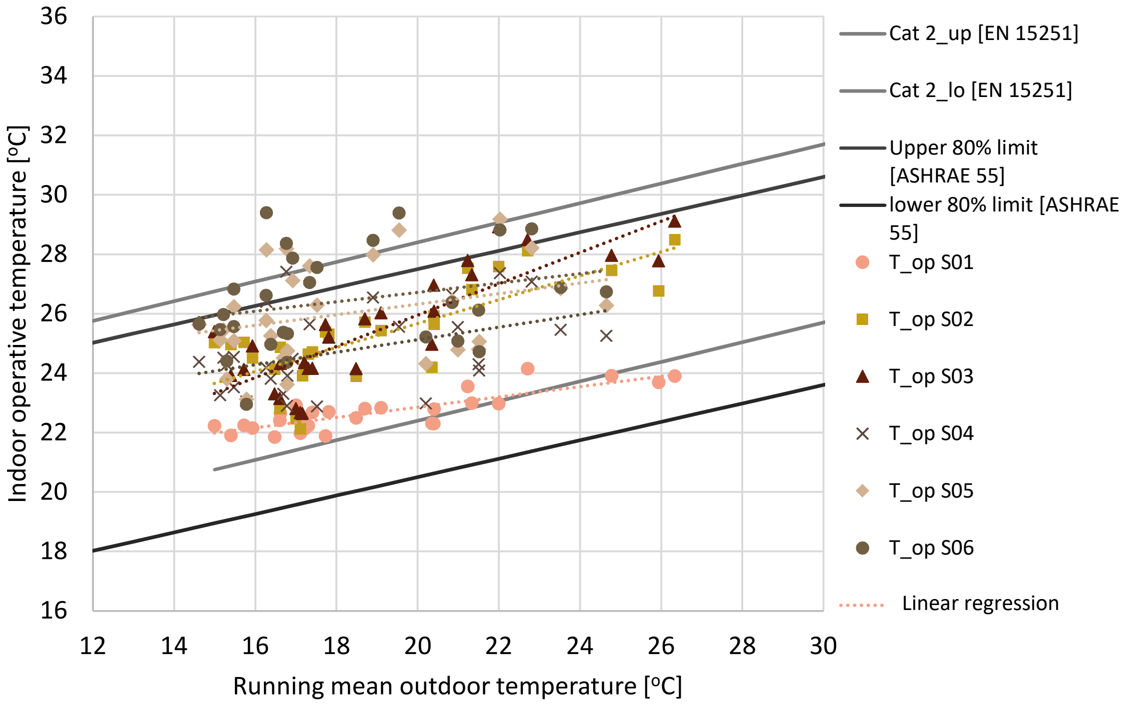


Figure 4.48: Acceptable operative temperature ranges from the adaptive comfort model included in ASHRAE 55 standards, 2017. The colored dots represent indoor operative temperatures registered for each scenario.

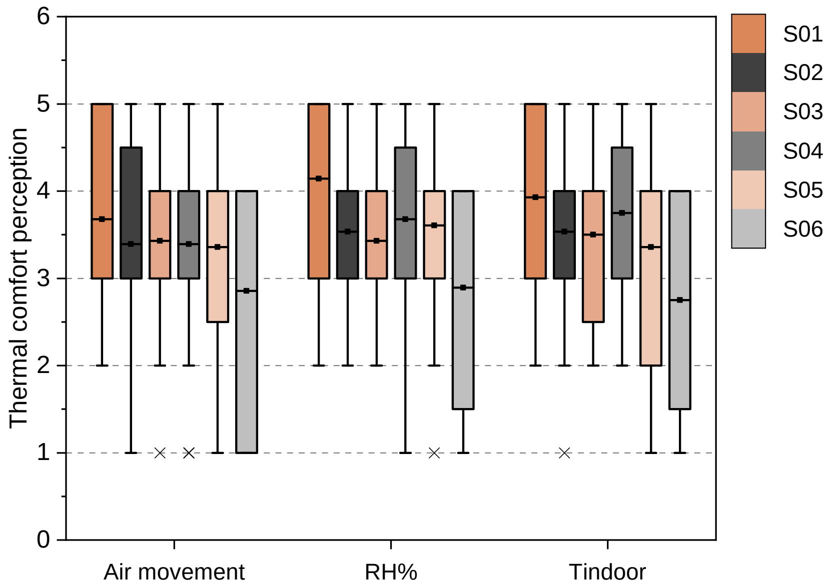


Figure 4.49: Thermal comfort perception of indoor temperature, relative humidity, and air movement for each scenario.

Paired scenarios evaluation

Paired t-test statistical analysis was applied to different scenarios to compare thermal comfort conditions using the aforementioned metrics and models. Based on Figure 4.51, the

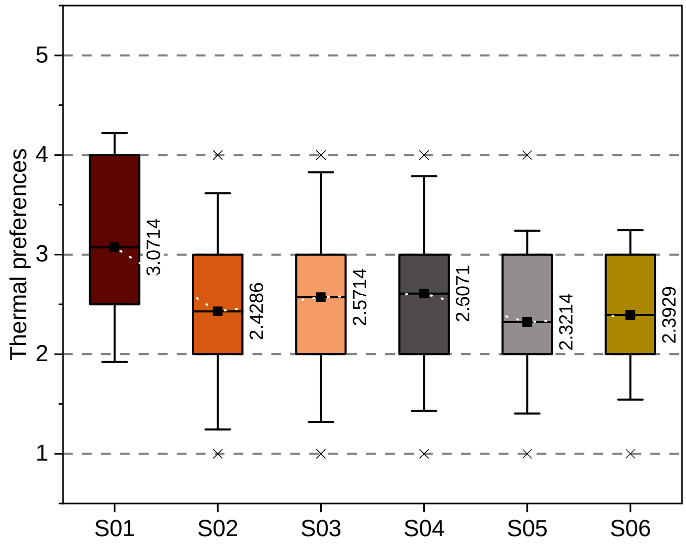


Figure 4.50: Thermal comfort preferences of indoor temperature for each scenario.

following conclusions are summarized:

- Case 01 [S01 vs. S02]: A statistical significant difference was found between the thermal condition in S01 and S02 in terms of T_{op}, T_{comf}, SET, PMV, and AMV. Participants were more satisfied with thermal conditions when the cooling system was active in S01 compared to S02 (without active-cooling). This is likely because the cooling system and the mechanical exhaust air in the test room maintain reasonable comfort conditions.

- Case 02 [S02 vs. S03]: a non-significant difference was found between S02 (simple strategy) and S03 (multi-objective strategy) in terms of T_{op}, T_{comf}, SET, PMV, and AMV metrics. However, a statistically significant difference was found in mean shade occlusion and blind frequency adjustments in both scenarios. To conclude, blind use patterns were not affected by the indoor thermal conditions of both strategies.

- Case 03 [S02 vs. S04]: AMV was significantly lower and close to neutral in S04 than S02. However, a non-significant difference was found in terms of T_{op}, T_{comf}, SET, and PMV metrics. Remembering that people were allowed to use the ceiling fan in S04 while it was not permitted in S02. Therefore, people's satisfaction increased by increasing the number of adaptive opportunities. This is in agreement with Schweiker et al. [111] findings. The authors found a higher satisfaction with the thermal conditions when interaction with the built environment permitted by using a fan or opening a window.

- Case 04 [S02 vs. S05]: Significant difference was found in SET and PMV comfort evaluation between S02 and S05. However, people did not feel any significant difference

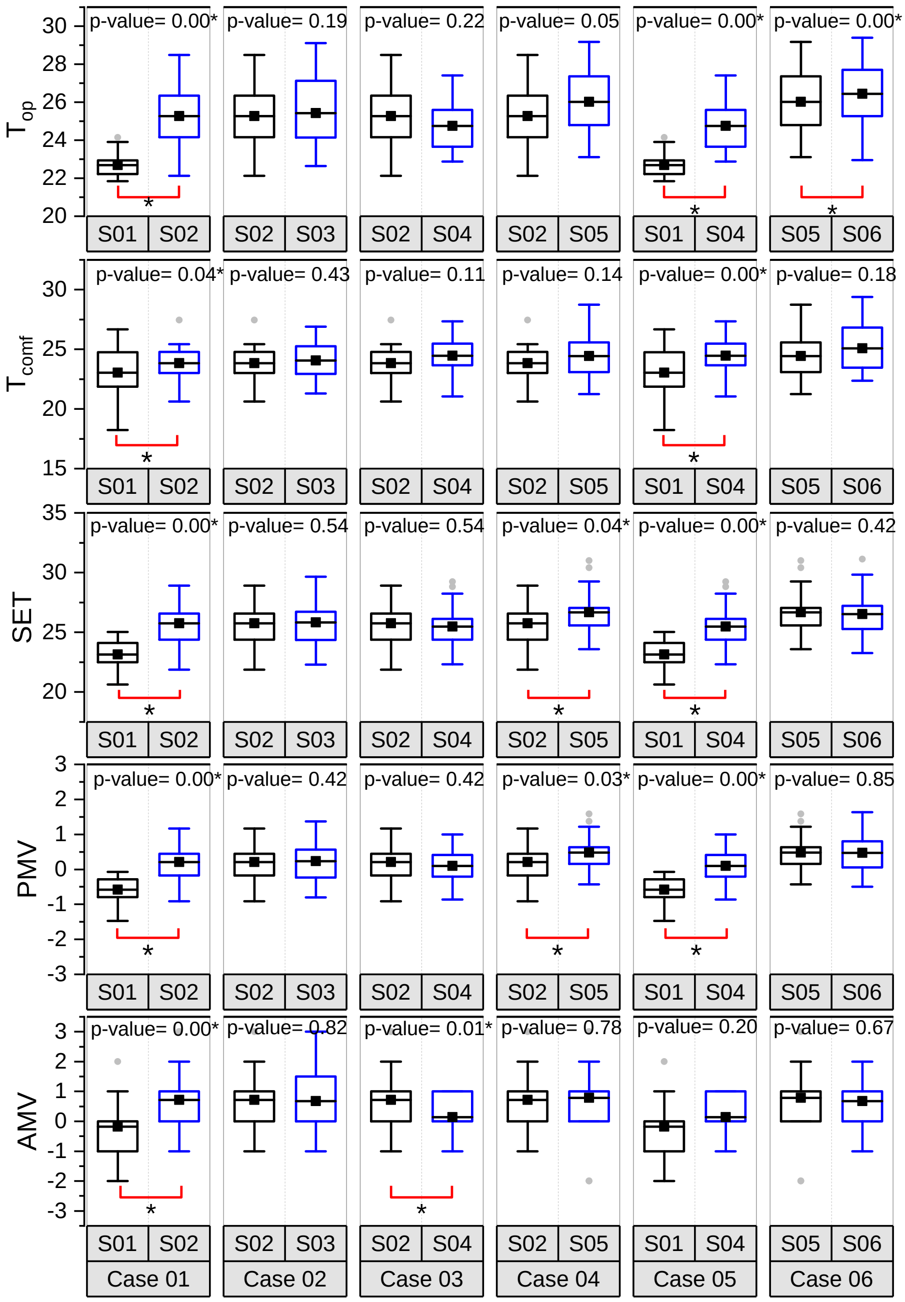


Figure 4.51: Paired scenarios comparison in terms of T_{op}, T_{comf}, SET, PMV, AMV.

in indoor thermal conditions. Moreover, a non-significant difference was observed in mean shade occlusion.

- Case 05 [S01 vs. S04]: A statistical significant difference was found between the thermal condition in S01 and S04 in terms of T_{op}, T_{comf}, SET, and PMV. However, people felt neutral in both scenarios. It is suggested that people feel comfortable either with active cooling or having high degree of control over the physical environment. Thus would improve thermal comfort and the overall satisfaction with the indoor environment.

- Case 06 [S05 vs. S06]: The indoor operative temperature was higher in S05 compared to S06. The PMV model and SET index didn't predict any difference, and people sensation votes were the same. To conclude, using a low or high irradiance thresholds to lower the blind had no impact on thermal conditions and occupants' perception.

4.4.3 Visual comfort results

In this section, the visual comfort is evaluated using several performance indicators under the different scenarios, such as daylight workplane illuminance (W_p), vertical illuminance at the eye level (E_v), simplified discomfort glare probability (DGPs), and glare sensation votes (GSV) reported by the participants. The hourly profile of outdoor irradiance and indoor illuminance average during the daytime (9:00 am - 5:00 pm) in sessions A&B are shown in Figure 4.52. The indoor illuminance in session A was below the upper limit of the acceptable range (3000 lux), excluding the workplane illuminance recorded in the first 15 minutes of S03. In session B, the workplane illuminance continuously exceeded the upper limit, clearly at the second half of S04 and the beginning of S05&S06.

Daylighting performance

Daylighting performance was evaluated by measuring horizontal workplane and vertical illuminance at eye level during the experiments. Relative frequencies of vertical and horizontal indoor illuminance are presented in Figure 4.53, a&b. Relative frequency was between 0-6% when vertical illuminance exceeded 2000 lux and 0-10% when workplane illuminance exceeded 3000 lux. Figure 4.54, a&b shows the box-plot distribution of horizontal and vertical illuminance at the eye level related to the mean shade occlusion for each scenario. The highest average of workplane illuminance was observed in S05 and S06 (2800 lux), while the lowest average was in S01 and S02 (1440 lux). The latter is explained due to the high shade occlusion value (74%). The highest average was observed in S01 (1100 lux) regarding vertical illuminance since the MSO was 7%. The lowest average was observed in S05 (554 lux) compared to other scenarios. It is explained due to the high occlusion value (MSO=65%) and small window size (WWR = 40%) in this scenario. Overall, the workplane illuminance was within the acceptable range (300-3000 lux), except in S05 and S06, the 3^{rd} quartile was above the permitted limit. In contrast, the average vertical illuminance was below the upper limit (2000 lux) for all scenarios.

Participants were asked about their perception of daylighting in the indoor environment on a 7-point scale (1: very dark, 4: neutral, 7: very bright) (see Figure 4.55). People perceived the highest average of daylighting in S01 and S04 (4.4 and 4.3, respectively). In S05, people perceived their work environment as slightly dark (3.7). This is in line with the monitored data findings, as the vertical illuminance was the lowest in S05 (WWR=40%). Moreover, a positive medium correlation was observed in Figure 4.56 a&b between indoor

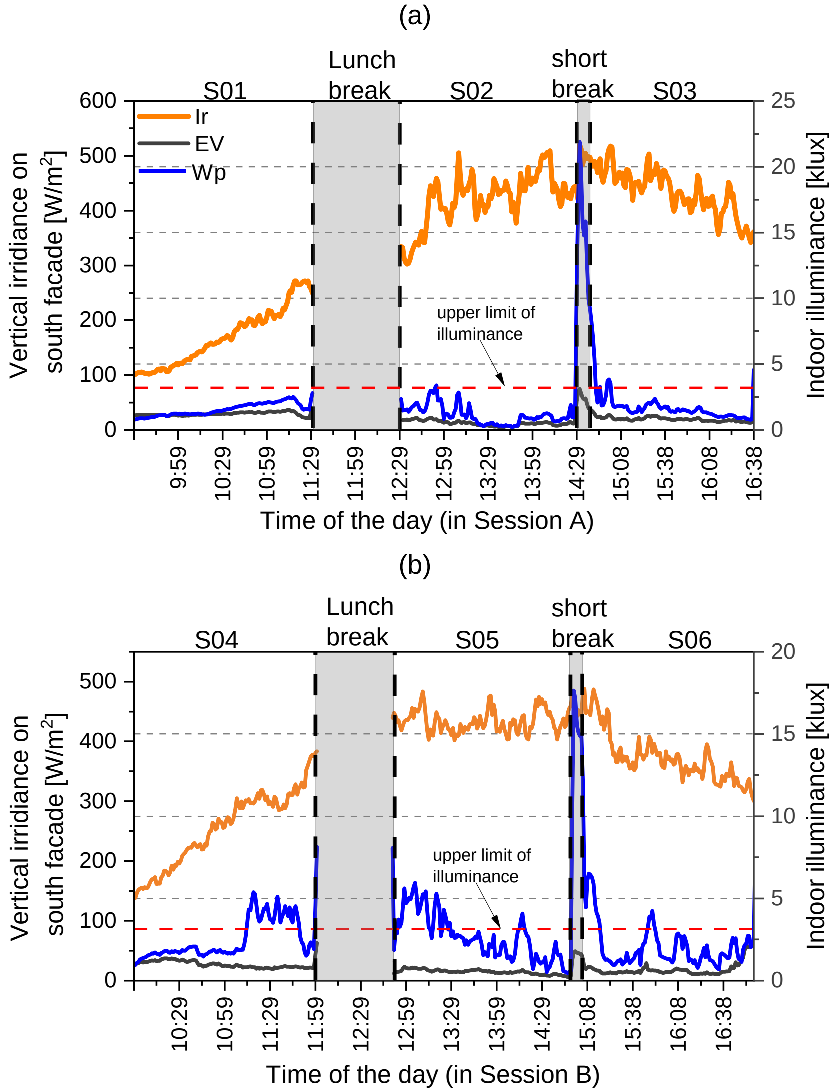


Figure 4.52: Hourly profile of solar irridiance on the facade, horizontal and vertical indoor illuminance in (a) session A and (b) session B during the daytime of the experiment.

illuminance and daylight perception votes. This result indicates that daylight perception was almost similar to the actual illuminance conditions.

Glare discomfort

Figure 4.57 demonstrates the box-plot distribution of DGPs values related to the participants' glare sensation votes (GSV) in S01-S06. It is noticed that the average of DGPs was within the range of (0.2-0.3), thus indicating that the DGPs values were below the upper limit of DGPs acceptable range (0.35) in all scenarios. Similarly, the participants (75%) perceived the glare as imperceptible to noticeable (average of 1-2) on the glare sensation scale, except in S03, where 28% reported a disturbing level of glare. It is surprising since the

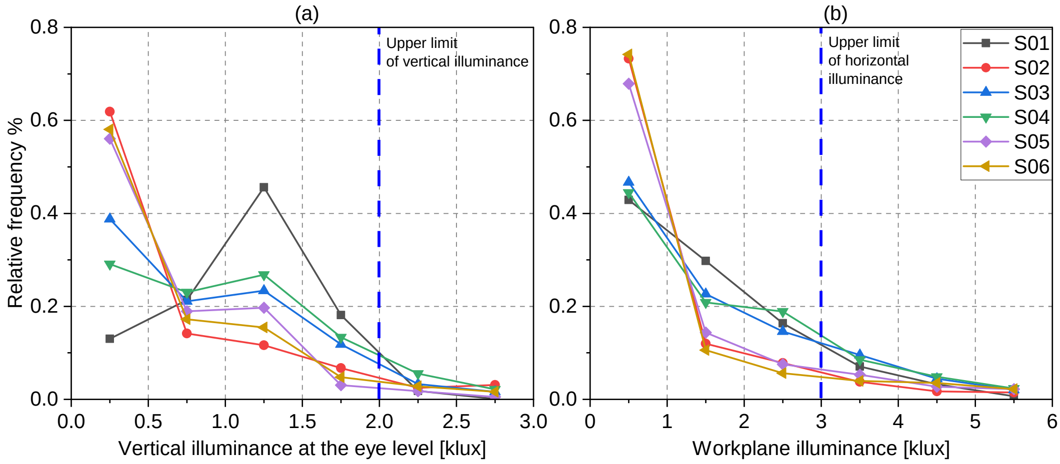


Figure 4.53: Relative frequency of workplane and vertical illuminance during the entire study period.

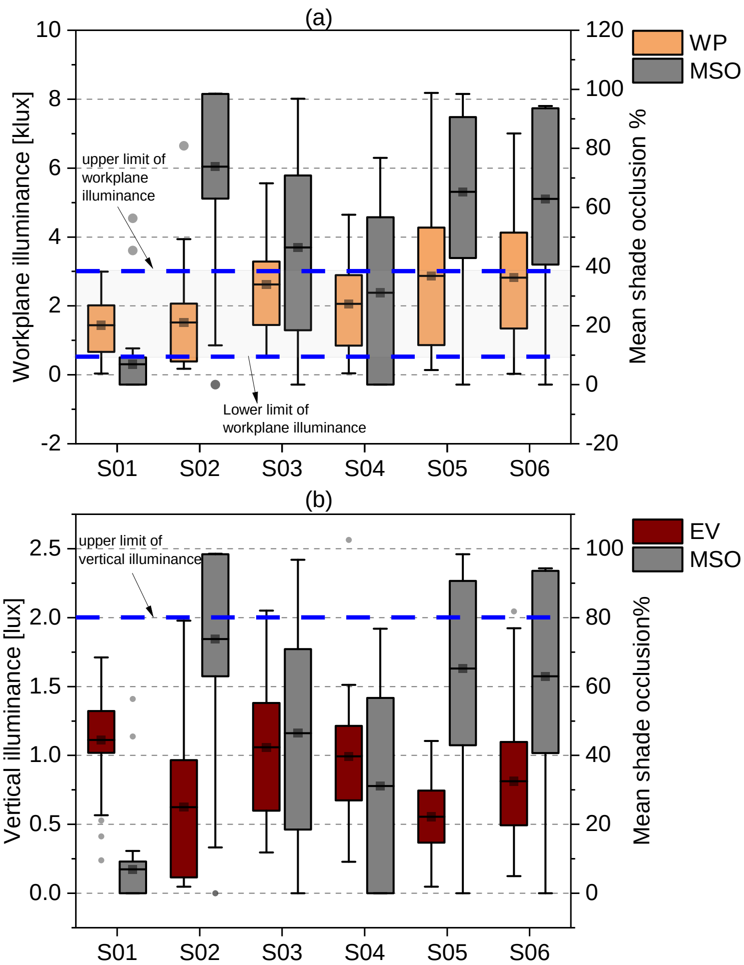


Figure 4.54: Box-plot distribution of (a) horizontal and (b) vertical illuminance related to mean occlusion value for each scenario.

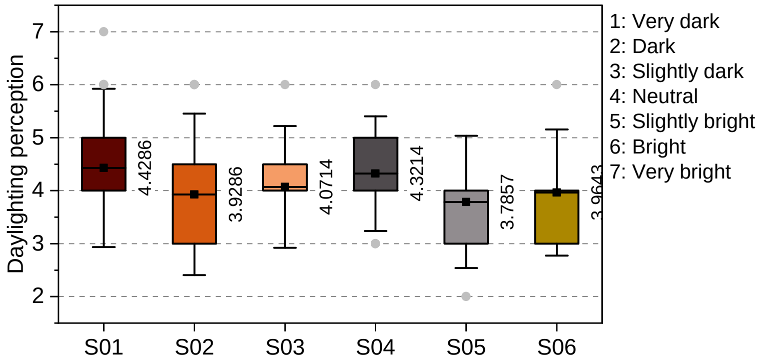


Figure 4.55: Questionnaire results: daylight perception votes for each scenario.

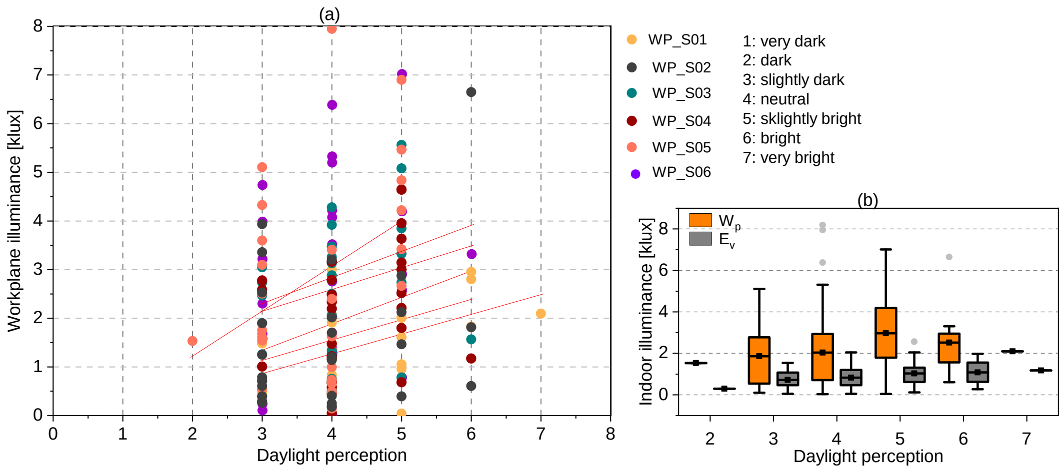


Figure 4.56: (a) Linear regression of workplane illuminance and (b) box-plot distribution of indoor illuminance as a function of daylight perception.

upper limit of E_v was below 2000 lux in this scenario (multi-objective strategy). Probably, people overestimated glare perception since they are not familiar with glare discomfort scale.

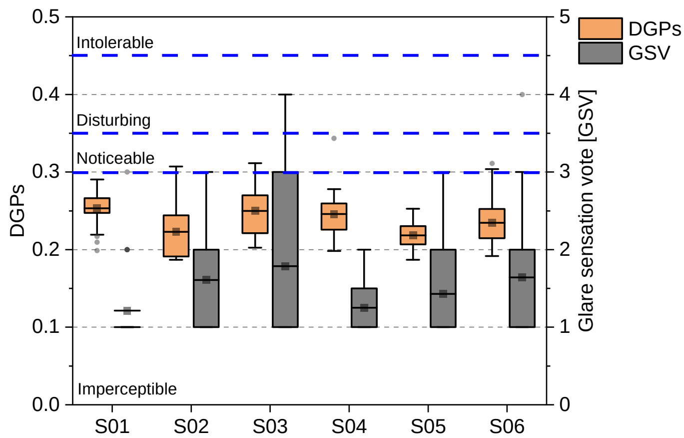


Figure 4.57: Box-plot distribution of DGPs in relation to GSV for each scenario.

Figure 4.58 shows that the highest frequency of glare sensation was reported in S02, S03, and S06 (35%, 39%, and 35%, respectively). People mentioned that direct sunlight and bright desk were the primary sources of glare discomfort (38% and 31%, 29% and 41%) in S03 & S06, respectively. However, 29% of the respondents in S02 reported that bright screen and sky were the primary sources of glare, keeping in mind that the luminance density of the monitor was 300 cd/m^2 (45% brightness), and 25% of respondents reported that the artificial light was turned on.

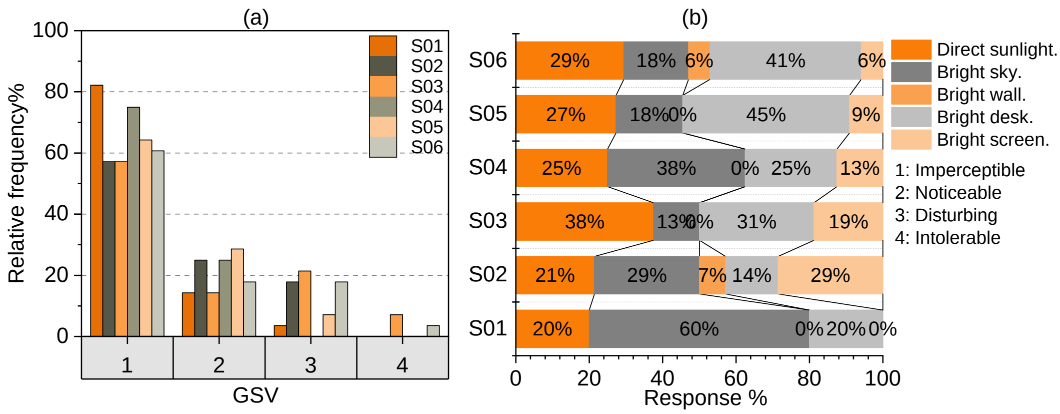


Figure 4.58: Relative frequency of (a) glare sensation votes and (b) sources of glare.

Figure 4.59 shows an unclear association between the prediction of disturbance by glare (DGPs) and participants' response to perceived glare (GSV). It is explained either that (a) DGPs model of glare prediction was not a good indicator at high peak glare sources in this study or (b) the participants overestimated glare perception. Probably the latter since people do not know the exact meaning of glare discomfort scale. For instance, few people in S03 and S06 (7% and 3.6%, respectively) reported intolerable glare perception ; however, the DGPs averages were within the acceptable range in both scenarios. This result confirms the findings of Karlsen et al. [63] in their study; they suggested that the DGPs equation should be renewed.

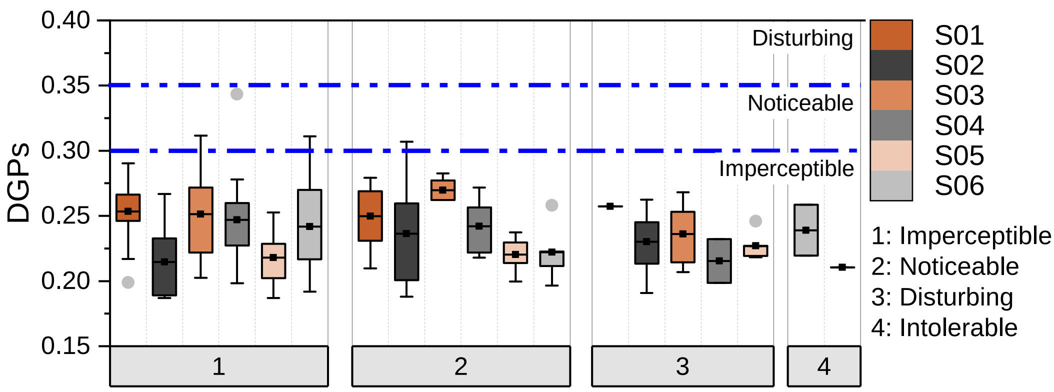


Figure 4.59: DGPs as a function of GSV votes for each scenario.

Questionnaire results: Visual comfort perception and satisfaction

Figure 4.60 shows that majority of people perceived the lighting conditions as comfortable to very comfortable in S01, S04, and S06, with an average of 4.07, 4.1, and 4.0, respectively. Less people (60-70%) perceived the lighting as comfortable in S02, S03, and S05 due to high mean shade occlusion values. Similarly, the monitored data showed the comfort average of workplane illuminance in S01-S04.

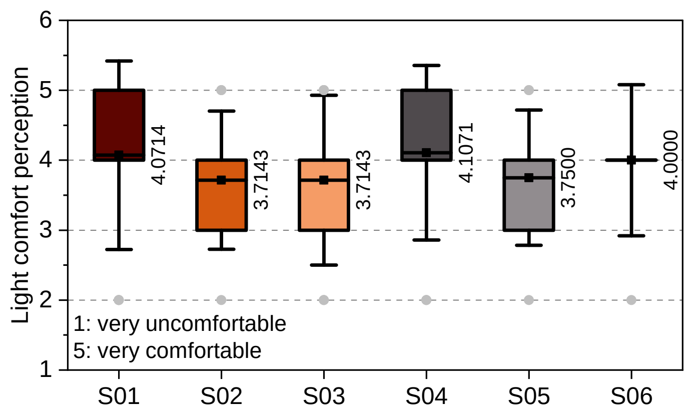


Figure 4.60: Questionnaire results: Lighting comfort perception.

Participants were asked to assess their satisfaction with lighting conditions in their workplane environment on a 5-point scale (1: very dissatisfied and 5: very satisfied). The "0" code was assigned when the artificial lighting was not used (see Figure 4.61). People were more satisfied with daylighting conditions in S01, S03, and S04 compared to other scenarios, where only half of the participants were satisfied with daylighting in S02, S05, and S06 since MSO was high (see Figure 4.20). Similar results were found in terms of overall lighting, as the majority of people were satisfied in S01, S03, S04, and S06. These results may explain why 60-75% of people did not use artificial lighting during the experiment scenarios.

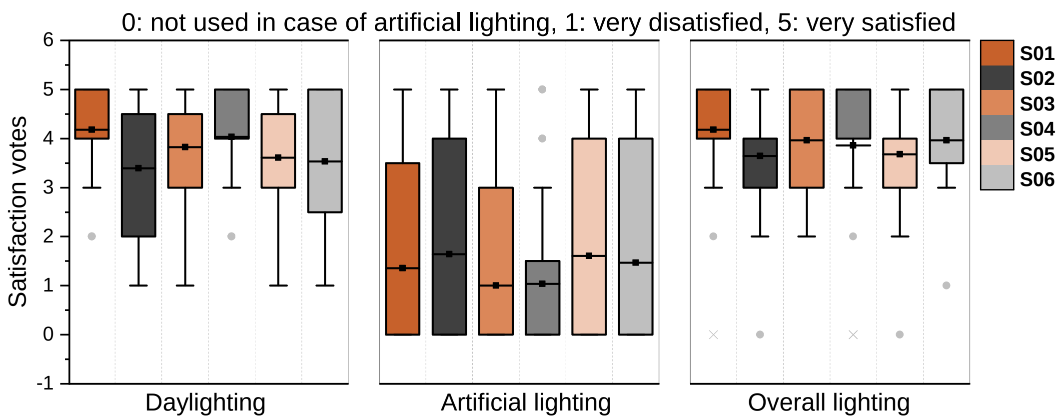


Figure 4.61: Questionnaire results: Visual comfort satisfaction in terms of daylighting, artificial light, and overall lighting for each scenario.

View-to-the outside satisfaction

Another variable of interest is the participant satisfaction of view connection to the outside. Majority of people (85%) were satisfied with the view-to-the outside in S01 with an average of 4.39. The lowest average of satisfaction vote was noticed in S02 and S05 (2.6, 3.1 respectively) (see Figure 4.62, a). This result is expected as mean occlusion values were the highest in S02 and S05. Figure 4.62 (b) shows a negative correlation between blind occlusion average and view-to-the outside satisfaction.

In S03, more than 60% of the people were satisfied with view-to-the outside since 80% of the time, the blind was kept open or in intermediate position. However, the highest glare sensation was in S03 according to participants votes. Similar results was noticed in S01 and S06. In S06, high irridiance threshold was used to lower the blind. These findings are consistent with the fact that people may tolerate some glare discomfort once they have a better view connection to the outside [104, 95].

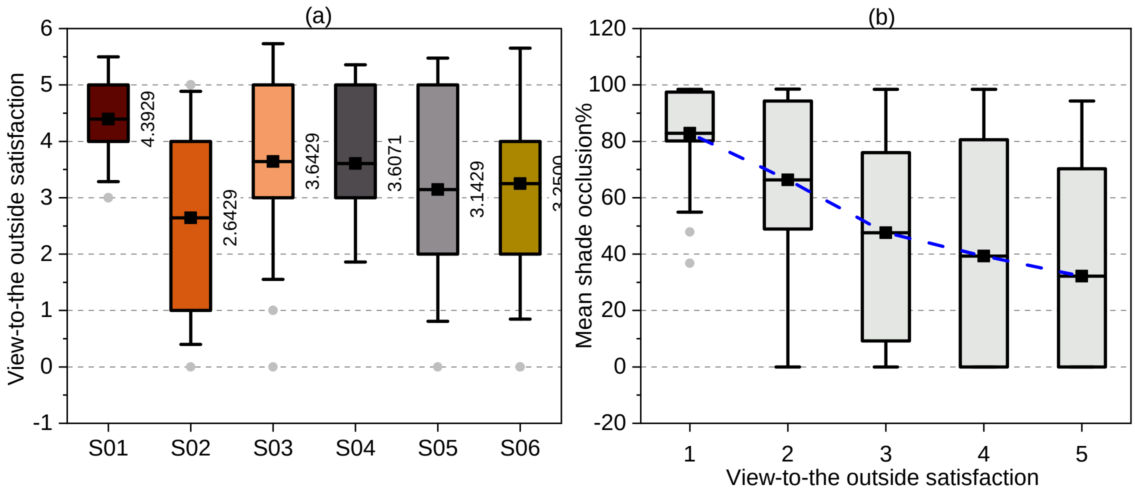


Figure 4.62: (a) Box-plot distribution of View-to-the outside satisfaction votes (b) as a function of MSO for each scenario.

Paired scenarios evaluation

Based on paired t-test statistical analysis, the visual performance of the automated shading system under different conditions was evaluated (see Figure 4.63). Table 4.12 summarizes the descriptive statistics of visual comfort indices for each scenario. The following conclusions are summarized:

- Case 01 [S01 vs. S02]: People were significantly more dissatisfied with the view-to-the outside in S02 (without active cooling) compared to S01 (with active cooling) due to high shade occlusion value (73.7%). However, E_v and DGPs values were significantly higher in S01.

Table 4.12: Descriptive statistics of MSO, W_p, E_v, DGPs, GSV indices and view-to-the outside (VTO) for each scenario.

Scenarios	S01		S02		S03		S04		S05		S06	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
MSO%	6.9%	13.29	73.7%	31.1	46.4%	32.6	31%	28.47	65%	33.82	63%	35.29
I_r [W/m^2]	157.37	50.36	388.15	146.86	386.10	176.79	256.44	122.01	434.20	239.93	375.76	209.46
W_p [klux]	1.44	0.86	1.52	1.47	2.62	1.30	2.06	1.29	2.87	2.30	2.82	1.86
E_v [klux]	1.11	0.35	0.62	0.51	1.06	0.47	0.99	0.44	0.55	0.27	0.81	0.50
DGPs	0.25	0.02	0.22	0.03	0.25	0.03	0.25	0.03	0.22	0.02	0.23	0.03
GSV	1.21	0.50	1.61	0.79	1.79	1.03	1.25	0.44	1.43	0.63	1.64	0.91
VTO	4.32	0.77	2.64	1.50	3.64	1.39	3.61	1.17	3.14	1.56	3.25	1.60

- Case 02 [S02 vs. S03]: The overall lighting conditions were statistically higher in S03 compared to S02 in terms of W_p, E_v, and DGPs metrics. However, the lighting condition in S03 was within the visual comfort acceptable range, as illustrated in the previous section. People were statistically more satisfied with the view-to-the outside in S03 than in S02, could suggest that the multi-objective control strategy provides sufficient daylighting conditions and view-out maximization while avoiding glare discomfort.

- Case 03 [S02 vs. S04]: a higher average of vertical illuminance and DGPs values was observed in S04 (with ceiling fan control) compared to S02 (without ceiling fan). According to the questionnaire responses, people perceived a higher glare perception in S02 and were more satisfied with the external view connection in S04.

- Case 04 [S02 vs. S05]: a non-significant difference was found between S02 and S05 in terms of E_v, DGPs, GSV, and view-out satisfaction since both have the same shading control strategy. Surprisingly, the workplane illuminance was higher in S05 (WWR% = 40%) compared to S02 (75%) since higher user-shade raising actions were recorded in S05. To suggest, a smaller window size could not improve the shading utilization since people are willing to have sufficient daylight.

- Case 05 [S01 vs. S04]: A higher average of workplane illuminance was in S04 than in S01, and people were less satisfied with the view-connection to the outside. A non-significant difference in glare indices was found. It is expected since both scenarios were conducted in the morning, and the blind was activated using the same control strategy.

- Case 06 [S05 vs. S06]: A statistically significant difference in vertical illuminance and DGPs averages were found between S05 and S06. It is expected to see more glare problems in S06 since the shading system was lowered if incident irradiance exceeded 450 W/m^2. However, the average of E_v and DGPs indices were below the upper glare occurrence limit. People were slightly more satisfied with the view- connection to the outside in S06 than in S05. It is suggested that using the high irradiance threshold

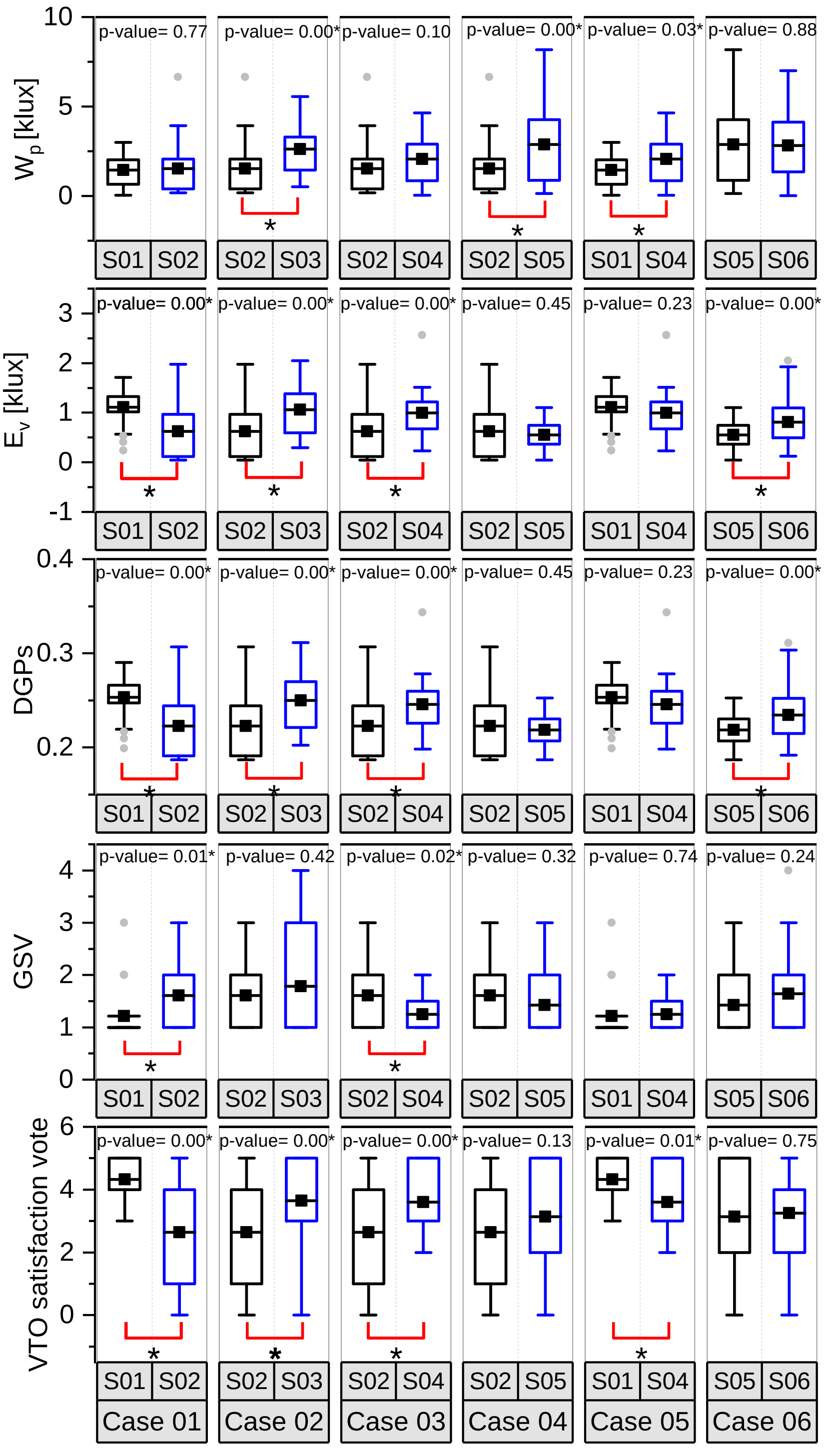


Figure 4.63: Paired cases evaluation in terms of W_p, E_v, DGPs, GSV, and satisfaction votes with the view-to-the outside.

of shade lowering could slightly improve the view-connection to the outside while increasing glare incident probability.

4.4.4 Questionnaire results: adaptive behavioural patterns

The participants were allowed to control different adaptive behavior options during the experiment scenarios (e.g., window opening, blind up/down, turn on/off the light, and ceiling fan). In S01, the participants' control was limited to adjusting the blind and the electric light. In S04 and S06, they were allowed to control more devices such as windows and ceiling fans. Figure 4.64 shows the relative frequency of shade adjustments related to other adaptive control options in each scenario. The highest frequency of shade lowering was observed in S03&S06, while the lowest was in S01&S04. Regarding shade raising actions, the highest frequency was noticed in S02&S05, and the lowest was in S03. This is consistent with our quantitative findings of the monitored data analysis.

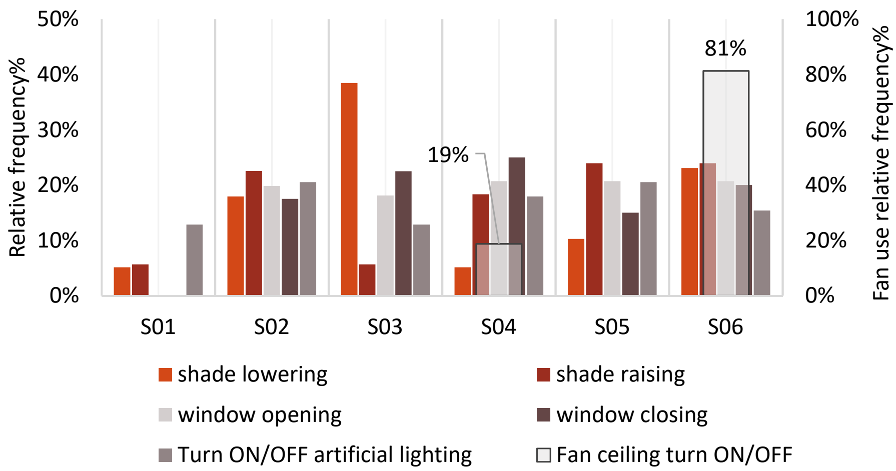


Figure 4.64: Relative frequency of adaptive behaviours for each scenario.

The highest frequency of window opening was observed in S04, S05, and S06 (21% per each), considering that the operable windows were fully closed in S01 due to active cooling mode. Improving the air movement and the warm conditions inside the room were the main reasons behind window opening (see Figure 4.65). People tended to close the windows more frequently in S03 and S04 compared to other scenarios. The primary reason was to avoid noise outside as the test room is located in the middle of the Haspel campus, Wuppertal University. The temperature inside or outside the test room was the secondary reason behind closing the windows.

In terms of lighting control, lights were turned off approximately 60-80% of the time during the experiment. Reducing the overall brightness of the workplane, reducing the glare on the computer screen, and saving energy were the main reasons why people didn't use the light (see Figure 4.66). However, the highest frequency of light adjustment was in S02&S05 since the mean shade occlusion was the highest (74% and 65%, respectively). The primary reason behind using artificial lighting was to increase the amount of light in the workplace.

The main reasons reported behind using the ceiling fan were the improvement of the air movement and it was hot inside. Participants were allowed to adjust the ceiling fan

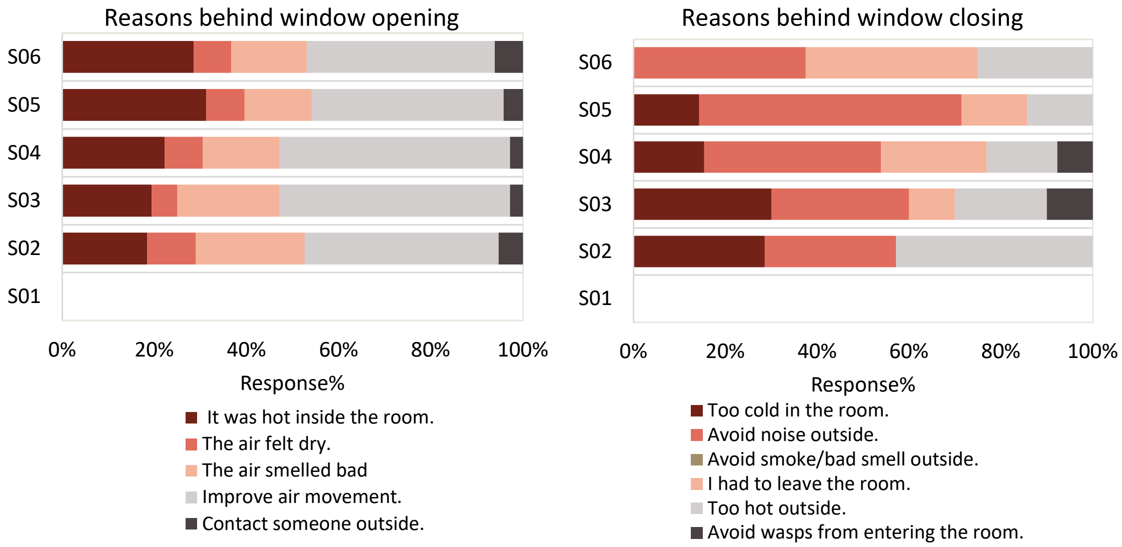


Figure 4.65: Reasons behind window opening and closing for each scenario.

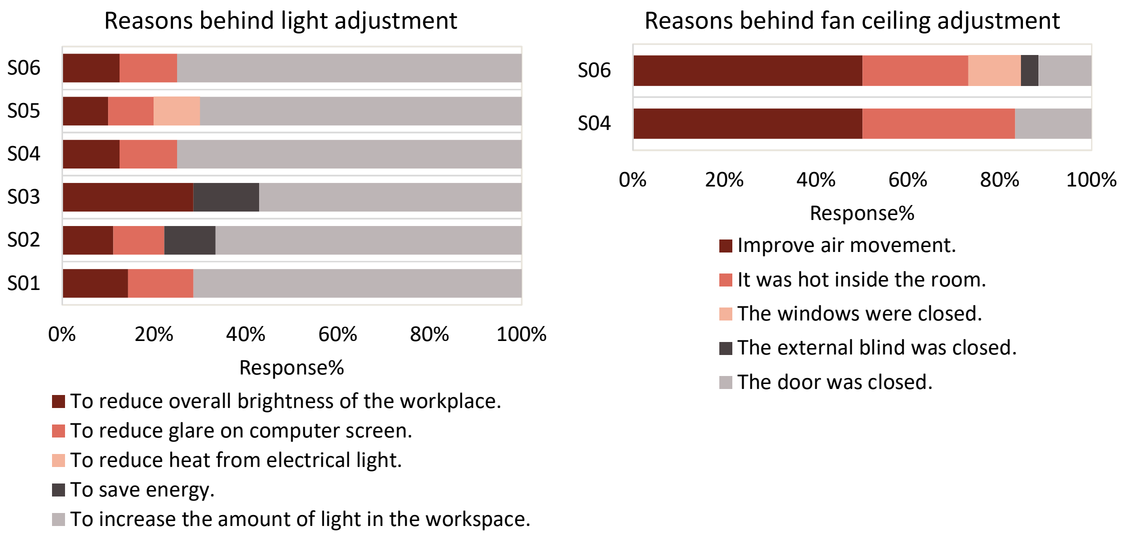


Figure 4.66: Reasons behind lighting and ceiling fan adjustments for each scenario.

using a desk remote in S04&S06. About 20% of the adjustments occurred in S04, whereas 80% occurred in S06 due to higher average operative temperature (26.44 °C) compared to S04 (24.74 °C). Figure 4.67 shows the thermal sensation air movement acceptance in S04, S05 & S06, while not in S01, S02 & S03 since the ceiling fan was not used. It is noticed that thermal sensation was more accepted in S04 compared to S05. A slight difference was observed between S05 and S06 in terms of thermal and air movement acceptance votes. More than half of the respondents preferred no change in air movement in S04&S06. These results indicate that people's satisfaction with the thermal conditions increased when interacting with the built environment was permitted using a fan or opening a window. This is in agreement with Schweiker et al. [111] findings in their experimental study in "btga-box" at the University of Wuppertal.

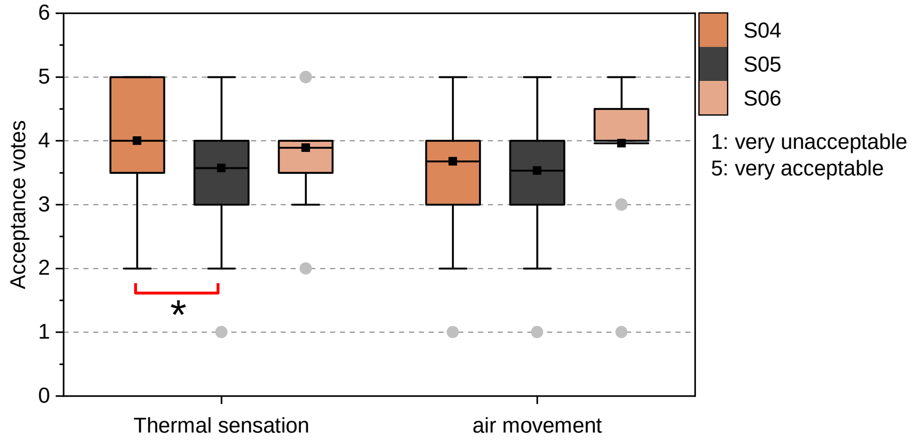


Figure 4.67: Questionnaire results: thermal sensation and air movement acceptance votes in S04, S05& S06.

Correlation between shade occlusion and current state of window and light

Figure 4.68 represents the current state of artificial lighting (on or off) as a function of mean shade occlusion. It is observed that light was turned on when MSO was high in S02, S05&S06. Surprisingly, it is observed that the light was turned off also when the mean occlusion value was also high.

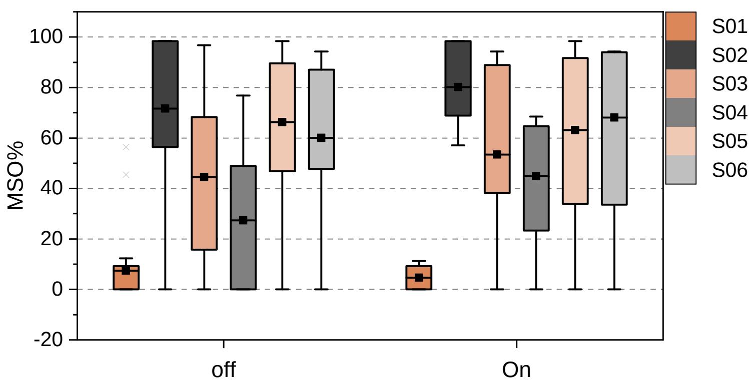


Figure 4.68: Lighting state as a function of mean shade occlusion for each scenario.

The window state was also analysed as function of mean shade occlusion as shown in Figure 4.69. It is noticed that the window was fully open when the mean shade occlusion was high except in S04, where the participants were able to use the ceiling fan. It is explained that people preferred to use the ceiling desk remote (easy-to-access) more than opening the window to improve the air movement when the blind was closed or the temperature outside was low. Blind closure could prevent the air movement, so people tend to open the window or use the ceiling fan to improve air movement.

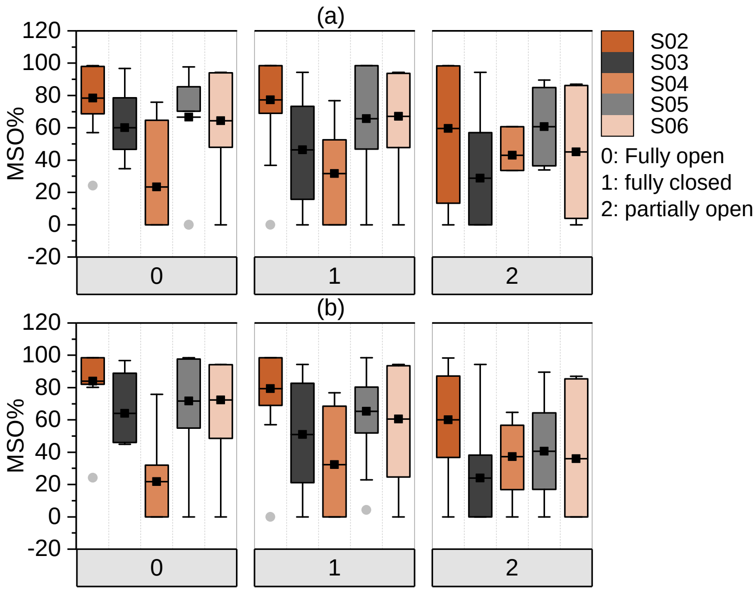


Figure 4.69: Window state as a function of mean shade occlusion for each scenario.

4.5 Conclusions and recommendations

This study is carried out with the objective to evaluate the performance of automated shading systems in terms of occupant interaction and satisfaction, thermal and visual comfort. An experimental study in a full-scale test cell was conducted under different environmental conditions, design solutions and shade control strategies for optimizing shading design and operation. The main conclusions and recommendations can be summarized as following:

- Time of the day, sky conditions (sunny or cloudy), solar irradiance on the facade, and indoor operative temperature influenced the blind occlusion substantially. However, only 20% of the respondents adjusted the blinds to reduce the heat from the sun. Therefore, it is recommended that the building designers consider the visual and thermal stimuli while selecting the optimal shading control strategy for each facade to ensure a comfortable indoor environment and less disturbing hours to the view outside.

- More than 70% of the participants preferred the performance of automated shading using the multi-objective control strategy. It is found as a robust shade control strategy (less override actions) since 86% of the respondents never or rarely adjusted the blind. The thermal and visual comfort results indicate that the multi-objective control strategy with an intermediate position could balance between solar heat and glare protection as well as daylight availability and view-connection to the outside, improving user satisfaction with the automated shading system. Therefore, it is recommended that occupant-centric control parameters (i.e., indoor illuminance and temperature) and intermediate positions should be incorporated into shading design selection criteria to a greater extent than what is common today.

- Active cooling system, mechanical ventilation by exhaust air, window opening, and use of ceiling fan were found to keep the indoor thermal conditions within the comfort range during the different scenarios in the experiment. Approximately 40-45% of participants preferred no change in the indoor thermal conditions when (a) the cooling system was active or (b) when they were permitted to open the window and use the fan. Therefore, considering a good cooling and ventilation system as well as control devices (e.g., window and fan) in the early stage of the building design can improve user satisfaction with the indoor thermal environment and shading operation. However, the selected cooling system should be considered within energy-saving implications.

- Using a small window size (WWR=40%) increased the frequency of shade raising actions by 24% compared to the original window design. However, a small window combined with a high irradiance lowering threshold maximized the view-to-the outside and decreased the shade raising actions by 26%. Therefore, it is recommended that designers select the optimal design of window size and solar shade control strategy in terms of user behaviour and acceptance.

- Using a high irradiance threshold (450 W/m^2) in controlling shading systems could reduce the number of shade raising actions by 49% compared to low irradiance threshold (300 W/m^2). However, 34% of the respondents tend to lower the blind to prevent both glare and heat gain from the direct sun. Therefore, it is recommended that designers may consider a high irradiance lowering threshold in north and west-facing facades while low irradiance threshold in south and east to prevent glare and overheating problems.

- Providing occupants a decent level of adaptive control options over their workplaces (e.g., window opening, turn on/off artificial light, adjusting the blind and using the ceiling fan) leads to higher acceptance with the indoor environment. More than 70% of respondents were satisfied for having the ability to override the shading system. About 80% are willing to use a desk remote or mobile application to control the shading system. Therefore, it is recommended that the designers consider deploying a high degree of control options, easy-to-access interfaces, and the ability to override while designing and planing the automated shading systems.

4.6 Limitation of the study

There are some limitations in this study outlined as follows:

- Thematic introduction before the experiment and periodic visits to the test cell to modify setups and retrieve data might exacerbate the "Hawthorne effect." Therefore, the "Hawthorne effect" may alter participants' natural behaviour towards interacting with the test room devices and systems due to their awareness of the study. Therefore, the next Chapter 5 represents an in-situ monitoring study performed in a real office building to explore user behavioural patterns related to the use of automated shading systems without the occupants' awareness.

- The number of people took part in the experiment was 28 instead of 43, which was the estimated number using the g-power statistical tool. However, a significant difference was found between the paired tested scenarios in terms of different performance indicators. Probably, the effect size (i.e., the difference between groups) was higher than the estimated.

- Participants tested three different scenarios per day, each scenario endured only two hours. As a consequence, indoor operative temperature slightly differed between the scenarios, and it was hard to evaluate the impact of different shading control strategies on indoor temperature.

- The findings show that sun position and time of the day greatly influenced the shade deployment in the different scenarios, however, both are considered as covariates variables (i.e., not of direct interest) in this study.

Chapter 5

Learning from shading design and utilization: Luxembourg case study

This case study presents the methods and key findings of a field study conducted on a mid-rise office building located in Niederanven, Luxembourg. The study focused on the building's automated shading system activation and the interaction between occupants and the shading systems with the aim of identifying occupant-centric rules for optimal shading design solutions. The study included a design investigation, data monitoring statistical analysis, a questionnaire, and a simulation-based analysis. An interview with the designer was conducted to investigate the shading system design characteristics and selection criteria. The data monitoring was performed under summer conditions in 2019, and the questionnaire was conducted in 2021 under similar conditions. Finally, a simulation-based analysis was performed to evaluate the daylighting and energy performance of the established shade control strategy. Contrary to expectations and previous studies' findings [101, 84, 119], the study found relatively few interactions between the occupants and the shading system. However, more interaction occurred when the occupant was located closer to the push button of shade manual adjustment. Additionally, building orientation, social constraints, and time of day were found to influence the manual activation of shading systems. The statistical analysis of the monitored data showed the low performance of a regression model and the superior performance of data mining techniques. The main lessons to designers and researchers include: (1) the use of (internal/external) shading systems can lead to user satisfaction (i.e., less override actions), (2) the definition of control thresholds is essential, and (3) the deployment of lighting sensors is beneficial. On the operation level, robust and simple shade control strategies are recommended.

5.1 Introduction

Automated shading systems represent a promising solution for improving indoor thermal and visual comfort as well as energy-saving for cooling. However, a recent review of the literature [93] indicates that many of the existing blinds automation systems fail to improve occupants' visual comfort and reduce the lighting energy use as intended in the design phase. These automation problems result in temporary or permanent occupant overrides. For example, Reinhart and Voss [101] reported that occupants overrode 88% of the attempts of an automation system to close window blinds. In another study, a total number of 3433 external blind adjustments were recorded—an average of 0.86 per office per day. The users triggered 73.6% over 100 working days in 40 offices. They explained the high rate of user adjustments that the majority of the users switched off the automatic mode and did not use it during the trial [84]. Therefore, there is a necessity to better understand occupants in the operation phase to enhance the robustness of building automation solutions over occupant overrides.

Despite high control over environmental conditions and flexibility to manipulate the configuration of building design and control systems in laboratories, studying occupants in a real environment provides insights into how occupants react to their built environment. Based on field studies of monitoring occupants' operations, researchers may extract data about occupant behaviour patterns to understand occupant behaviour as well as improve occupant-centric design practices [40]. Based on the aforementioned literature in Chapter 2, limited research focused on the design and post-occupancy evaluation of buildings equipped with dynamic shading systems in their facades in terms of user interaction and acceptance [67]. To this end, the current study provides a detailed and in-depth analysis on exploring behavioural patterns related to using the automated external shade in Luxembourg office building to derive occupant-centric rules for optimal shading design solutions.

5.2 Case study description

5.2.1 Building overview

The new headquarter Goblet Lavandier is a five-story office building located in Niederanven, Luxembourg (see Figure 5.1). The building is located in a temperate oceanic climate (Cfb) with a mild marine winter and warm summer with no dry season. The investigated building has been designed as a nearly-zero energy building and complies with the latest sustainable design criteria. The building received DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) Platinum certification in 2018. The building is a quadrilateral concrete structure (25×25 m) with a galvanized metal sheet façade (see Figure 5.2). It consists of three underground parking floors, a ground floor, and four upper floors. The reception area, conference halls, and a canteen are on the ground floor. The building core comprises circulation and sanitary units and creates a naturally daylit office zone and a passive night cooling. The workspaces are along the building perimeter, providing an excellent view to the outside and a lot of natural daylighting. The moderate use of transparent surfaces (fenestration) in combination with external Venetian blind and inner textile screen play a central role in the energy efficiency and daylight concept of the building design. Table 5.1 provides further details about the building.

Figure 5.1: Golav building map view (https://www.bing.com/maps/aerial)

Figure 5.2: Perspective view of the building[1], Christian Bauer & Associes Architectes

5.2.2 Monitored offices

The monitoring and data collection were performed in all 47 offices of the building over 66 working days from June to mid-September 2019. The majority of the offices are located along the quadrilateral perimeter facing one of the fourth cardinal directions (north, south, west, and east) (see Figure 5.4). These offices are situated on three floors and occupied by an average of 2-6 workers per office (see Figure 5.5). The offices' windows are designed to have the same height and width. Each window is equipped with a double shading system, an automated external Venetian blind, and an inner textile screen operated manually to avoid glare discomfort. Two office layouts can be distinguished: single-facade offices and double-facade corner offices (see Figure 5.3). The main differences between the offices are related to the following features:

- Office orientation: 9 offices facing the east, 9 to the west, 9 to the north, and 11 facing

[1]Source: Lucas Roth, https://www.golav.lu/

Table 5.1: Luxembourg building general characteristics [74]

Items	Specifications
Net floor area	2600 m^2 NFA
A/V ratio	0.31 m^{-1}
Window-to-wall ratio (WWR)	43% per facade
Number of employees in offices	138 employees, 30-40 employees during COVID-19 pandemic in 2021
Year of completion	2018
Thermal characteristics	Thermal insulation (U-walls: 0.13 W/m^2K, U-roof: 0.13 W/m^2K, U-floor: 0.17 W/m^2K)
Windows	U-value: 0.75 W/m^2K, g-value: 0.49, color rendering: 96%
Ventilation	11,000 m^3/h total air volume control depending on CO2 concentration, individual air volume control in meeting rooms. The fresh air supply is through a mechanical exhaust ventilation system with highly efficient heat recovery (80.8%)
Shading system	External Venetian blind type Warema E80 A2S DB703 (g-tot = 0.07, fully closed). Inner textile screen type Solar Screen International/ Ecran Clip Toile Screen PS 365 (Ts = 8%, Rs =12%, As =80%)
Cooling system	Passive night cooling to cover 20% of the cooling energy demand. Passive ground cooling to cover 80% of the rest of the cooling demand. A heat pump can be switched on only in extreme hot summer.
Heating system	Geothermal heat pump with a vertical array of probes.
Electricity demand and generation (without usage related consumers)	23.7 kWh/(m^2a), PV yield = 14.5 kWh/(m^2a)

the south, and 9 offices facing two directions. For grouping purpose, double-facade offices are assigned to one direction based on the largest window orientation.

- Occupancy level: 16% private offices (single person), 46% shared offices (2 to 3 people), 32% open-space offices (4 people or more).
- Floor level: 1^{st} floor hosts 16 offices, 2^{nd} floor hosts 15, and 3^{rd} floor hosts 16, and three conferences room.
- Window area: 2.38 m^2 (1 unit), 4.76 m^2 (2 units), 4.76 m^2 (3 units), 9.52 m^2 (4 units).

5.2.3 Shading system design "Double approach"

The automated Venetian blind combined with inner manual glare protection are a reflection of design considerations such as more individual workplace control and passive solar gain in winter. Due to the extra cost, this "double system approach" (see Figure 5.6) is not common. The designer was interviewed and the design briefs and architectural documents were investigated to define the design characteristics and selection criteria of the shading systems.

The shading control strategy was developed based on the designer's experience. The external shading system is operated automatically based on light and temperature control

[2] Source: Goblet Lavandier & Associés Navigation
[3] Source: Goblet Lavandier & Associés Navigation
[4] Source:Jürgen MÜLLER, https://www.golav.lu/

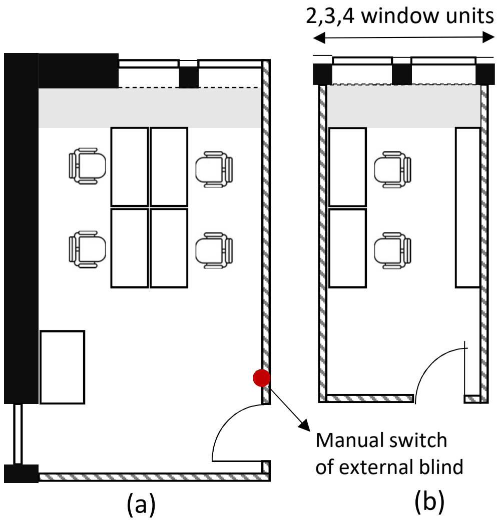


Figure 5.3: Typical layout of the monitored offices (a) double-facade office (b) single-facade office.

Figure 5.4: Typical floor plan in Luxembourg building.[2]

thresholds. Individual shades in the same office are grouped, so one actor and motor control multiple shades. Occupants can override the blind position and tilt the slat angle at different positions (0, 60, and 80 degrees) using a wall-mounted switch button next to the office door (see Figure 5.7). Manual control is possible except in the case of storms and cleaning. Any manual interventions disable the automated system until it resets at 11:00 am and 3:00 pm.

The KNX Elsner sensor controls the blinds in each facade. The shade activation is monitored by the building system dashboard (see Figure 5.8). The blind is lowered when

[5]Source: Jürgen LEICK, https://www.golav.lu/

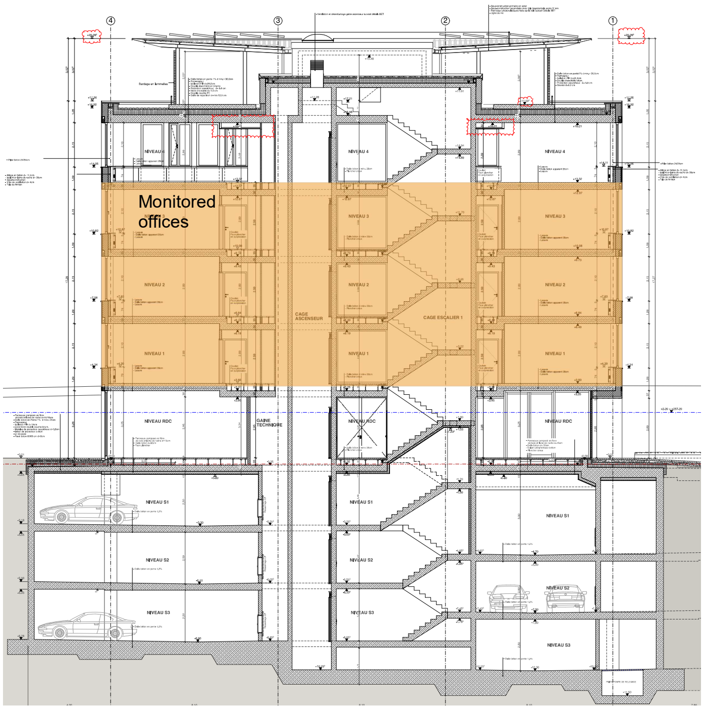
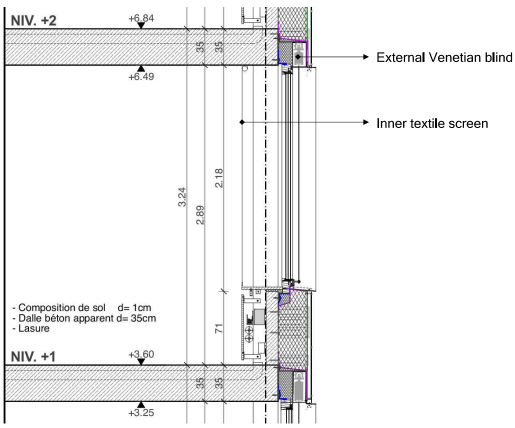


Figure 5.5: Section view of the building[3]

(a) Interior view of the "double shading"



(b) Section view

Figure 5.6: The double shading system approach[4]

the solar irradiance on the facade exceeds 120 W/m^2, and the outdoor temperature is above five °C without any delay time. When the irradiance is below 50 W/m^2, the blind is raised after 60 minutes. The blinds are automatically raised and blocked when wind speed exceeds 12 m/s. During the operation phase, the established thresholds were modified, including (a) the lowering threshold is set up to 250 W/m^2 with a horizontal slat position (0^o) to maximize the view to the outside, (b) when the irradiance exceeds 400 W/m^2, the slat angle inclines up to °15 instead of °80 to provide sufficient daylight, and (c) threshold values can be increased (e.g., temporary cloud sky cover) for less disruptive blind movements. Table

Figure 5.7: The manual switch of the external blind[5]

5.2 summarizes the shading control settings during the design and operation phase of the building.

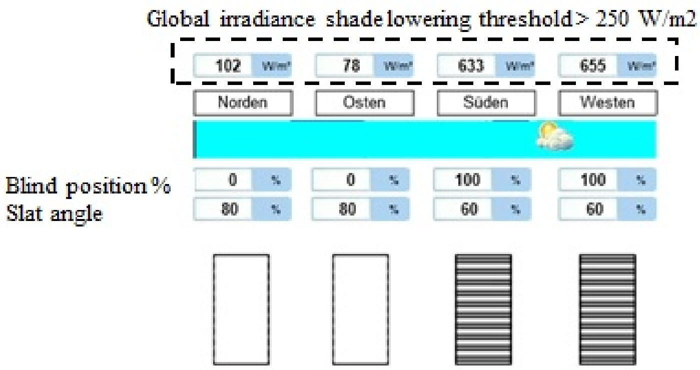


Figure 5.8: The monitoring dashboard of shade deployment[6]

Table 5.2: Control settings of automated shading systems during design and operation phase.

Settings parameters	Design phase	Operation phase
Operation Days Per Week	All days (Mo-Sn)	All days (Mo-Sn)
Operation Hours Per Day	6:00-20:00 (14 hours)	6:00-20:00 (14 hours)
Irradiance on the facade lowering threshold (upper value)	>400 W/m^2, slat angle = 80°	>400 W/m^2, slat angle = 15°
Irradiance on the facade lowering threshold (lower value)	>120 W/m^2, slat angle = 0°	>250 W/m^2, slat angle = 0°
Delay time of lowering	0 min	0 min
Irradiance on the facade raising threshold	<50 W/m^2	<50 W/m^2
Delay time of raising	60 mins	60 mins
Outdoor temperature lowering thresholds	above 5 °C	above 5 °C
Wind raising threshold value	12 m/s	12 m/s

[6]Source:Jürgen MÜLLER, https://www.golav.lu/

5.3 Methods

Figure 5.9 outlines the workflow of this study. The study began with a written interview conducted with the designer to define the shading system's design characteristics and selection criteria. Then, regression statistical analysis and data mining techniques were performed on the monitored datasets to explore behavioural patterns of user interaction with automated shading systems. Third, a web-based questionnaire was conducted under a similar condition to the monitoring study to reveal subtle triggers behind shade interaction and better understand the findings of the monitored datasets. Finally, a simulation-based analysis evaluated the established control strategy in terms of energy efficiency and daylighting compared to other shading control strategies.

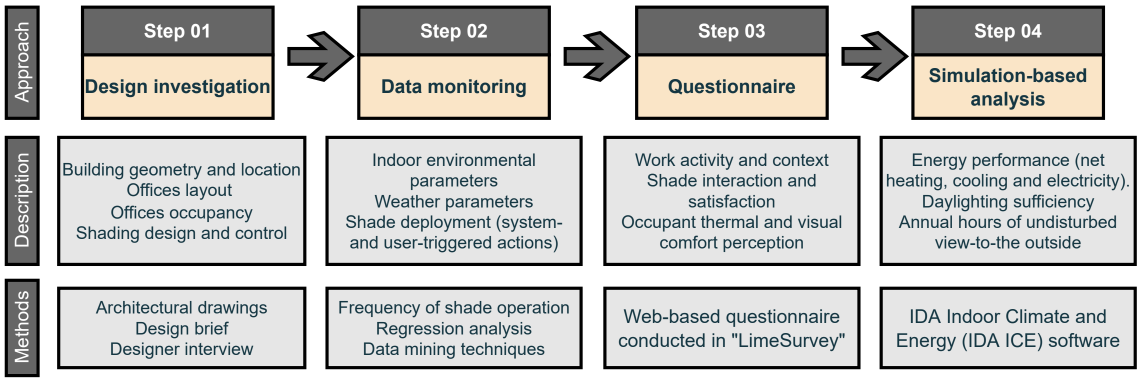


Figure 5.9: The workflow of the study

5.3.1 Designer interview

A written, structured interview with the building's designer was conducted via email to explore if any of the questions below were considered during the shading system design. To streamline the interview, potential responses were provided for many of the questions (in brackets below).

- Which solar shading scenarios were proposed before selecting the final shading design? (e.g., Internal roller shades, fixed, dynamic, vertical, complex, combined).
- Which selection criteria were considered during the solar shading design optimization? (Environmental and climatic parameters, energy concern, aesthetics, safety, privacy, cost, user comfort, code...etc.).
- What was the basis for selecting shading control established thresholds? (Codes and standards, guidelines, literature, design brief, designer experience).
- Which occupant assumptions were considered during the shading design? (Number of occupants, demographic, occupancy, work activities, preferences).

- Did the designer consider any simulation-based evaluation to select the optimal shading design? If yes, which metrics were used?
- Was there any cooperation between stakeholders (designer, client, energy modeler, etc.) with regard to shading selection and design?

5.3.2 Data monitoring

Monitored parameters

Monitored weather parameters included global horizontal irradiance (I_gl) W/m^2, external vertical illuminance (E_{out}) Lux, air temperature (T_{out}) °C, solar azimuth, and altitude. These parameters were measured using a weather station mounted on the rooftop of the building (see Figure 3.3). Indoor parameters included air temperature (T_{in}) °C, relative humidity (RH)%, and CO2 concentration (ppm). The indoor parameters were measured with Netatmo data loggers distributed in 9 workspaces (see Table 5.3). Shading system-triggered actions and user-triggered actions were recorded as event-based measurements. The external automated blind position was expressed as 0% fully open and 100% fully closed. The datasets were resampled every 5 minutes using an excel tool developed by Mr. Jürgen Leick from Goblet Lavadier. For the analysis purpose, the range of the data was limited to working daytime between 6:00 am and 8:00 pm.

Table 5.3: General characteristics of the 9 monitored offices using Netatmo data loggers.

Netatmo data logger	Office number	No. of employees	Orientation	Floor level
GLA-HQ-1OG-1	office 01	3	East	1^{st} floor
GLA-HQ-1OG-2	office 02	4	North	1^{st} floor
GLA-HQ-1OG-B	office 03	3	East	1^{st} floor
GLA-HQ-2OG-1	office 04	4	North west	2^{nd} floor
GLA-HQ-2OG-2	office 05	4	North	2^{nd} floor
GLA-HQ-2OG-B	office 06	3	West	2^{nd} floor
GLA-HQ-3OG-1	office 07	3	North west	3^{rd} floor
GLA-HQ-3OG-2	office 08	3	North	3^{rd} floor
GLA-HQ-3OG-B	office 09	3	West	3^{rd} floor

Data preprocessing

The monitored dataset was extracted from the KNX-based BMS beginning with June until mid-September 2019. The raw data was converted from XML to CSV readable format using ETS 05 professional software. Data preprocessing was performed on the raw datasets, including cleaning, removing outliers, interpolating missing data, and normalization (rescale a variable to have a value between 0-1). Consequently, the statistical analysis was performed on clean and complete datasets over 66 working days.

Data statistical analysis

The frequencies of shade deployment were analyzed in terms of system and occupant-triggered events. In statistics, the frequency of an event is the number of times the observation occurred/was recorded in an experiment or study. The preliminary occupant behaviour patterns were explored by the "rate of change" of the blind use. The "rate of change" was defined as the number of user-shade override actions (UOAs) per day or office [124]. Afterward, logistic regression was applied to the given datasets to predict the likelihood of UOAs as a function of physical explanatory variables. Generalized linear regression (e.g., logistic) is commonly used in adaptive behaviour modeling. It employs a non-linear link function to map the explanatory variables (e.g., indoor temperature) into binary (0 or 1) response variables (e.g., the probability of observing blind override) [24].

Alternatively, data mining techniques such as clustering analysis and association rules mining were applied to the same datasets to discern typical office user profiles. The analysis was conducted to allow more accurate assumptions on group behaviours in office buildings and overcome the limitation using regression analysis. Data mining was defined as: "The analysis of large observational datasets to find unsuspected relationships and to summarize the data in novel ways so that owners can fully understand and make use of the data" [50]. Clustering analysis was used to obtain distinct behavioural patterns using the K-means algorithm. *Cluster analysis* is the process of merging data into different clusters so that instances in the same group have high similarity and instances in different groups have low similarity [92]. Association rules mining (ARM) is used to transform the clustered patterns into typical office user profiles. ARM is a classification technique used to identify associations and correlations between parameters (attributes) [92]. The frequent pattern growth algorithm (FP growth) is used to discover patterns (user profiles) in the given datasets and generate a classification tree (FP-tree). Both regression and clustering analyses were performed in IBM SPSS Statistics V21.0 software, while Rapid Minor -an open source data mining program- was used for ARM analysis.

5.3.3 Questionnaire

A cross-sectional web-based questionnaire using LimeSurvey was conducted to reveal subtle and non-physical triggers behind blind use and better understand the findings of the monitoring study. The questionnaire was distributed in summer 2021 to ensure that occupants had experienced the same thermal and visual conditions as those studied in the monitoring period. The questionnaire was issued to Golav staff on 30^{th} of July 2021 via the firm manager and followed by a reminder three weeks later. A total of 32 participants (25% of the population) working in single-occupancy offices completed the questionnaire. Employees who were working from home due to COVID-19 pandemic were excluded from population sample. The questionnaire is anonymous, and no personal identification has been collected. Instead, each participant was asked to provide a code at the beginning of the survey.

Survey questions were designed based on previous studies [1], [8], [25], [7], [106]. New questions were added to achieve the aim of this study. The questionnaire was available in English and German to increase the response rate. The time required to answer the questionnaire was 15-20 minutes. The questionnaire included 8 sections and 46 questions (see Appendix A1.3). The questionnaire included questions about participants' demographic details, mood, work activity, contextual environment (e.g., window orientation, seating position, window size), thermal and visual discomfort, interaction with the shading systems, their satisfaction and preferences regarding shading system performance.

Statistical analysis was performed in IBM SPSS Statistics V21.0 software to identify and quantify the main attitudes and behaviours of the occupants related to the use of automated shading systems. First, frequency and density analysis were performed. Second, the Spearman's rank order correlation test was used to analyze the relationships between occupants' perceived comfort, control, and overall satisfaction.

5.3.4 Simulation-based analysis

Daylighting and energy performance of different shading control strategies were evaluated using a simulation-based analysis implemented in IDA Indoor Climate and Energy (IDA ICE) software. Tuğçin Kırant-Mitić did building zones modeling in her Ph.D. thesis, titled "Investigation of Building Energy Flexibility at Cluster Level for a Promising Energy Flexibility Market" (not published yet). Annual heating, cooling, and lighting demand (kWh/m^2) was calculated under different shading control strategies, including the original design. Useful daylight illuminance (UDI) was used for daylighting performance assessment. Achieved UDI is defined as the annual occurrence of illuminance across the workplane where illuminance is within the range of 300-3000 lux [87].

5.4 Results and discussions

The main key findings of the designer interview, the monitoring study, the questionnaire and the simulation-based analysis are introduced in this section. Moreover, lesson learned from shade design and operation are extracted and summarized for building designers and operators.

5.4.1 Designer interview

The designer was involved as an engineer, consultant of HVAC design, and simulation expert during the planning and design of shading systems. A written interview was conducted with the designer to investigate the shading systems' characteristics and selection criteria during the design process of the building. Based on the designers' feedback, the following points are summarized:

- External Venetian blind and inner textile screen are suggested from the early stage of shading design. The shading system was selected based on different parameters such as environmental performance, climatic parameters, energy concerns, aesthetic aspects, safety and maintenance, economic restrictions defined by the client, thermal and visual comfort, building codes and standards (ASHRAE, DIN, DIN-EN... etc.).

- The shading system control strategy was selected based on the designer's experience. However, the shade activation thresholds (e.g., irradiance and temperature) and slat angle rotation were modified during the operation phase to improve the blind visual performance. New photocell and light measuring sensors were installed to improve the quality and performance of hardware systems.

- The designer did a simulation-based analysis to find the optimal shading design in terms of thermal comfort, daylight, glare discomfort, and energy performance. However, none of the occupant-related assumptions (number of occupants, occupancy profiles, occupants' demographics, preferences, etc.) was considered in the simulation analysis.

- The stakeholders, including the designer, client, and energy modeler, were all involved in shading system design decision-making.

Overall, the findings indicate that the designer intended to maximize the user satisfaction and comfort in their workspaces throughout the building life-cycle (design and operation phase). This is in alignment with the notion of occupant-centric design, which refers to placing occupants and their well-being as a top priority throughout the building life-cycle [5].

5.4.2 Data monitoring

The shade operation patterns in terms of system-triggered actions and user-triggered actions, regression and data mining results and limitations of this study are introduced and discussed in the following sections:

5.4.2.1 System behaviour

Table 5.4 shows the number of system-triggered lowering and raising actions, the average occlusion value (AOV%), and slat angle degree triggered by the system. It is noticed that AOV% was the highest in the south-facing offices (32.41%) and the lowest in the north-facing offices (19.03%). This is in line with the high variance of irradiance intensity on the south facade, a range of 0-1105 W/m^2 (SD = 265.5). 576 blind adjustments (287 raising and 289 lowering actions) were recorded during the study period—an average of 8.72 blind changes per day.

Figure 5.10 shows that the highest system-triggered actions were observed in the west-facing offices, while the lowest was in east-facing offices. The opposite occurred in terms of user-triggered override adjustments, where the highest frequency of override actions was in the east, and the lowest was in the west. The high rate of system-triggered adjustments occurred in the west, and south-facing offices can be due to (a) the high daily average of irradiance on the facade, which exceeded 400 W/m^2, and (b) the shading system was occasionally corrected and disabled by the occupants.

Table 5.4: AOV%, number of system-triggered adjustments (up and down), and relative frequency of slat angle position for each facade.

Building orientation	AOV%	System-triggered up	System-triggered down	Slat angle (0)	Slat angle (60)	Slat angle (80)
East	24.20%	53	53	6%	66%	28%
North	19.03%	67	71	30%	37%	33%
South	32.41%	77	73	13%	57%	30%
West	28.71%	90	92	7%	57%	35.8%

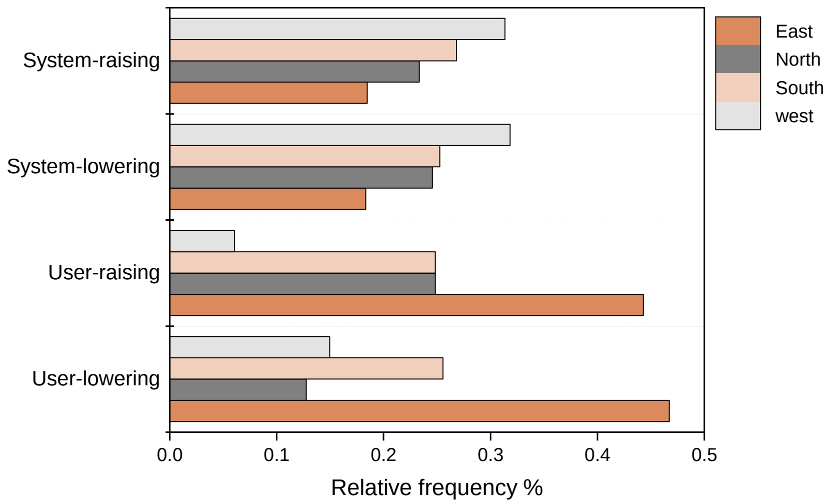


Figure 5.10: Relative frequency of system- and user-triggered adjustments for each facade.

Figure 5.11 shows the box-plot distribution of global horizontal irradiance (I_{gl}) as a function of user-shade lowering and raising and system lowering actions per each facade. In east, north, and west-facing offices, the results show that the I_{gl} average at the moment of system lowering was higher than the I_{gl} average at the moment of user-shade lowering actions. The average value of system-lowering threshold was found above 400 W/m^2 except for the north facade. Overall, 45%-60% of user-shade lowering occurred when the irradiance average exceeded 250 W/m^2 and less than 400 W/m^2. It can be explained that the occupants are less tolerant to high solar irradiance, so they tend to lower the blind before the system reacts. This is in line with Inoue et al. [58] findings in their study. They reported that the manual blind trigger rate increases over the range of 100-325 W/m^2 of vertical irradiance. Similarly, Reinhart and Voss [102] found that people do not usually shut the shades when solar radiation is below 50-60 W/m^2, while they need to close them above 250-360 W/m^2.

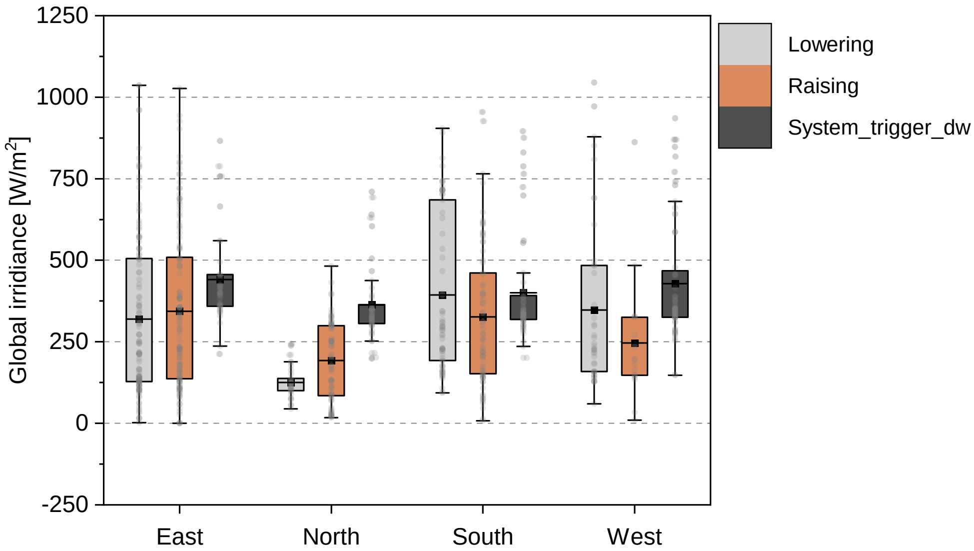


Figure 5.11: Box-plot distribution of global horizontal irradiance (I_{gl}) as a function of user-shade lowering and raising actions vs. system lowering actions for each facade.

To conclude, the shade operation revealed that the average value of the system-lowering threshold was above 400 W/m^2 in all offices as designed. However, 45%-60% of manual blind closure occurred when the irradiance was between the range of 250-400 W/m^2 mainly in east and south-facing offices. These findings emphasize the necessity for considering low irradiance thresholds in east and south-facing offices to decrease occupant override adjustments.

5.4.2.2 User behaviour

A total number of 1148 blind adjustments were recorded over 66 working days in 47 offices. The users triggered approximately 49% of the blind movements, where 274 user-shade lowering actions and 298 raising actions were recorded—resulting in an average of 0.184 blind adjustments per day and per office. Approximately 20% of blind raising adjustments were a correction of automated blind position within 15 mins after closure. It is a low rate of corrections compared to Reinhart and Voss [102] findings, where they found 88% of user corrections were to reopen the blinds after an automated closure occurred. When the shade was fully lowered, the slat angle was kept horizontal to maximize the view to the outside. Thus, occupants may not need to reopen the blind. Figure 5.12 shows the relative frequency of user-shade override adjustments (UOAs) (i.e., lowering, raising, and total adjustments) in terms of window-to-wall ratio (WWR%), floor level, space orientation, and occupancy level. The following shade use patterns in the monitored offices are observed:

- The highest rate of UOAs was observed in east-facing offices—an average of 3.93 adjustments per day. This can be explained due to the greatest variations in daily

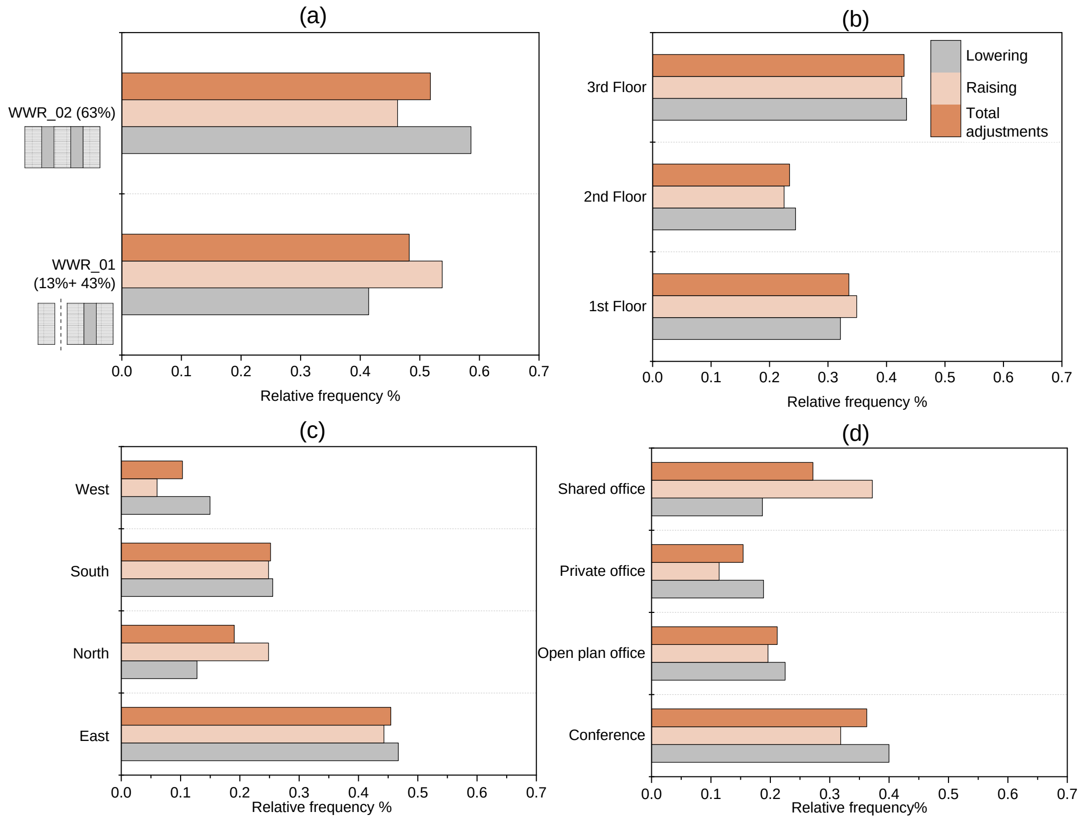


Figure 5.12: Relative frequency of UOAs in terms of (a) WWR% (b) floor level (c) office orientation (d) occupancy level.

average of global irradiance (0-1115 W/m^2), and the highest monthly average of work-plane illuminance as shown in Figure 5.13. Compared to the east and south, fewer interactions were observed in the west and north-facing offices. This result is in line with Mahdavi et al. [82] findings during a survey in three office buildings. They found that the east-facing offices showed higher shade adjustments variability than the south and north facades. Therefore, it is recommended for designers to consider small window size or fixed shading, combined with manual inner glare protection in east-facing offices as a robust design strategy to decrease visual discomfort. The simulation results of O'Brien and Gunay [94] study showed that implementing more passive features (fixed solar shading and window size) can reduce the energy use and the frequency of occupants' adaptive actions.

- Additionally, it is noticed that the highest rate of UOAs was in the 3^{rd} floor level with an average of 3.72 adjustments per day. It is expected that people on lower floors tend to operate the blind less frequently than those on the upper floors because of visual privacy [75], while in higher offices people prefer to have better views [95].

- In terms of occupancy level, a higher frequency of UOAs was observed in shared offices—an average of 0.19 changes per day per office, compared to single-occupancy and

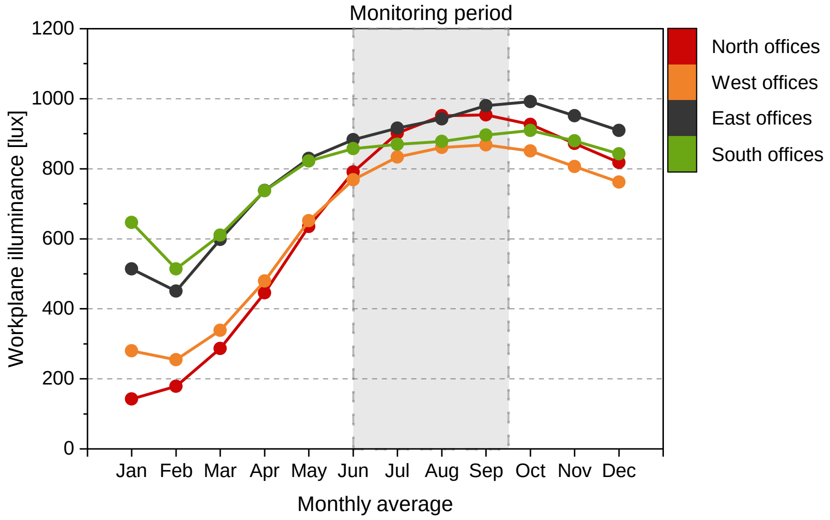


Figure 5.13: Monthly average of workplane illuminance for each facade (simulation-based calculation).

open-plan offices. This is not in agreement with O'Brien et al. [95] as well as Schweiker and Wagner [112] findings. They found that occupants tend to be more reluctant to control their environment if others are present because of social constraints. Private offices are located on the south facade of the building, where 75% of these offices are located on 1^{st} floor, and the remaining on 3^{rd} floor. Based on occupants' feedback (survey results), most single-occupancy offices are occupied by managerial employees. The researcher assumed that they were too busy or less often in the office to override the blind position.

- Window size and position influenced UOAs. For instance, higher raising actions and fewer lowering actions were observed in double-facade offices (WWR% = 43% & 13%) compared to single-facade offices (WWR% = 63%). The daily rate of blind use was approximately the same for both offices.

Figure 5.14 demonstrates that shades on the east, north, and south were adjusted by occupants more frequently in the early morning and morning than the rest of the day. This is in line with previous studies [48], [19], they found that occupants interact with blinds more frequently on arrival. People tend to set up their office environment at the beginning of the work period. In west-facing offices, occupants adjusted the blind more frequently in the noon and afternoon. Only for north-facing offices occupants tended to raise the blinds most frequently in the evening and all the day. This is similar to Inoue et al. [58] study findings.

Overall, the daily rate of change of UOAs was relatively low compared to the findings of previous studies (see Table 2.3). For instance, Reinhart and Voss [102] reported a mean of 3.7 blind movements per day per office for 174 weekdays in 10 south-facing offices. The offices were distributed on the ground and first floor and occupied with one or two person

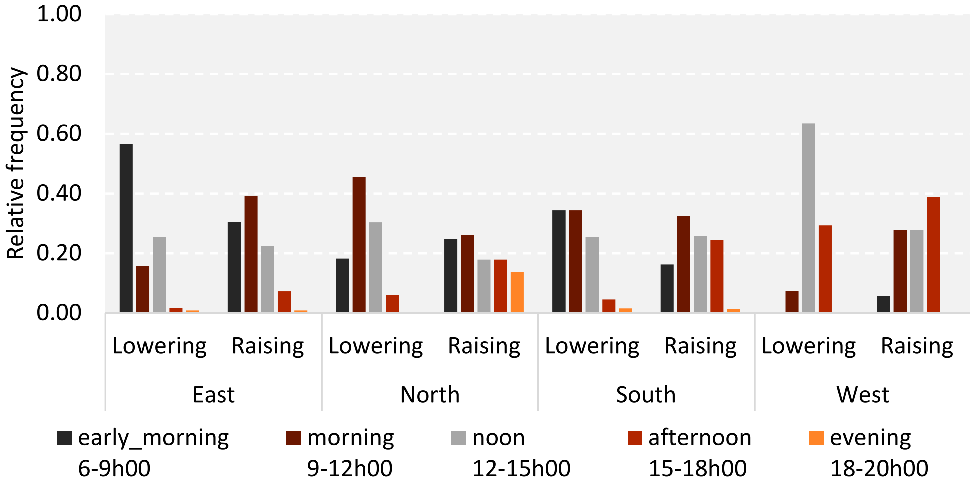


Figure 5.14: Relative frequency of UOAs during the time of the day for each facade.

per office. In another study, an average of 0.86 blind adjustments per day per office was recorded over 100 working days in 40 offices. An external motorized blinds and an individual manual indoor roller shades was equipped. The monitored offices were distributed on third to seventh floor with two or three person per office [84]. Both studies were conducted in temperate climatic zones same as the case study. Therefore, this finding can be explained due to (a) correct and acceptable automated shade control settings, (b) high-quality light sensors, and (c) the additional inner glare protection, which provides less effort to avoid glare discomfort.

Occupancy presence based on daily average profiles of CO2 level

Occupancy is a fundamental factor in shade operation patterns. A vacant office means no override blind adjustments. To evaluate the occupancy level in the offices during the study period, the CO2 concentration level was collected in 9 monitored offices. Figure 5.15 shows the daily average profile of CO2 concentration in each of the monitored offices and the overall average. It is noticed that these averages varied from 400 to 900 ppm per day per office. The average CO2 level was calculated during the weekends and compared with the CO2 level during the weekdays. Based on the box-plot distribution of CO2 concentration in Figure 5.16, the office was assumed to be empty when the daily average of CO2 was around or less than the CO2 average on the weekends. For approximately 97% of the study period, these offices were occupied. To conclude, the low manipulation rate of blind use was not related to occupancy absence during the study period.

5.4.2.3 Regression analysis results

The initial aim of the present study was to derive occupant behaviour models, as high rate of shade adjustments was expected. The logistic regression was used to predict the likelihood of user-shade override adjustments (UOAs), either for lowering or raising actions, as a function

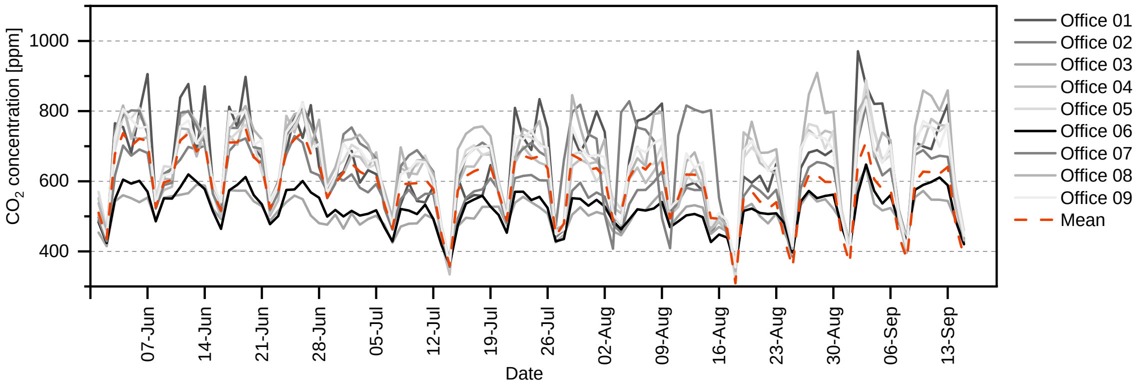


Figure 5.15: Daily average profile of CO2 level in 9 offices during the study period.

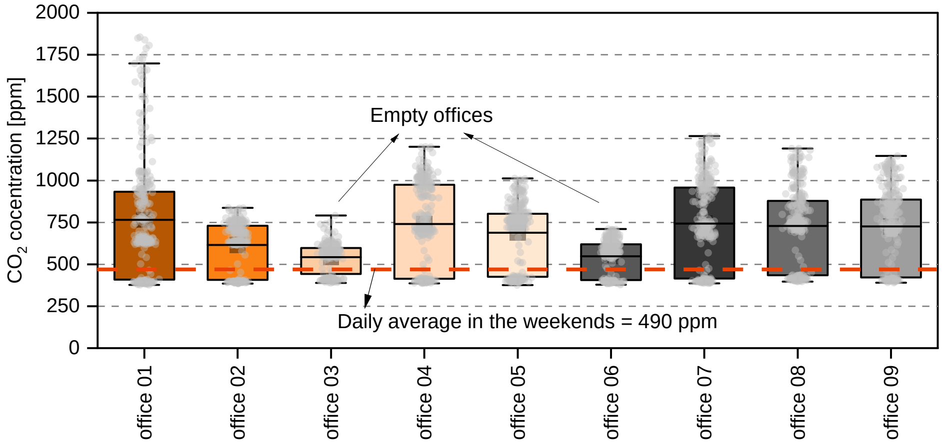


Figure 5.16: Box-plot distribution of CO2 level in 9 offices during a weekday 03.06.2019.

of the measured indoor and outdoor environmental parameters, blind state and slat angle position, and the time of the day. The dependent variable was considered a binary variable (only takes two values, 0 or 1) for each observation time-step (every 5 mins). The shading "action" took a value of "1", while "no action" was equal to the "0" value. The following formula represents the probability of UOAs as a function of several explanatory variables:

$$logit(UOAs) = \beta 0 + \beta 1(Eout) + \beta 2(Igl) + \beta 3(Tout) + \beta 4(tan\alpha) + \beta 5 \\ (Tin) + \beta 6(Rh\%) + \beta 7(CO2) + \beta 8(AOV\%) + \beta 9(\Theta slatangle) + \beta 10(timeoftheday) \tag{5.1}$$

where E_{out}: outdoor vertical illuminance (Klux), I_{gl}: global irradiance (W/m^2), T_{out}: outdoor air temperature (°C), tan (α): tan of solar profile angle, T_{in}: indoor air temperature (°C), Rh: Relative humidity (%), AOV%: Average occlusion value (fully open: 0%, fully closed: 100%), Θ slat angle: Slat angle position (0, 60, 80 degrees), $\beta 0$: the intercept and βn: variable coefficient. Tan(α) is equal to tan(solar altitude) divided by cos(solar azimuth). Tan(α) is negatively correlated with solar penetration depth which defined as the normal distance from the façade that the beam solar radiation reaches the workplane [102], [58].

Thermal and visual stimuli were identified by earlier research as influencing blind use. Table 5.5 presents descriptive statistics of the explanatory variables measured during the study period and the reference study of each parameter. The normality test showed that all the numerical explanatory variables were not normally distributed based on skewness and kurtosis z-values (not equal to the range between -1.96 and + 1.96). Accordingly, the measured data was standardized to have a value between 0 and 1.

Table 5.5: Descriptive statistics of explanatory parameters during daytime (6:00 am -8:00 pm).

Explanatory variables	Min.	Max.	Mean	SD	Previous studies
Eout_south [klux]	0.00	129.9	39.5	32.3	Sutter et al., 2006
Eout_west [klux]	0.00	129.9	38.6	32.8	Mahdavi et al., 2008
Eout_east [klux]	0.00	108.05	29.8	23.5	Haldi and Robinson, 2008
Igl_north [W/m^2]	0.00	858.24	155.3	133.8	
Igl_east [W/m^2]	0.00	1114.24	218.0	227.2	Sutter et al., 2006
Igl_south [W/m^2]	0.00	1105.28	295.6	265.5	Mahdavi et al., 2008
Igl_west [W/m^2]	0.00	1059.84	265.3	266.5	
Tout [oC]	4.40	42.20	21.7	6.4	Nicol and Humphreys, 2004 Haldi and Robinson, 2008
Tin [oC]	21.06	25.01	23.3	.62	Mahdavi et al., 2008 Inkarojrit, 2005
Solar azimuth	0.00	83.00	41.6	22.6	Haldi and Robinson, 2010
Solar altitude	0.00	17.00	9.3	5.04	
RH%	37%	64%	49%	5%	
CO2 [ppm]	359.1	1389.6	712.3	116.5	

Before formally inferring the regression model, the distribution of the explanatory variables at the moment of user-shade lowering and raising actions was analyzed as shown in Figure 5.17 & 5.18. The non-significant statistical difference in the average of T_{out}, T_{in}, CO2 concentration, RH%, and solar angle profile was observed at the moment of shade lowering and raising actions. However, raising actions occurred when the AOV% of the blind was high. It can be explained by the fact that people are more likely to accept that their blinds are opened than closed [102]. Figure 5.18 presents the box-plot distribution of E_{out} and I_{gl} as a function of shade override lowering and raising adjustments for each facade. Noticeably, low values are associated with raising and, conversely, with lowering actions. These findings indicate strong evidence for the prevalence of visual stimuli for triggering user actions.

Model prediction and goodness-of-fit

The forward logistic regression method was used to select the explanatory variables that have a statistically significant influence on the value of the dependent variable (p-value < 0.05). Separate analysis were conducted to predict the probability of USOs (lowering and raising actions) for each façade, including eight sub-models (M1-M8) (see Figure 5.19). Table 5.6 presents the logistic regression coefficients for each predictor and the performance test for

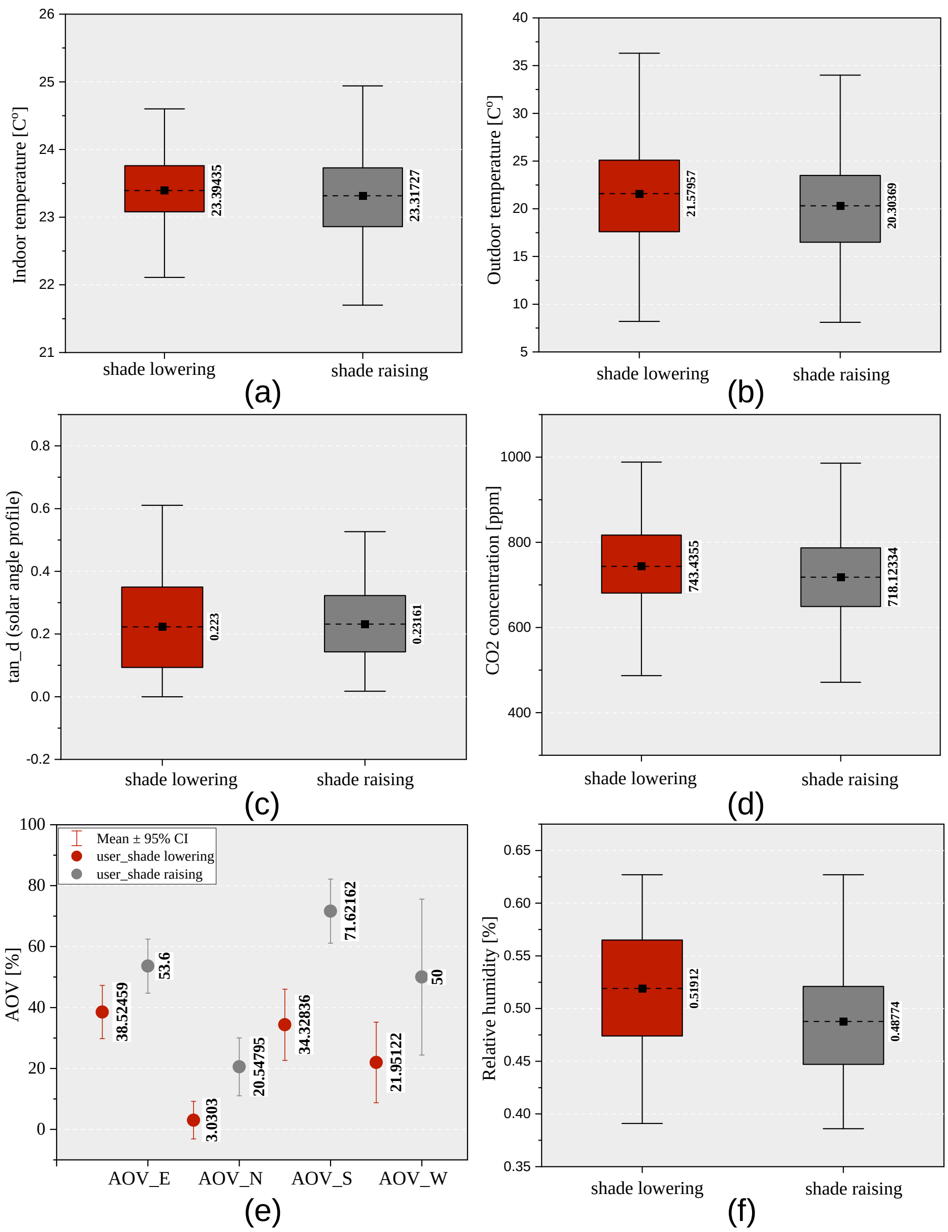


Figure 5.17: Box-plot distribution of user-shade lowering and raising actions as a function of T_{out} (b), T_{in} (a), CO2 (d), RH% (f), tan α (c), and AOV% (e).

each model (AIC and Nag. R squared values). Logistic models show a considerably low Nag. R squared of all models (M1=0.137, M2=0.067, M3=0.107, M4=0.089, M5=0.125, M6=0.039, M7=0.227, M8=0.041) for both lowering and raising actions, which show a weak relationship between model predictions and observations. To conclude, all the developed regression models could not predict user-shade lowering or raising actions, even if they are particularly accurate for "no action=0" (100% of prediction success).

Based on regression model results, the outdoor vertical illuminance, presence (CO2 concentration), outdoor temperature, and time of the day (early morning, morning, and noon)

Table 5.6: Logistic regression coefficients and goodness-of-fit for the eight sub-models.

Predictors	M01 SA_L_E β |p-value	M02 SA_R_E β | p-value	M03 SA_L_N β | p-value	M04 SA_R_N β | p-value	M05 SA_L_S β | p-value	M06 SA_R_S β | p-value	M07 SA_L_W β | p-value	M08 SA_R_W β | p-value
I_{gl}	2.85| <0.05	2.34| <0.05	n.a.^{b}	9.92| <0.05	n.a.^{b}	-2.28|<0.05	n.a.^{b}	n.a.^{b}
E_{out}	n.a.^{b}	n.a.^{b}	n.a.^{b}	n.a.^{b}	2.34| <0.05	n.a.^{b}	5.18 |<0.05	n.a.^{b}
T_{out}	2.94 |<0.05	n.a.^{b}	3.34| <0.05	n.a.^{b}	n.a.^{b}	n.a.^{b}	-5.15| <0.05	n.a.^{b}
tan_d	n.a.^{b}	n.a.^{b}	n.a.^{b}	n.a.^{b}	n.a.^{b}	n.a.^{b}	n.a.^{b}	n.a.^{b}
RH	n.a.^{b}	-1.50 |<0.05	n.a.^{b}	n.a.^{b}	n.a.^{b}	n.a.^{b}	4.22| <0.05	-3.71 |<0.05
CO2	n.a.^{b}	n.a.^{b}	n.a.^{b}	-4.86|<0.05	3.52|<0.05	5.31|<0.05	n.a.^{b}	n.a.^{b}
T_{in}	n.a.^{b}	1.90 |<0.05	n.a.^{b}	n.a.^{b}	4.20|<0.05	n.a.^{b}	n.a.^{b}	3.63 |<0.05
Time of the day (1)	4.30| <0.05	3.24| <0.05	<0.05	2.83| <0.05	<0.05	n.a.^{b}	n.a.^{b}	n.a.^{b}
Time of the day (2)	2.24 <0.05	2.84 <0.05		2.40 <0.05				
Time of the day (3)	2.54 <0.05	2.53 <0.05		1.61 <0.05				
AOV%	n.a.^{b}	n.a.^{b}	n.a.^{b}	1.22 |<0.05	1.79| <0.05	- 0.908|<0.05	2.25| <0.05	n.a.^{b}
Slat angle (0)	17.19| 1.00	n.a.^{b}	-0.855| 0.12	n.a.^{b}	n.a.^{b}	n.a.^{b}	n.a.^{b}	n.a.^{b}
Slat angle (60)	16.66| 1.00		0.506| 0.38					
Slat angle (80)	17.19| 1.00							
Constant	-26.17|.99	-7.78| <0.05	-23.70 |0.98	-7.86 |<0.05	-26.65| 0.98	-6.04|<0.05	- 22.94|<0.05	-7.073 |<0.05
AIC	1020.9	1053.4	315.92	723.14	529.2	672.71	421.08	256.95
- 2 Log likelihood	1010.9	1045.4	307.92	713.14	517.2	664.71	407.08	252.95
Nag. R^2	0.137	0.067	0.107	0.089	0.125	0.039	0.227	0.041
Prediction success	98.80%	98.90%	99.70%	99.30%	99.40%	99.40%	99.60%	99.80%
(“0” | “1”)	(100% | 0%)	(100% | 0%)	(100% | 0%)	(100% | 0%)	(100% | 0%)	(100% | 0%)	(100% | 0%)	(100% | 0%)
Observation No.	107	102	25	66	53	57	40	18

Logit P = constant + $\sum Bixi$, n.a.^{b} NOT ELECTED BY THE LOGISTIC REGRESSION

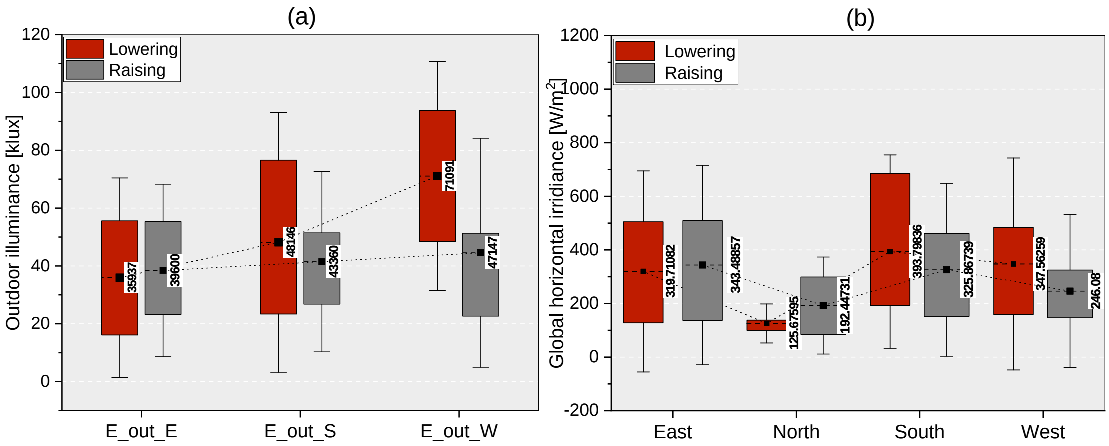


Figure 5.18: Box-plot distribution of user-shade lowering and raising actions as a function of (a) E_{out}, (b) I_{gl}.

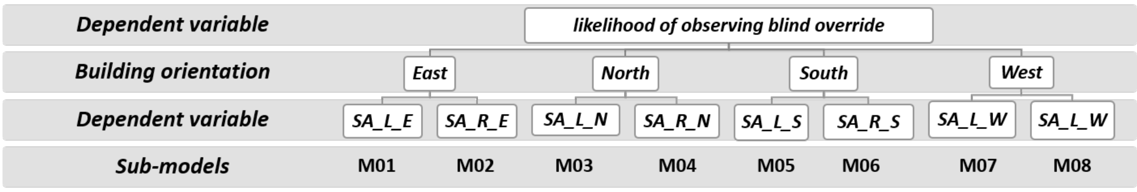


Figure 5.19: Eight sub-models using regression analysis.

had a statistically significant influence on the variance of lowering actions (p-values < 0.05). The most significant variables of raising actions predictions were reduced to global horizontal irradiance, relative humidity, time of the day (early morning, morning, and noon), and blind position. The logistic regression did not elect the remaining explanatory variables. Figure 5.20 shows the probability of user-shade lowering actions as a function of outdoor illuminance; the orange dashed line represents the predicted lowering frequencies.

To conclude, the limited approach for regression taken in this study did not successfully explain occupant behaviour. To overcome the model limitations, an alternative method for analyzing the given dataset is introduced in the next section 5.4.2.4. Moreover, a web-based survey is conducted (see section 5.4.3) to (a) provide explanations for any abnormal report found in the observed datasets and (b) to reveal subtle correlations that may not be considered due to the complexity of occupant behaviour.

5.4.2.4 Data mining results

Data mining techniques such as clustering analysis and association rules mining were applied to the given datasets to discern typical office user profiles, which may allow for more accurate assumptions on group and complex behaviours in office buildings.

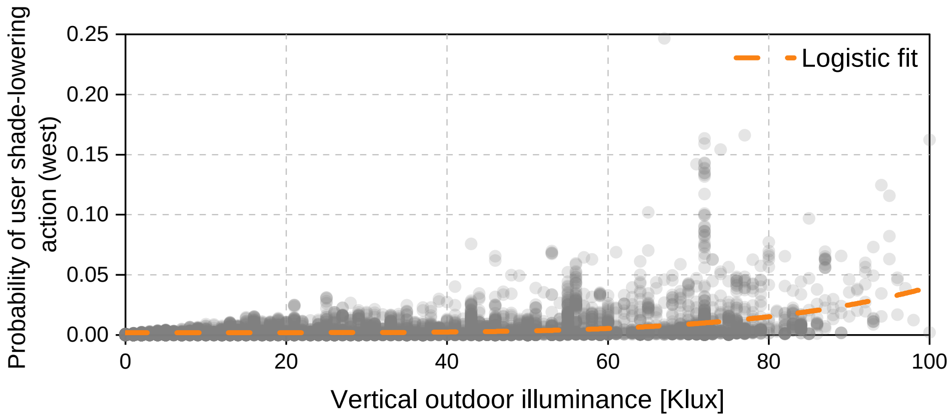


Figure 5.20: Probability of user-shade lowering action as a function of outdoor vertical illuminance on the west elevation.

Clustering analysis

Clustering analysis was performed to obtain distinct behavioural patterns using the k-means algorithm. Two patterns of behaviour were mined in the given dataset: (a) interactivity and (b) motivational patterns.

(a) Interactivity behavioural patterns

Interactivity patterns cluster occupant behaviour based on the frequency of user-shade override adjustments per day. The dataset of 47 offices was reorganized based on the daily "rate of change" of blind use per office. The daily average of user-shade adjustments varied from 0 to 0.58 changes per office. The user-control ratio was calculated by dividing the number of user-triggered adjustments per office by the total number of adjustments (system and user-triggered actions). The activity ratio was calculated by dividing the total number of user-shade override adjustments for an office by the average number of adjustments per 47 offices. In Figure 5.21, 47 offices are labeled by a number and plotted in which the x-axis indicates the activity ratio and the y-axis represents the user-control ratio. It is noticed that the user-control ratio was positively correlated with user-shade adjustments. Based on these two ratios, three clusters of offices with similar blind usage were identified:

- Passive adjustments [C01]: 66% of offices were assigned (range of 0-0.17 times per day).
- Neutral adjustments [C02]: 21% of offices were assigned (range of 0.18-0.36 times per day).
- Active adjustments [C03]: 13% of offices were assigned (range of 0.44-0.58 times per day).

More than half of the occupants were passive users since they override the shading system less than 0.17 times per day. This result is in line with our quantitative results of the monitoring study. In contrast, Meerbeek et al. [84] found that 20% of the offices were passive users, and 30% were regular and 20% active users in their field study.

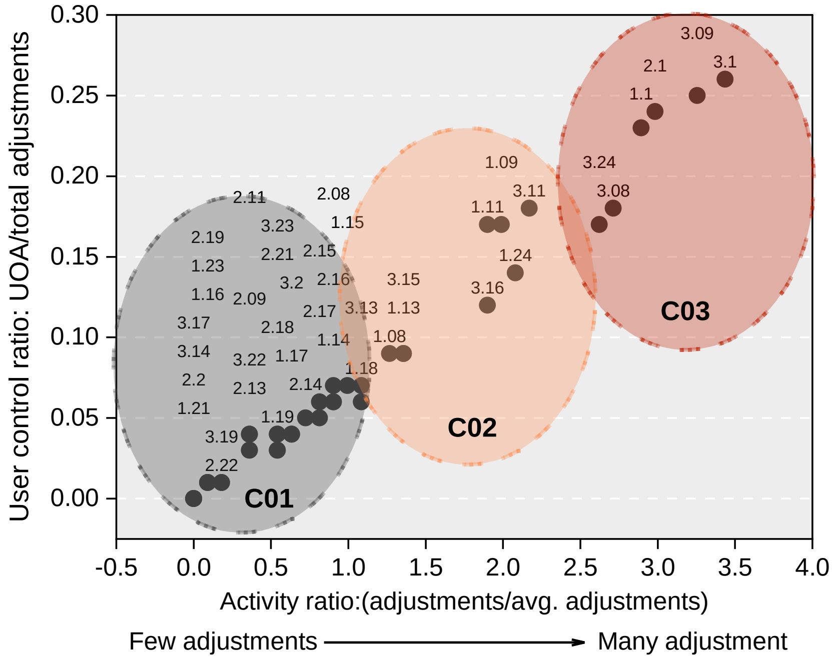


Figure 5.21: Interactivity behavioural clusters.

(b) Motivational behavioural patterns

Motivational patterns cluster the factors which derive the users to override the automated shading systems. The clusters were based on each variable's impact factor (regression coefficients) that could influence the user-shade override actions. Accordingly, logistic regression was performed to define each office's most statistically significant variables. About 25-30 of the building offices were considered in the analysis. The rest counted the low frequency of user-shade adjustments. Table 5.7 shows the coefficients' impact factor of each variable on user-shade lowering. Patterns of user-shade lowering were clustered in 25 offices based on the impact of influencing variables on these actions, and three clusters were defined as following (see Figure 5.22, a):

- Shade lowering cluster 01 [C01-L]: 12% of offices were assigned.

  Cluster 01 was mainly driven by a combination of outdoor weather conditions such as solar profile angle and outdoor temperature, and the time of the day (early morning and morning). Offices assigned to this cluster were therefore associated with a time and outdoor weather-driven shade lowering behaviour.

- Shade lowering cluster 02 [C02-L]: 24% of offices were assigned.

Table 5.7: Calculated variables and coefficients' impact factors for user-shade lowering adjustments.

Office number	Intercept	[time of day=3]	time of day=2]	[time of day=3]	[AOV-E=0]	[slat angle E=0]	[slat angle E=60]	[slat angle E=80]	E_{out} (E)	I_{gl} (E)	T_{out}	tan_d	T_{in}	RH%	CO2
E3.10_L	40.08	-18.55	-17.95	-17.93	0.17	-15.69	-14.73	-15.94	0.95	0.96	-0.13	-1.73	-0.62	-1.11	-0.41
E3.09_L	34.23	-27.16	-4.66	-16.84	-0.8	0.76	3.3	-0.11	-4.9	0.43	-0.65	-14.1	-2.15	0.46	4.08
E2.10_L	37.48	-17.81	-14.2	-15.58	1.86	-12.13	-11.87	-12.62	-1.26	0.42	1.34	-2	-4.98	-0.45	0.03
E1.10_L	37.77	-15.75	-12.43	-13.02	0.75	-16.71	-15.07	-16.78	-5.43	-0.64	-0.71	4.13	-3.33	2.92	2.56
N3.24_L	27.41	-18.72	-18.67	-18.54	-1.79	0.72	-0.32	0	n/a	-2.69	-4.61	3.69	-1.29	1.88	-2.01
E3.11_L	52.98	-27.83	-7.39	-5.43	-14.35	-4.18	11.01	8.53	-6.57	-2.61	-11.82	-11.8	1.54	0.09	16.07
E1.09_L	46.05	-17.99	-13.49	0.9	-0.47	-14.68	-14.86	-0.85	-4.25	1.84	-9.6	-2.16	-1.56	2.34	-7.42
N1.24_L	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S3.16_L	67.53	-40.34	-28.63	-7	-3.51	-10.44	-10.72	2.91	-0.85	-3.76	-12.96	-37.42	0.78	5.38	3.73
E1.11_L	41.55	-19.02	-13.99	1.59	-0.61	-14.68	-12.62	-15.84	-4.32	-1.44	2.18	-4.61	2.31	-4.34	-1.25
S3.15_L	45.13	-15.1	-13.19	-12.72	-1.87	-17.19	-16.93	-17.46	-4.33	-1.64	3.64	6.22	-9.96	-1.38	-2.83
S1.13_L	53.54	-23.67	-4.94	-18.13	-2.82	-15.54	-0.81	-15.52	-0.52	-1.35	-1.4	-12.76	0.18	-4.47	-4.34
E1.08_L	21.33	-15.97	-0.77	-0.52	0.19	0.31	14.75	-1.56	-0.02	2.66	-5.21	10.96	-2.11	2.42	0.47
S3.13_L	43.05	1.03	-14.97	-16.69	-3.99	-17.21	-18.25	-17.63	-3.18	1.01	-5.64	6.33	0.85	1.02	0.23
W1.18_L	42.25	2.3	-10.72	-12.47	-2.3	-13.85	-13.57	-14.03	-3.27	-0.08	2.69	-1.14	1.18	-6.54	-10.08
E2.08_L	19.38	-12.28	-3.92	-4.4	18.72	2.32	21.86	2.81	-16.75	1.89	3.81	-0.44	-8.82	0.68	4.69
S1.14_L	63.69	-22.25	-22.74	-5.62	-16.79	-14.95	-1.88	-15.23	-1.62	1.78	-19.22	0.67	3.47	3.89	-2.05
W2.17_L	42.25	2.3	-10.72	-12.47	-2.3	-13.85	-13.57	-14.03	-3.27	-0.08	2.69	-1.14	1.18	-6.54	-10.08
S2.15_L	57.96	-2.16	-18.88	-17.09	-14.94	-16.2	-1.52	-15.14	0.41	2.04	-6.42	1.32	-6.39	4.82	-1.71
S2.14_L	55.16	-16.6	1.87	-12.79	-5.76	-15.64	-14.09	1.89	-13.78	-1.41	4.34	-3.31	-7.98	-11.62	6.91
N3.21_L	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W3.20_L	43.22	1	3.1	-12.66	-0.25	-15.59	-15.61	-14.65	-5.07	4.08	11.03	-2.19	-6.91	-4.62	-10.08
W2.18_L	55.82	-10.24	-5.49	-16.69	-3.64	-16.13	-16.29	-17.63	-7.03	-5.59	6.45	-12.19	-4.29	-0.96	-1.02

Cluster 02 appeared to be more influenced by the time of the day (early morning, morning, noon, and afternoon) than physical drivers. Offices assigned to this cluster were associated to a time-driven shade lowering behaviour.

- Shade lowering cluster 03 [C03-L]: 64% of offices were assigned.

  Cluster 03 appeared to be more influenced by slat angle position (0, 60,80 degrees) than the physical and time-related drivers. Offices assigned to this cluster were associated to a blind state-driven shade lowering behaviour.

Patterns of user-shade raising were clustered in 30 offices based on the impact of influencing variables on these actions, two clusters were defined (see Figure 5.22, b):

- Shade raising cluster 01 [C01-R]: 63% of offices assigned.

  Cluster 01 appeared to be more influenced by the slat angle position and time of the day (noon and afternoon) than physical drivers. Offices assigned to this cluster were associated to a time & blind state-driven shade raising behaviour.
- Shade raising cluster 02 [C01-R]: 37% of offices assigned.

  Cluster 02 was mainly influenced by time of the day and indoor physical parameters such as indoor temperature. Offices assigned to this cluster were associated to a time & indoor thermal-driven shade raising behaviour.

Association rules mining results (ARM)

The clustered patterns constitute a base for association rules classifying the building occupants into typical office user profiles. The frequent pattern growth algorithm (FP growth) is the most commonly used algorithm to discover patterns in a given dataset. The FB growth algorithm was employed to mine the association rules. To obtain significant results from ARM analysis, support of 50%, the confidence of 50%, and a lift of 1, were set as the minimum thresholds. Such criteria indicated that at least 50 percent of the dataset contained a premise and conclusion for each association rule mined. The probability that a specific premise leads to a specific conclusion was more than 50%. Such mining generated 20 rules which provide useful information for the study purposes (see Table 5.8). Based on the 20 rules mined, two possible working user profiles (user ß, user µ) are drawn in this study:

- User ß (rules 5,7,8,14,15,18,20): acts as a passive user

  A user type tends to override the automated shading systems on the average between 0.09-0.17 times per day (passive adjustments). User ß was mainly influenced by the time of the day and the current blind state for lowering and raising adjustments.

- User µ (rules 4,9): acts as a medium user

  A user type tends to override the automated shading systems on the average between 0.18-0.36 times per day (neutral adjustments). User µ was mainly influenced by time of the day and the current blind state only for raising adjustments.

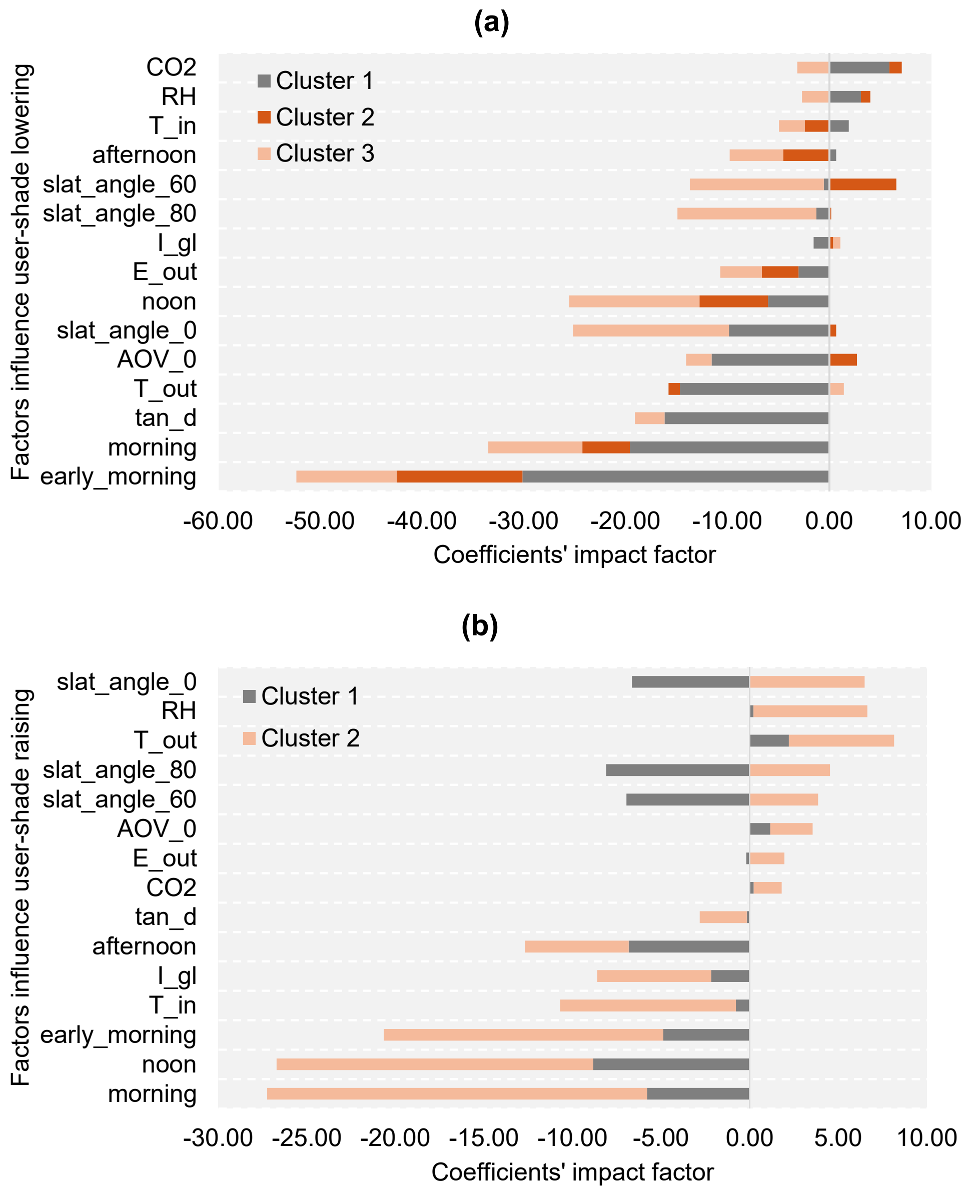


Figure 5.22: User-shade (a) lowering and (b) raising clusters based on motivational patterns.

Lessons learned for designer and operators

- The manipulation rate of user-shade override adjustments was relatively low compared to the findings of related previous studies [102, 84]. For more robust shading systems (less override actions), the building designers may consider (a) correct and acceptable range of automated shade control settings (b) high-quality light sensors and (c) inner glare protection in addition to external automated blinds which provides more flexibility to avoid glare discomfort.

- Higher rate of override adjustments were observed in the east-facing offices compared to the south and west elevations. Therefore, it is recommended for designers to consider

Table 5.8: Association rules mining of behavioural patterns.

Rules	Premise	Conclusion	Support	Confidence	Lift
4	passive adjustments	medium adjustments	0.32	0.63	1.94
14	medium adjustments	passive adjustments	0.32	1.00	1.94
12	C1_R	C2_R	0.29	0.69	2.38
17	C2_R	C1_R	0.29	1.00	2.38
6	C2_R	C3_L	0.19	0.67	1.38
10	C2_R	C3_L, C1_R	0.19	0.67	2.95
11	C1_R, C2_R	C3_L	0.19	0.67	1.38
13	C3_L, C1_R	C2_R	0.19	0.86	2.95
15	active adjustments	passive adjustments	0.19	1.00	1.94
16	C2_L	C3_L	0.19	1.00	2.07
21	C3_L, C2_R	C1_R	0.19	1.00	2.38
5	C2_L	passive adjustments	0.13	0.67	1.29
7	C2_L	passive adjustments, C3_L	0.13	0.67	2.95
8	C3_L, C2_L	passive adjustments	0.13	0.67	1.29
9	passive adjustments, C1_R	medium adjustments	0.13	0.67	2.07
18	C3_L, medium adjustments	passive adjustments	0.13	1.00	1.94
19	passive adjustments, C2_L	C3_L	0.13	1.00	2.07
20	C1_R, medium adjustments	passive adjustments	0.13	1.00	1.94

small or medium window size or fixed shading [94] combined with manual inner glare protection.

- Data mining techniques suggested another methodology in exploring occupant behaviour patterns and providing accurate assumptions of group and diverse behaviours. The findings may allow building designers and operating manager to tailor robust building design and shade control strategies in big office buildings against different user profiles.

5.4.3 Questionnaire

This section presents the quantitative and qualitative results of the questionnaire conducted to better understand the key findings of the monitoring study, and to reveal subtle and non-physical triggers behind override adjustments of the automated shade.

Participants demographics and work activity

A total number of 32 participants completed the survey, including 71.9% male and 28.1% female. Age ranges comprised 31% of the participants in the (26-35) years interval, 56.2% is between (36-55) years old, and only 12.5% are older than 55 years old. Considering work positions, about 68.8% of the occupants perform mainly professional jobs (e.g., engineer, draftsman, specialist planner), 18.8% occupy managerial and decision-making positions (e.g., director, managing director, member of the board), where only 12.5% are doing administrative work. In terms of offices' occupancy, more than half of the employees (62.5%) have been working in their offices for more than 2 years, and only 25% have been in their offices for less than 1 year. During the weekdays, most of the occupants (72%) spent around 80-100% of their worktime in their offices. Only 15.6% sometimes spent in the morning or sometimes in the evening. However, 90.6% of the employees have full-time jobs. In terms of work activity, occupants spend around 70.5% of their daily worktime in front of their computer, 7.7% in meetings, 8% outside the offices, and 13.8% outside the buildings (see Figure 5.23). 25% of the respondents occupied east-facing offices, 18.8% in south-facing offices, 31.3% in west and 25% in north. Before COVID-19 pandemic, 15.6% of the respondents occupied a single-occupancy office, 43.8% occupied shared offices, and 40.6% occupied open-plan spaces. During the study, all participants occupied a single occupancy office due to COVID-19 restrictions.

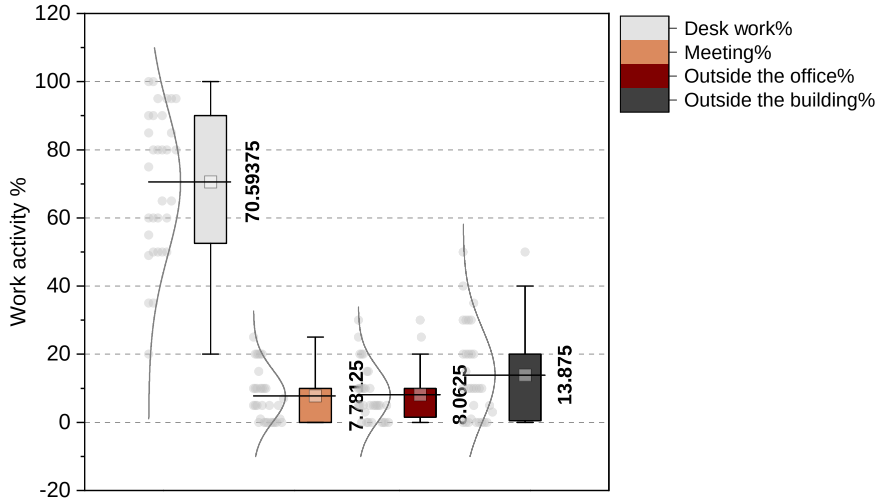


Figure 5.23: Survey results: box-plot distribution of work activity percentage.

Comfort sensation and perceived satisfaction of IEQ parameters

To ensure occupants' satisfaction with their workplace, the basic principle is to provide comfortable environmental conditions for buildings' occupants. To evaluate the thermal and visual comfort conditions in the working environment in the current case study, participants rated their comfort sensations. They assessed their satisfaction with different IEQ parameters (room temperature, daylight conditions, artificial lighting conditions, and view connection to the outside) according to a five-point Likert-scale in terms of office orientation. Considering that neutral sensation is equal to (3) on a Likert-scale, it is noticed that 18.8% of the occupants feel slightly warmer in west-facing offices (ø=3.3), while in east elevation, 12.5% respondents feel slightly cooler (ø=2.8). The rest, 68.8% of the occupants, indicated that they felt comfortable (see Figure 5.24, a). The majority of the respondents (84.4%) receive sufficient daylight in their workplaces. However, more than half of them (65.7%) face glare discomfort frequently in their offices, mainly in east and south elevations (see Figure 5.24, b). Based on these findings, lower irradiance thresholds can be adapted to the automated shade deployment in east and south offices to decrease glare discomfort.

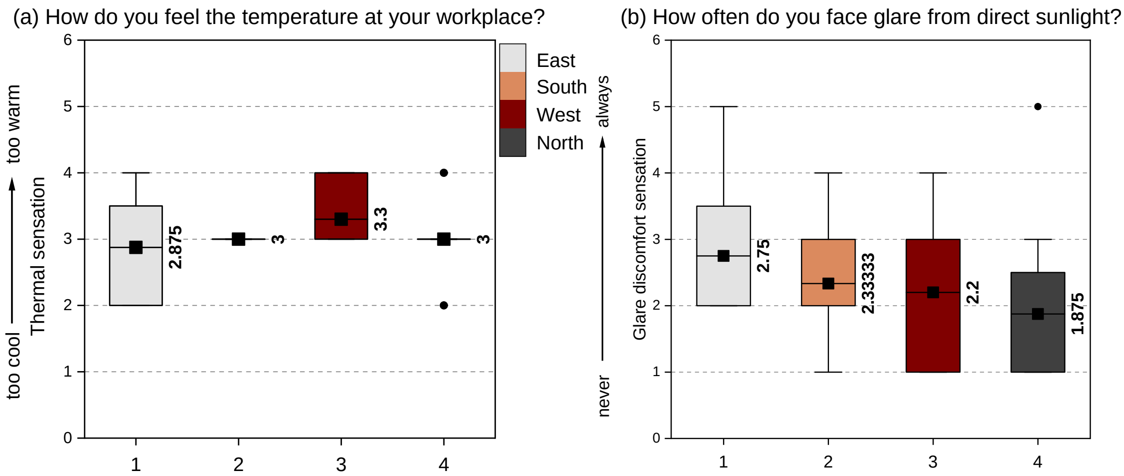


Figure 5.24: Survey results: box-plot distribution of (a) thermal sensation votes and (b) glare discomfort sensation for each facade.

User satisfaction with thermal and visual comfort parameters was evaluated. In Figure 5.25, none of the participants reported negative opinions about their satisfaction with indoor quality parameters (room temperature, daylighting, and view connection to the outside). Moreover, more than 80% of the occupants were satisfied with the indoor quality parameters. The primary sources of visual and thermal discomfort in offices are presented in Figure 5.26. About 75% of the respondents did not feel any thermal discomfort, and only 18.8% were annoyed by direct sunlight through the window, which can cause both visual and thermal discomfort. On the contrary, 62.5% of the respondents reported that they feel visual discomfort in their offices, and 37% of them indicated that glare through the window was a major source of visual discomfort (see Figure 5.26, b).

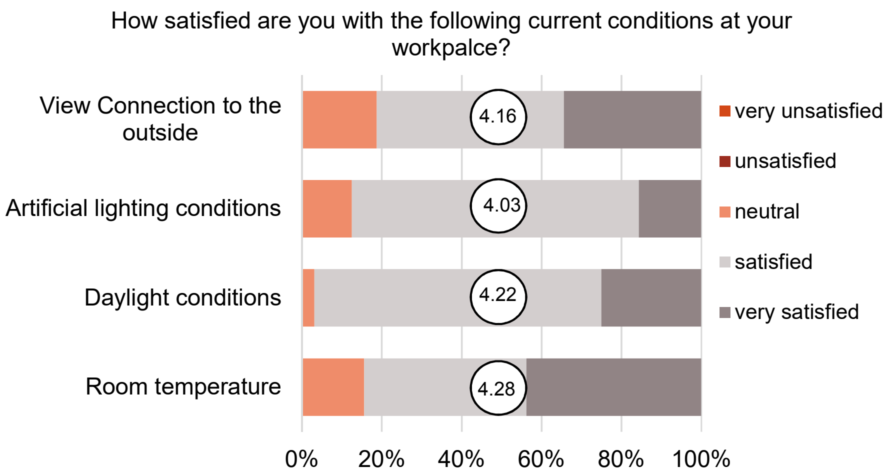


Figure 5.25: Self-reported satisfaction of indoor quality parameters.

To evaluate the importance of different IEQ parameters on the overall comfort of the

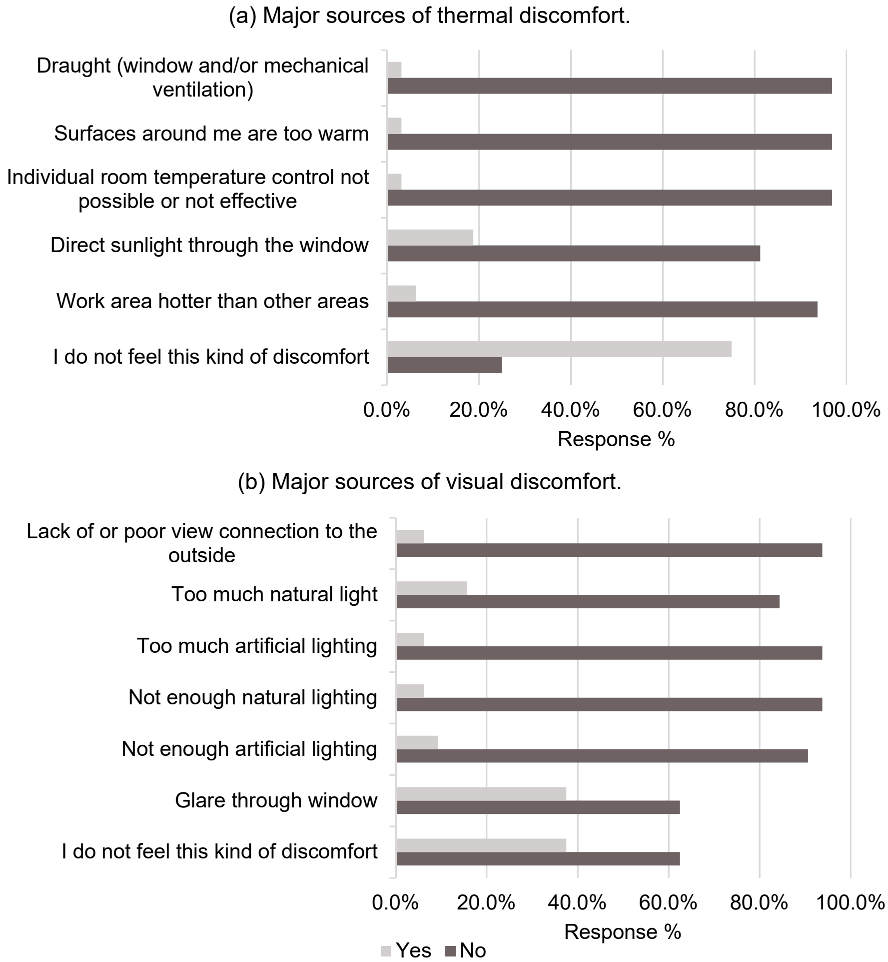


Figure 5.26: Major sources of (a) thermal discomfort and (b) visual discomfort reported by the participants.

working environment, a five-point Likert scale (unimportant=1 to very important=5) was used. Sufficient fresh air, comfortable room temperature, adequate daylight, and view connection to the outside were found to be the most critical factors that influenced the working environment satisfaction, with an average of 4.56, 4.5, 4.25, 4.13, respectively (see Figure 5.27).

Frequencies of user-shade interactions

To better understand the user interaction with the automated shading system and the primary triggers, the participants reported how often, when, and why they usually override the blind position for each lowering and raising action. About 37.5% of the respondents usually never open the external blind, where 21.9% do that once or twice per week. Concerning the lowering actions, few override adjustments were found. Only 10% of the occupants close the external blind a few times per week/day (see Figure 5.28). To conclude, a low rate of

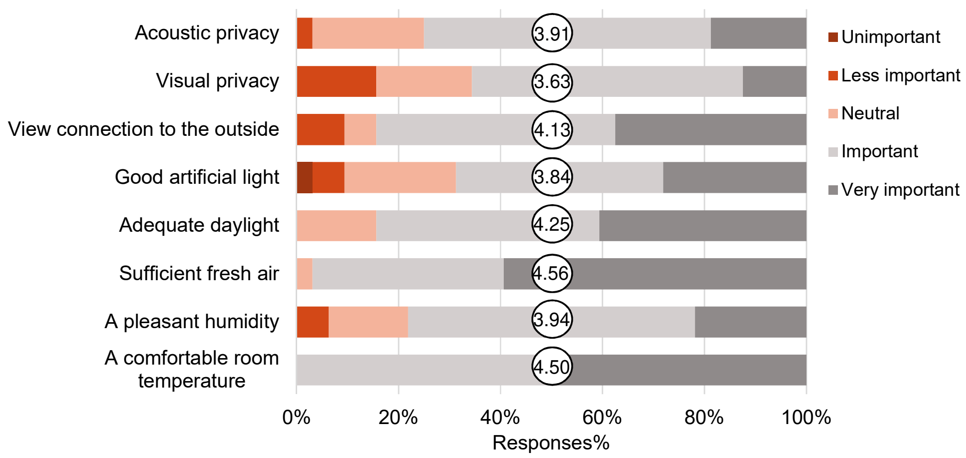


Figure 5.27: Importance of IEQ parameters on the overall satisfaction of the working environment.

manual override to the automated shading system. This is in line with our quantitative results of the observed datasets from the monitoring study performed in 2019.

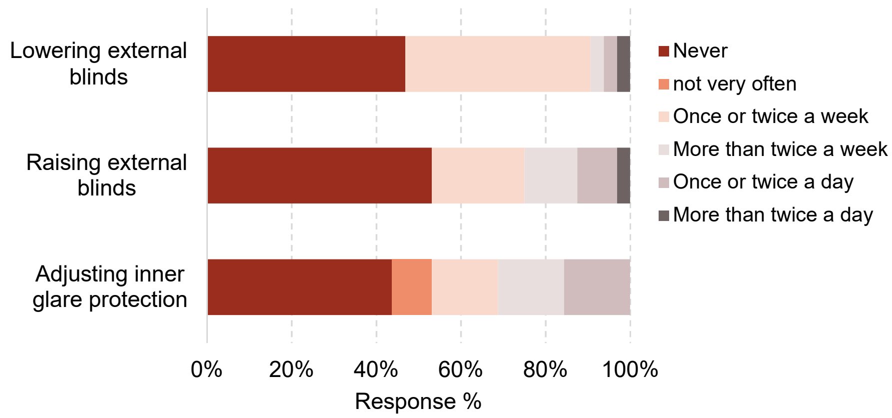


Figure 5.28: Survey results: frequencies of adjustments related to the use of automated blinds and inner glare protection.

For the occupants who decided not to override the automated blinds, more than half indicated that there was no need to adjust the blind, 20% stated that the blinds were fully open all the time, and 20% preferred the automatic position. When the shades were raised, the primary reason was to provide more daylight into the office, where 60.9% of all raising actions were for this reason. The second most common reason was to maximize the view to the outside (30.4%). This is in line with Meerbeek et al. [84] findings in their field study. 55.2% of the occupants usually lower the external blinds to avoid direct sun on their workplanes, where less people do that to avoid overheating (37.9%), and 6.9% to save energy (see Figure 5.29). Concerning inner glare protection, more than half (53.1%) of the respondents never or not very often adjust the inner glare protection, 31.2% do that once or several times per week, and 15.6% adjust it once or twice per day. Avoiding visual discomfort was the main reason behind adjusting the inner blinds (40.6%).

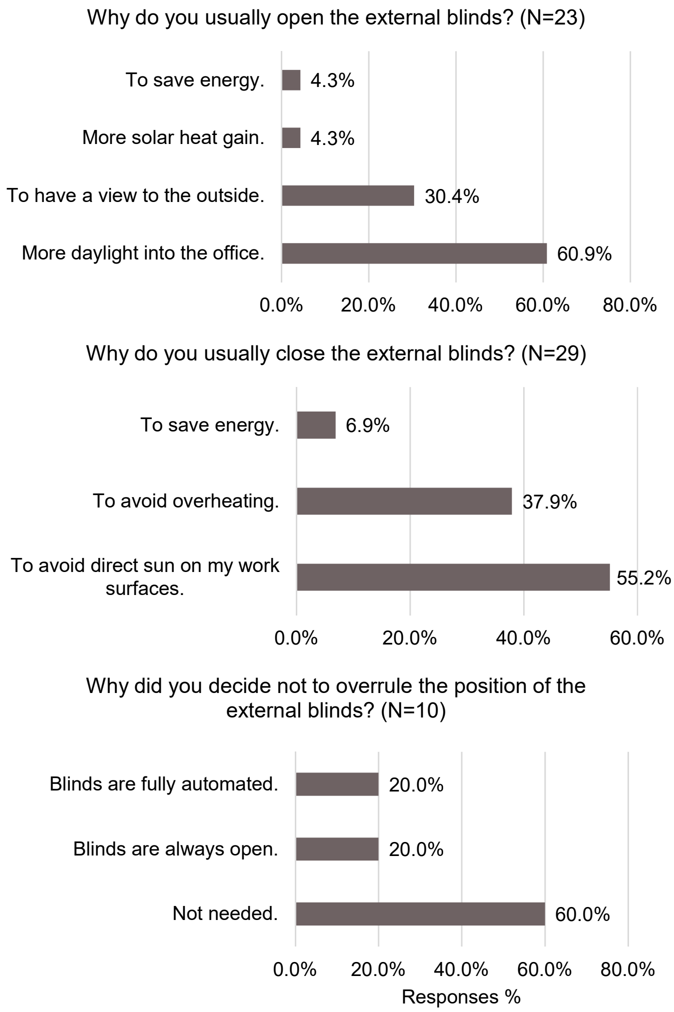


Figure 5.29: Survey results: main reasons behind shade lowering and raising actions and no action.

The time of the day is known to influence blind use as the solar geometry varies during the day. More than half of the respondents (56.3%) tend to raise the blind when automatic closure occurs. 36.8% tend to close the external blinds in the morning and 31.25% in the afternoon, regardless of the office orientation. In west-facing offices, most blind adjustments occurred in the afternoon, where 40% of raising actions occurred after automatic blind closure (see Figure 5.30). This is in agreement with our quantitative observations of blind use during the monitoring study in 2019 (see Figure 5.14). Similar patterns were observed in the north-facing offices, where 67% of lowering actions occurred in the afternoon and the rest in the morning. In east and south elevations, most of the lowering actions occurred in the morning and the rest in the afternoon. In east-oriented offices, 57% of the respondents raise the blind after automatic blind closure. To conclude, the peak periods of UOAs sometimes occurred in the morning, sometimes in the afternoon, or when a closure event occurred. This is not in agreement with Haldi and Robinson [48] findings; they found actions immediately upon arrival to be about five times more frequent than the rest of the day.

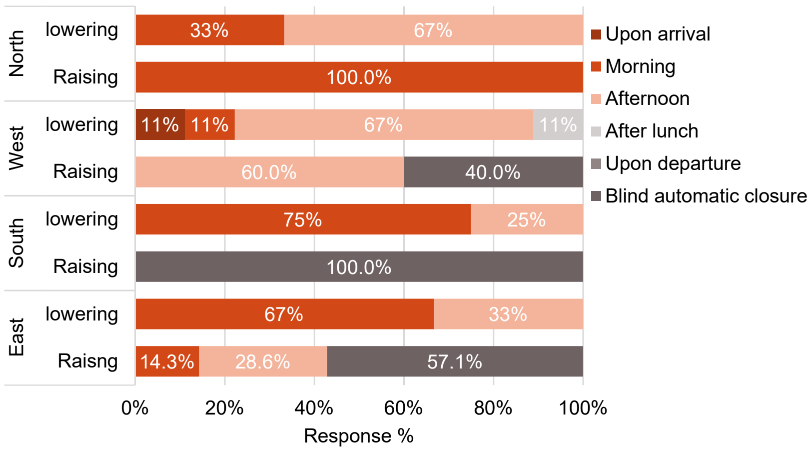


Figure 5.30: Questionnaire results: Frequencies of UOAs during the time of the day for each facade.

Figure 5.32 shows the relative frequency of UOAs (lowering and raising) in terms of floor level, space orientation, WWR%, and window-to-desk distance. Few respondents (15%), their offices located on the first floor, tended to raise the external blind once or more per day. Fewer raising actions was noticed on the upper floors, while 14.3% of the occupants in the 3^{rd} floor lowered the blind once or more per day. In east and south-facing offices, occupants open the external blinds more frequently than in the north and west. It is expected as more automatic blind closures occurred. Surprisingly, people setting up to 2 meters far from the window adjusted the external blinds more frequently than those setting close to the window. This can be due to (a) being closer to the push button of the automatic blinds, which is next to the office door, or (2) most of these offices are facing north (see Figure 5.31, b). The north elevation is the main entrance of the building; occupants in north-facing offices may lower the blind for visual privacy issues. In the offices with large window areas (WWR=75%) facing east and south elevations, occupants open the external blinds more frequently than with small windows (WWR=50% and 25%) (see Figure 5.31, a). Therefore, the moderate window size can be adapted in the east and south-facing offices to decrease the number of shade interventions.

User-shade satisfaction and preferences

Approximately half (56.5%) of occupants were satisfied with the performance of the automated shading system, with an average of 3.68 on a 5-point Likert scale. Figure 5.33 shows the percentage of the blind state per each facade based on the occupants' feedback. The external blinds are either fully open (46.9%) or fully closed with an open slat angle (37.5%), while the blinds are partially open about 15.6% of the time. 75% of the blinds are fully

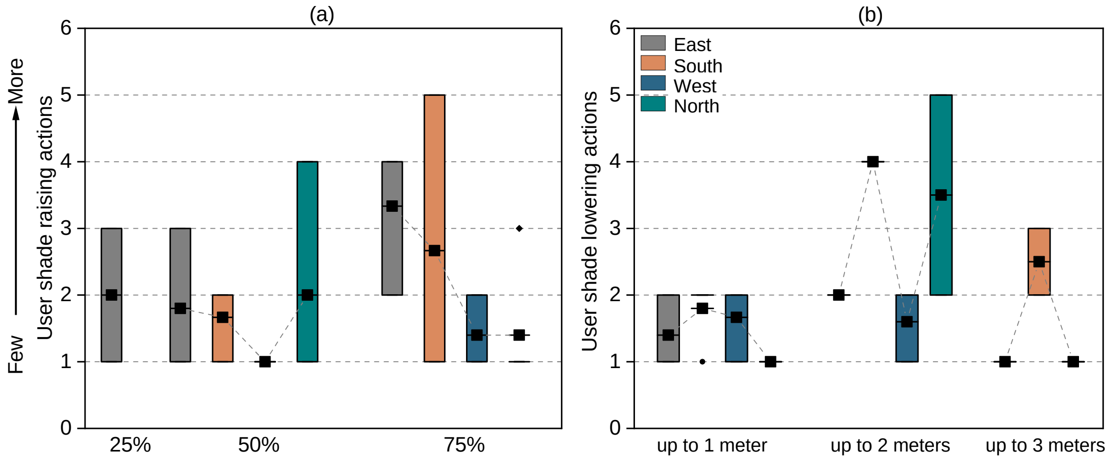


Figure 5.31: Questionnaire results: (a) user shade raising action in terms of WWR% and (b) window-to-desk position per each façade (1: never adjusted, 5: more than twice a day).

open in north-facing offices. On the contrary, the blinds are fully closed with an open slat angle in east-facing offices (75%). The people were satisfied when the blind were fully open or fully closed with an open slat angle with an average of 3.7 and 3.9, respectively.

More than half of the respondents (59.4%) reported that they are not annoyed or distracted by the movement of the external blinds, and 25% of them feel neutral. A significant positive correlation was found between the perception of external blind movement and satisfaction votes using the Spearman coefficient (ρ = 0.807) (see Figure 5.34). However, a slight decrease in user-shade override adjustments (lowering and raising) was noticed when people were more satisfied with the shading system performance (see Figure 5.35).

User preferences were investigated in terms of the "double shading" systems. 25% of the occupant preferred the inner glare protection because it is faster and easier to avoid glare discomfort than waiting for the external blind to move. 34.4% of the occupants preferred the external blinds more than the inner glare protection (see Figure 5.36), where 28.1% of the respondents preferred both systems. Some explained that the automated shading systems are much more efficient than glare protection and simple to operate via push button. However, 93.8% of respondents were satisfied with having the ability to control both shading devices "double approach," with an average of 4.43 on a 5-point Likert-scale (see Figure 5.37).

Influence of contextual factors on occupant behaviour

User-shade override adjustments were explored in different environmental context parameters (e.g., physical, social, and workplace). Figure 5.38 shows the lowering and raising actions of floor level, space orientation, window-to-desk distance, push the button-to-desk distance, window size, and position. Non-significant differences were found in user-shade override adjustments concerning the offices' floor level using a one-way ANOVA test (p-value $>$ 0.05).

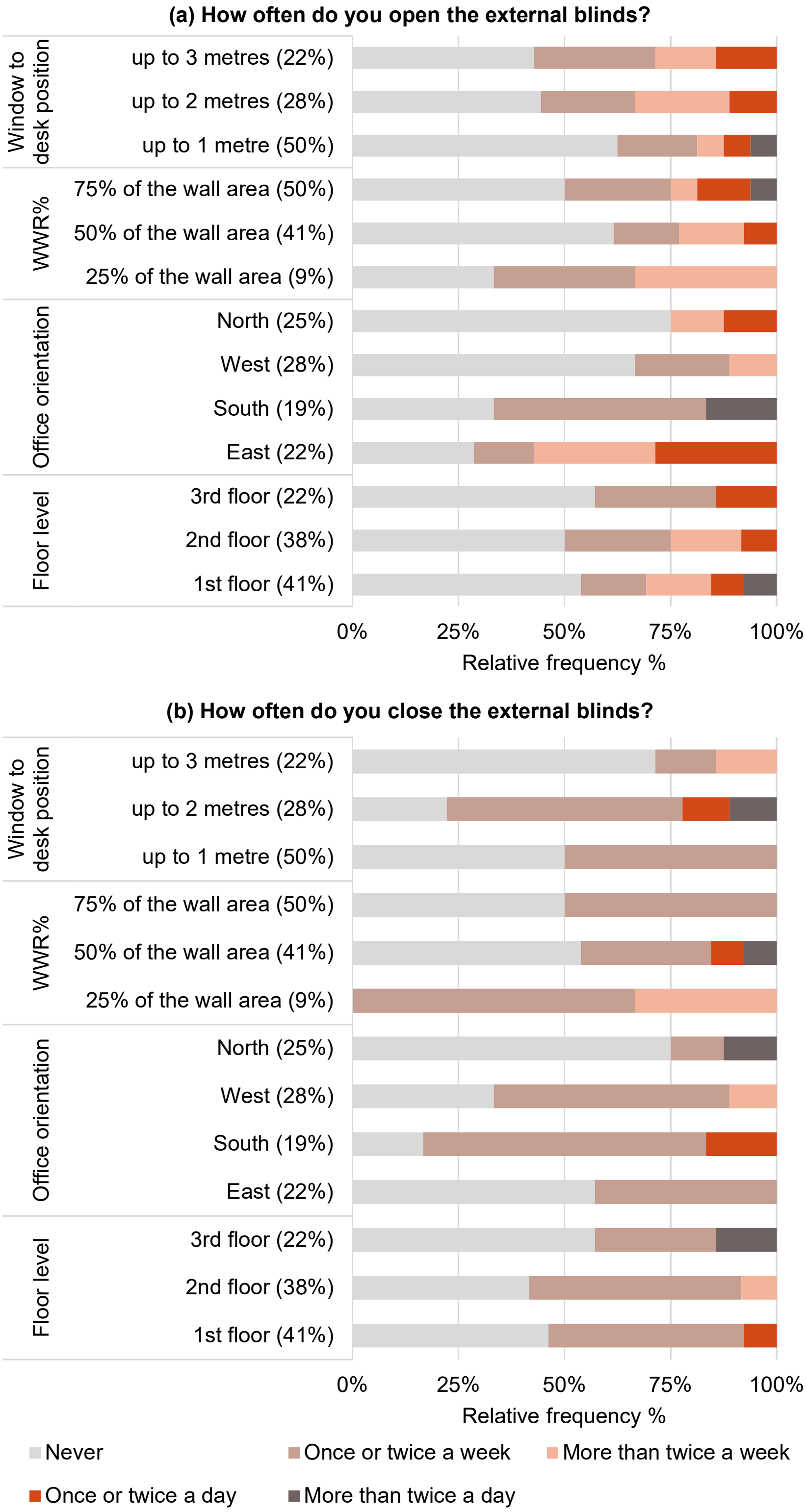


Figure 5.32: Questionnaire results: frequencies of (a) shade raising and (b) lowering in terms of Floor level, space orientation, WWR%, and window-to-desk position.

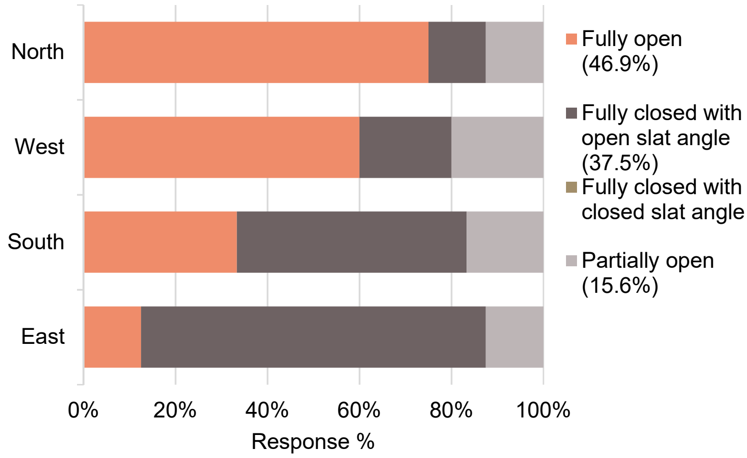


Figure 5.33: Questionnaire results: blind position status based on occupants feedback for each facade.

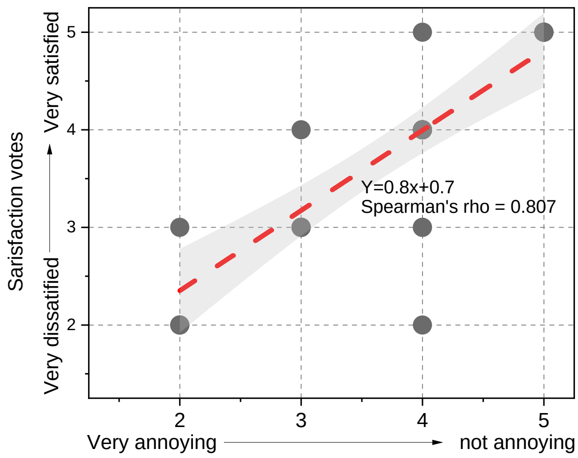


Figure 5.34: Correlation between occupant satisfaction and shade movement.

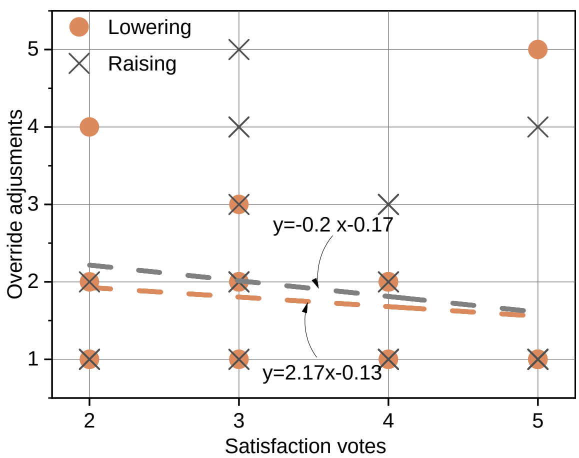


Figure 5.35: Correlation between UOAs and occupant satisfaction of shading performance.

Similar results were found in terms of space orientation. However, the highest raising actions were observed in the east elevation (ø=2.37), and the highest lowering actions were in the south elevation (ø=2.16). Furthermore, it is noticed that the shade raising actions slightly increase when the desk position is far from the window (up to 2 meters) and close to the external blind push-button. However, non-significant differences were found in blind adjustments in desk-to-window position or desk-to-push button position (p-value = 0.36, 0.13, respectively). Easy-to-access controls over comfort delivery systems would make the occupants more eager to act to improve their comfort [105].

Each office is equipped with one manual switch to override the grouped external blinds. More than 75% of the respondents indicated that they share the control of external blinds with other employees. In fact, shared interfaces often affect many people, which imposes unspoken or spoken social constraints on the degree to which an occupant can adjust an

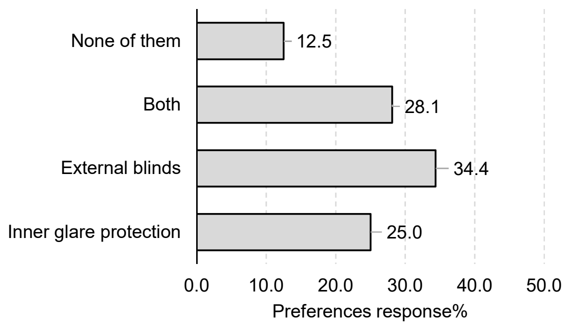


Figure 5.36: Subjective response to preferences of shading system used in the offices.

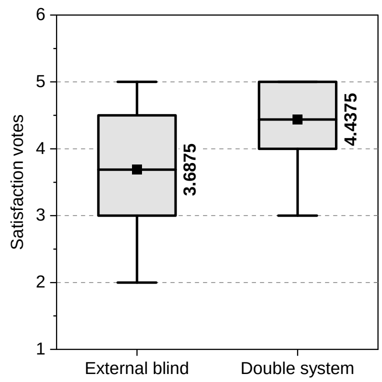


Figure 5.37: Subjective response distribution to satisfaction with the performance of external shade and the ability to control double systems.

interface for their benefit [23]. However, 65.6% of the respondents reported that they never avoid adjusting the external blinds for fear of bothering their colleagues, and 31.2% sometimes or rarely avoid doing that. Although, O'Brien et al. [95] suggested that occupants tend to be more reluctant to control their environments if others are present because of social constraints.

Half of the respondents were trained about using the automatic blinds, and the other 50% did not receive any training or information. However, non-significant difference was found in the use of automated external blinds between trained and non-trained groups (see Figure 5.39, a). Similarly, the hierarchy position of the respondents was found not to influence user-shade override decisions (see Figure 5.39, b). 30.4% of the respondents decided to open the external blinds to maximize the outside view. The importance of view-to-the outside could considerably increase the raising actions decisions of the external blinds, as shown in Figure 5.40.

Correlations between override adjustments and physical and non-physical parameters

Figure 5.41 shows the correlation matrix between the self-reported comfort sensation and satisfaction parameters, current state of mood, performance of automated shade, social constraints, blind movement, double shading control option related to the user-shade override adjustments (lowering and raising actions) using the Spearman's coefficients. Spearman rank correlation is a non-parametric test used to measure the degree of association between two variables. When Spearman's rank correlation coefficient (ρ) equals 1, it means a perfect positive correlation. When the value ρ equals -1, it means a perfect negative correlation. According to that, the following correlations are concluded:

- Few raising adjustments were associated with the availability of sufficient daylight in the offices (ρ= -0.396). While few lowering actions were associated with a good mood

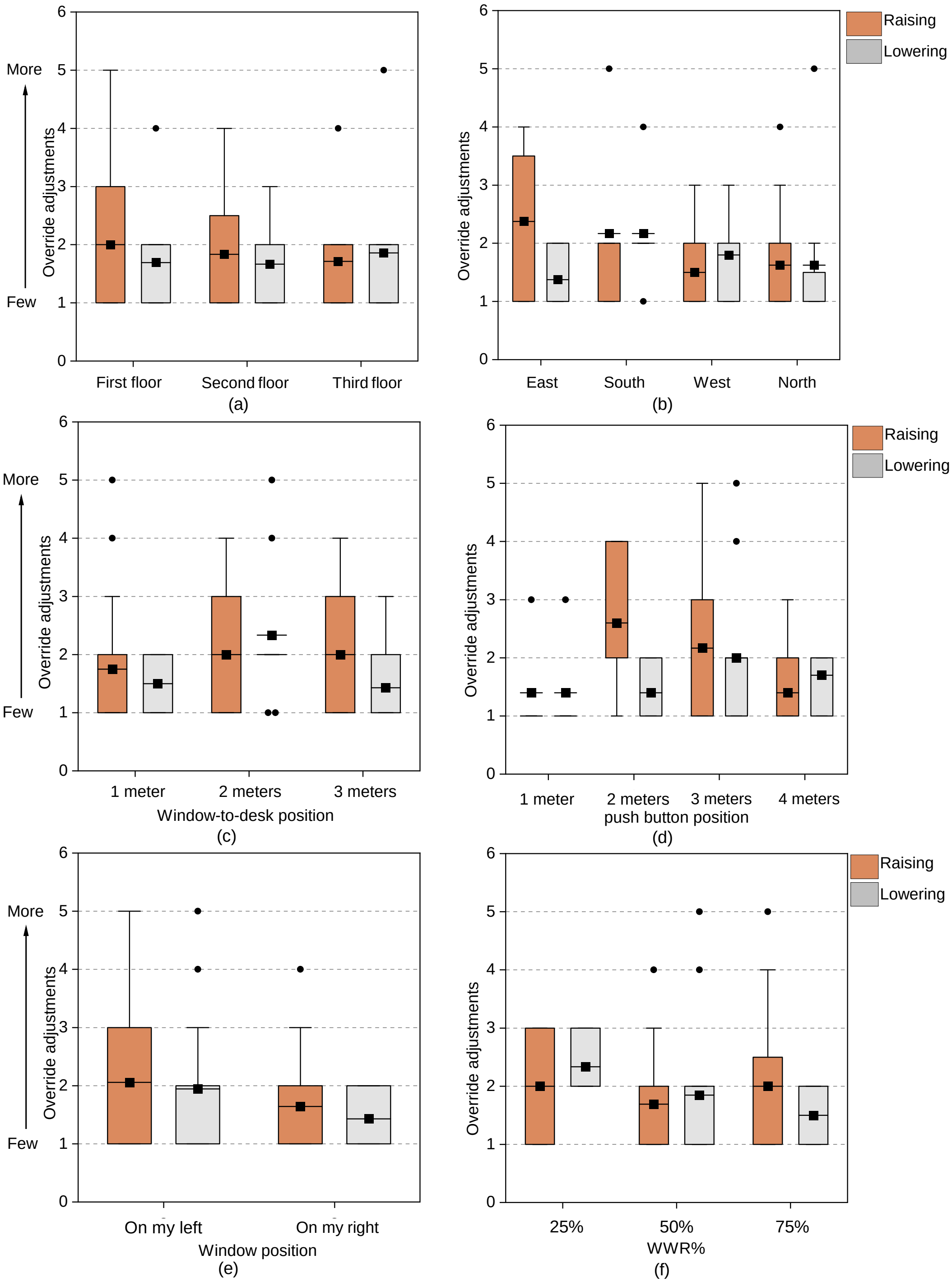


Figure 5.38: Questionnaire results: frequencies of override adjustments related to the use of automated blinds.

state of the occupants (ρ= -0.442) and a positive correlation with glare sensation (see Figure 5.43). Hence, 55.2% of the respondents tended to lower the external blinds to avoid direct sun.

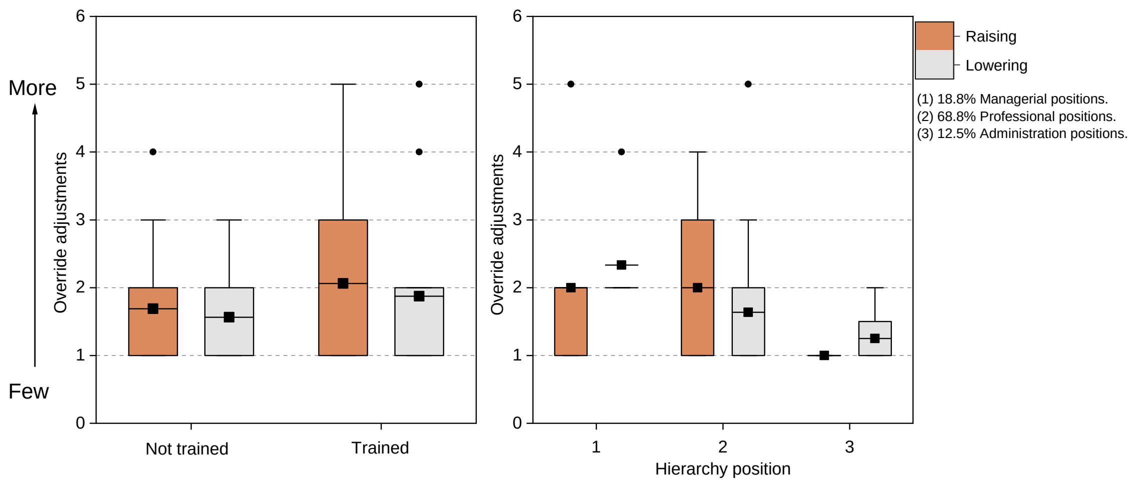


Figure 5.39: Questionnaire results: User-shade override actions in terms of (a) trained or not-trained (b) Hierarchy position.

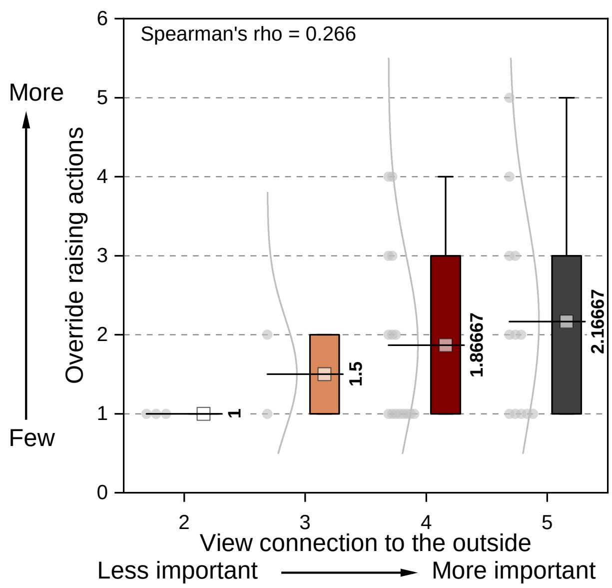


Figure 5.40: Questionnaire results: frequencies of raising actions as a function of view connection to the outside.

- Occupants' current mode state was highly correlated with their perception of blind movement noise level (ρ= 0.413). It is concluded that if they are in a good mode, they are less sensitive to blind movement.
- When people feel comfortable with the indoor temperature in their working environment, they are more satisfied with the overall lighting condition in the room (ρ= 0.350). It is concluded that comfortable room temperature could decrease the user-shade override adjustments as they are more satisfied with daylight conditions.
- Daylight availability , daylight conditions, and good artificial lighting conditions, com-

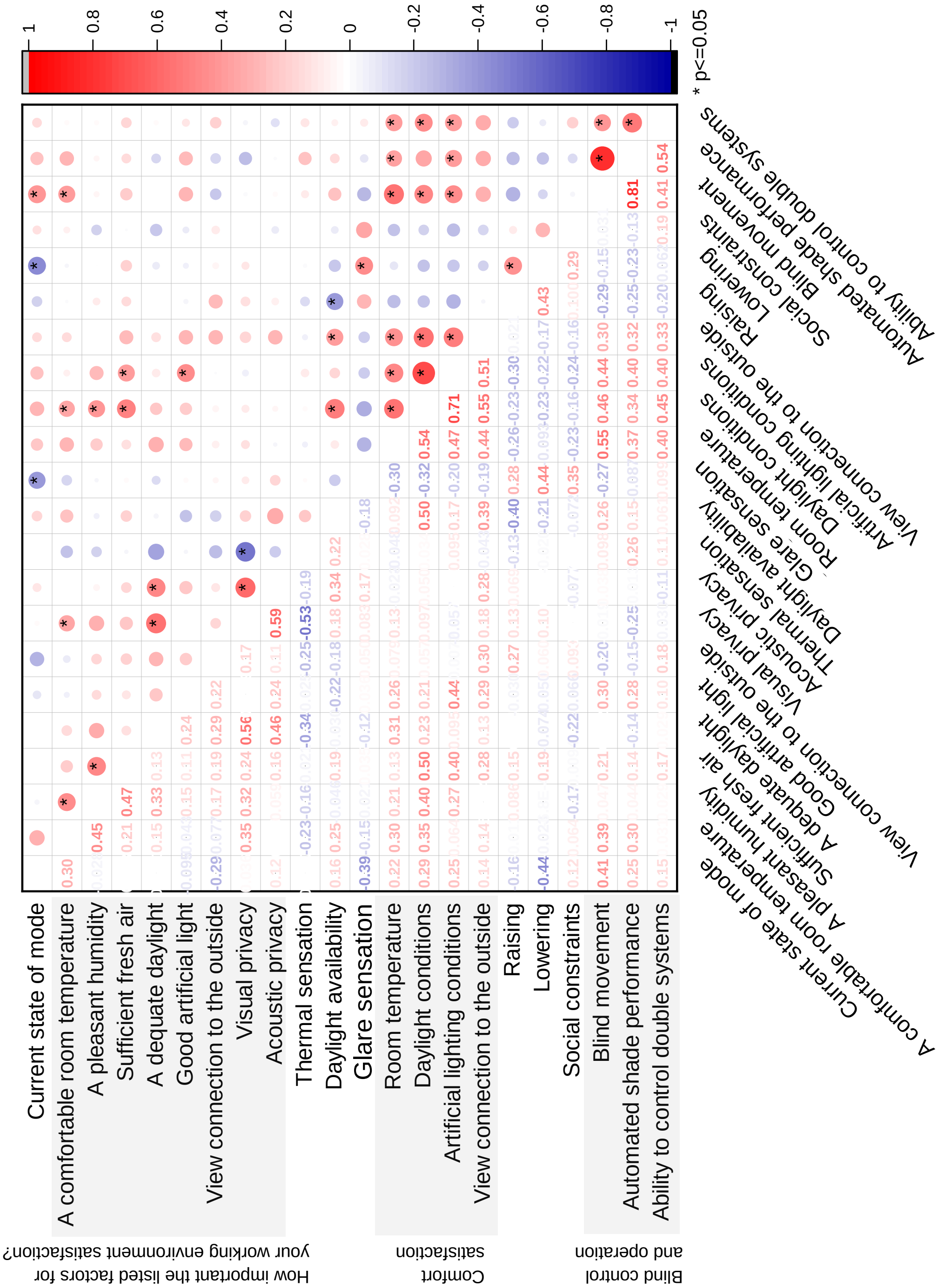


Figure 5.41: Questionnaire results: Correlation matrix between override adjustments and physical and non-physical parameters using Spearman's coefficients.

fort room temperature, are significantly correlated with view maximization satisfaction level (ρ= 0.392, 0.555, 0.509, 0.436, respectively).

- Satisfaction with the performance of automated shading was highly correlated with the blind movement noise level (ρ= 0.807) (see Figure 5.34). This is in line with Bakker et al. [7] findings, they reported that noisy operation tends to be seen as a precarious factor that has the potential to undermine the success of dynamic facade systems as a whole. Their study showed that the sound levels induced by dynamic facades' movement need not to be a problem, on the condition that special care is taken to ensure quiet operation.

- Moreover, providing occupant manual override capability in addition to manually control inner glare protection "double shading approach" was highly correlated with user satisfaction of automated shading performance (ρ= 0.54) (see Figure 5.42).

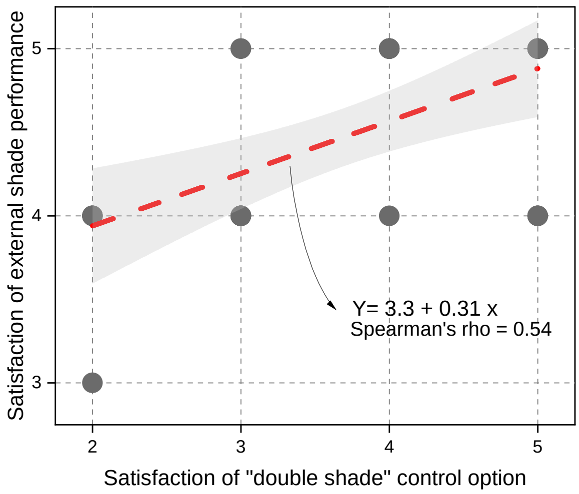


Figure 5.42: "Double shading" control option correlation with automated shading satisfaction.

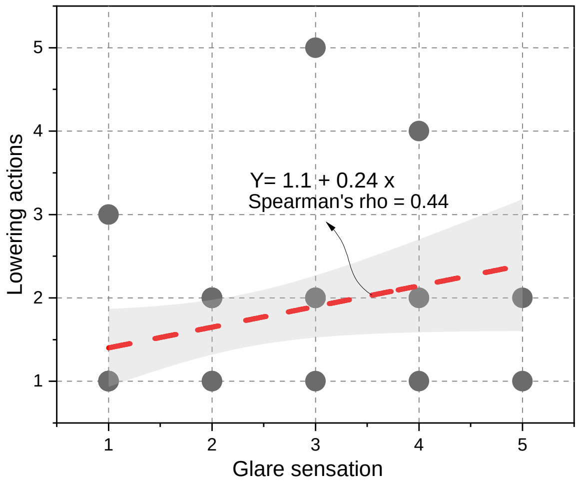


Figure 5.43: Lowering action correlation with glare discomfort sensations.

Lessons learned for designers and operators

- More than half of the respondents reported that they rarely or never adjust the automated external blinds, and they are satisfied with the performance of the automated shading systems. Most of the respondents were satisfied or very satisfied with having the ability to control both shading devices, external blinds in addition to inner glare protection. "Double shading approach" suggests for the building designer to consider more flexible interfaces in building systems design which increases occupant satisfaction.

- Most of the respondents reported that they don't feel any kind of thermal discomfort, and 37% of them indicated that glare through window was a major source of visual discomfort. The building was explicitly designed for high occupants' comfort, namely the thermal envelope (Passive House) and the HVAC system. This approach was found to be favorable. Lesson to be learned that design consideration for high indoor environmental comfort could increase occupants' satisfaction with their workplaces and systems performance.

- In terms of automated shading system performance, majority of the respondents (84.4%) reported that they are not annoyed or distracted by the movement of the external blinds. Quiet operation of the system was significantly correlated with high satisfaction of shade performance. Moreover, the designers and facility managers took many efforts regarding the building automation's system including the sensor hardware. These observations emphasize that designers and operators should consider high-quality automation devices to ensure high and acceptable performance of the automation systems.

- Occupants were found to have control on artificial lighting, heating thermostat, window, and blind operation (excluding cooling and air volume ventilation system control). The integration of automated shade operation with the control of other systems could improve the performance gains of the shading system and occupant satisfaction.

5.4.4 Simulation-based analysis: daylighting and energy performance

Daylighting and energy performance of different shading control strategies were evaluated using IDA Indoor Climate and Energy (IDA ICE) software. Different solar shading control strategies were tested, Low (S01: irradiance on the facade (90°) exceeded 100 W/m^2) and high (S03: irradiance exceeded 450 W/m^2) irradiance lowering thresholds were used. S02 was the established design lowering threshold (irradiance exceeded 250 W/m^2). S04 (fully closed) and S05 (fully open) were added to the analysis for benchmarking. The impact of inner glare protection was ignored in the investigation since non-sufficient information about the usage of the system was known during the study period. Twelve individual thermal zones were simulated, one zone per each façade in three typical floor levels (see Figure 5.44). The opaque facades and the floor and roof were considered adiabatic. Occupancy schedules were defined between 08:00 am and 6:00 pm on the weekdays. It is assumed that the required level of workplane illuminance was up to 500 lux. The artificial lighting is turned off when daylight guarantees 500 lux on the workplane (80 cm above floor level).

Table 5.9 summarizes the parameter settings of simulation modelling. The cooling setpoint was 25 C°, and the heating setpoint was 21 C° as used. The occupancy observed in the case study corresponded to 0.1 $person/m^2$. An infiltration ratio of 0.5 air changes per hour (ACH) was used in the simulated zones.

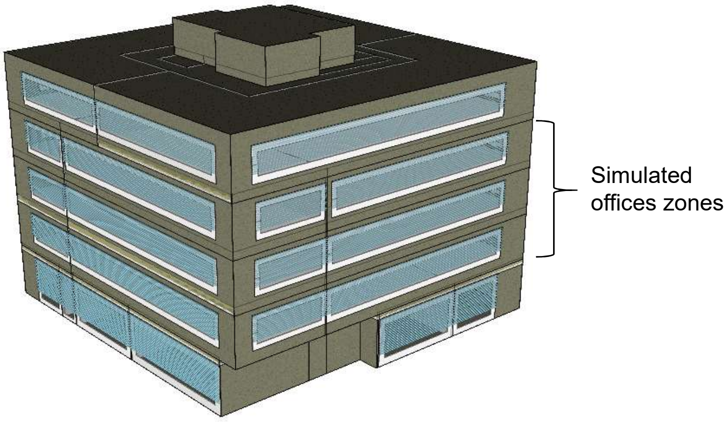


Figure 5.44: 3D model of building zones

Table 5.9: Parameter settings of simulation modelling.

Parameters	Assigned values
Thermal zones	12 thermal zones (4 thermal zones per floor level).
Roof/ground floor	Adiabatic
Interior walls	Adiabatic
Exterior walls	U-walls: 0.13 W/m^2K
Window	U-value: 0.75 W/m^2K, g-value: 0.49, color rendering: 96%.
Internal loads	Equipment: 6 PC per room – each 150 watts Lighting density: 2 W/m^2 People: 0.1 person/m2
Heating setpoint	21 °C
Cooling setpoint	25 °C
Occupancy schedules	8:00 am-18:00 pm (Weekdays)
Lighting control	When daylight guarantees 500 Lux on the work surface, the artificial light is turned off.
Energy efficiency coefficient	Heat pump – COP = 6 for heating / direct mode only, no heat pump operation
ACH (air changes per hour)	Infiltration ratio: 0.5 ACH @ 50pa

Daylighting performance

Figure 5.45 shows that the daily average of workplane illuminance can significantly vary between the different solar shading control strategies in the east and south-facing facades. However, slight differences in workplane daily average were observed between the different scenarios in north and west-facing offices, except when the blind was fully closed. The lesson to be learned is that the designers should consider the daylighting evaluation of shading control strategy, specifically in east and south facades of the building.

The ratio between the occupied hours of useful daylight illuminance (UDI) (300-3000 lux) [87] and total hours per year (8760 h) was calculated under different strategies (S01-S05). Figure 5.46 demonstrates the UDI % of the building offices located in the first floor

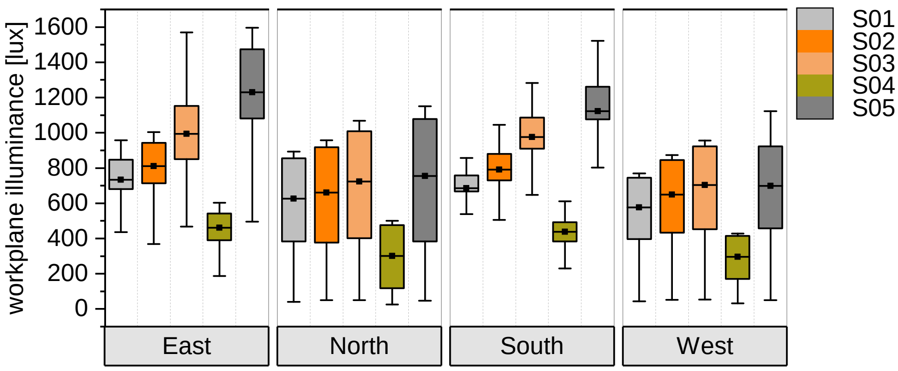


Figure 5.45: Daily average of workplane illuminance [lux] per each facade under the different scenarios.

for each facade under the different strategies. It is observed that S01&S02 strategies provide the highest UDI% values with slight differences in west and north-facing offices, while the lowest were in south and east. Providing useful daylight could decrease the electric lighting.

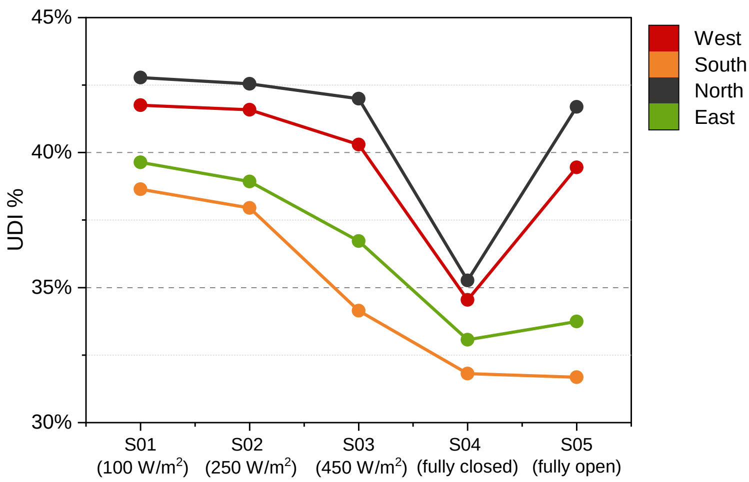


Figure 5.46: UDI% (300-3000 lux) distribution under the five control strategies for each facade.

Annual hours of undisturbed view-to-the outside

Undisturbed view to the outside was estimated based on the annual shade operation hours (closure). Figure 5.47 shows that the highest annual shade operating hours was in S01 (100 W/m^2), while the lowest was in S03 (450 W/m^2). S03 (original design) increased the undisturbed view-to-the outside by 60% compared to S01 and less by 75% compared to S03.

The ratio between the annual shade operating hours and overall annual working hours was estimated under the different solar shading control strategies, considering 261 working days over the year (2610 working hours) as presented in Figure 5.48. The highest ratio was noticed in S01, where 80% and 73% of the working hours the blind was fully lowered in

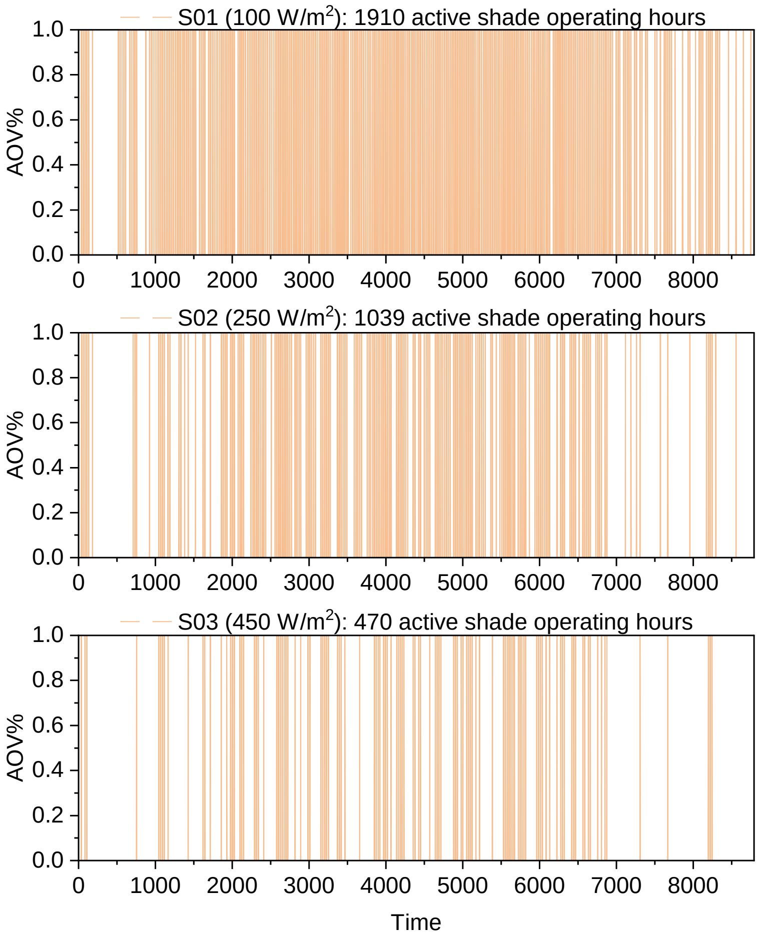


Figure 5.47: Annual shade operating hours in east facade under five shading control strategies.

the south and east-facing offices, respectively. Approximately 40% of the time, the blind was fully lowered in south and east facades, and 10% in west and north facades using the established shading control strategy (S02). The least ratio was observed in S03.

Energy performance

Figure 5.49 shows the annual cooling, heating and lighting demand in the building offices under different shading control strategies (S01-S05). Lighting demand was hardly affected by the different control strategies since the lighting was turned off if the workplane illuminance was above 500 lux. More significant differences were found in the heating demand, where the difference between the original design (S02) and the lowest demand (S05) reached up to 9.2 kWh/m^2. The total energy demand of S02 (original design) was higher than S01 by 43.74 kWh/m^2 and lower than S03 by 76.82 kWh/m^2. The main difference was in the cooling demand since it was lower by 183 KWh/m^2 in S02 compared to the highest demand (S05). Overall, the established shading control strategy seems to provide view maximization to the outside, and save 20% of total energy use compared to worst case (S05). This result

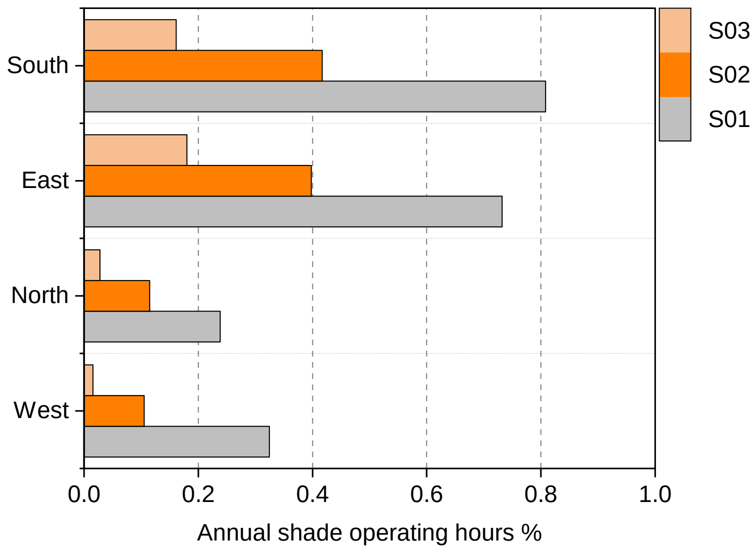


Figure 5.48: Relative frequency of annual shade operating hours to total annual working hours under different shading control strategies.

suggests to the designers to develop an acceptable range of shading control settings that ensure user comfort and satisfaction as well as saving energy.

5.5 Conclusions and lessons learned

The case study presents a successful example of automated shading system design and utilization. Based on the quantitative and qualitative analysis of the study, the main conclusions can be summarized as follows:

- Based on the results of the monitored datasets, the daily rate of change of user-shade override adjustments (i.e., occupants' interaction with the systems) was relatively few compared to previous studies [102, 84]—an average of 0.184 blind adjustments per day per office. Similar results were found in the questionnaire analysis, where more than 50% of the occupants indicated that they rarely or never adjust the automated external blinds. However, more interaction occurred when the occupant was located closer to the push button of manual shade adjustment.

- Based on data monitoring and questionnaire analysis, building orientation, social constraints, and time of the day were found to influence the manual activation of shading systems.

- The limited approach for regression analysis taken in this study did not successfully explain occupant behaviour. Using data mining techniques showed advantages for more accurate assumptions of complex and diverse behaviours in big office buildings.

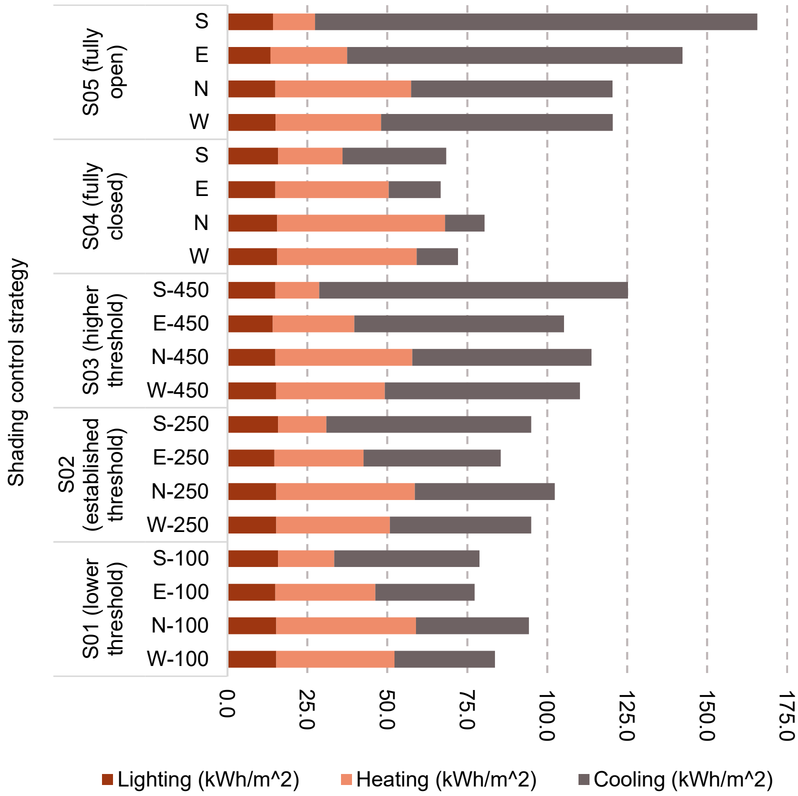


Figure 5.49: Useful energy demand (heating, cooling, and lighting) of different scenarios of shading control strategies including the original design.

- The simulation analysis results show that the established shading control strategy can provide view maximization to the outside (60% of undisturbed view hours in east and south facades) and an acceptable range of UDI% (37-42%), while keeping the useful energy demand close to the minimum compared to other shading control strategies.

This case study provides building designers and operators with potentially valuable insights about shading design features and operation strategies that may increase occupant comfort and satisfaction. Key insights include:

- Use of double shading system approach (internal/external) can improve user satisfaction and acceptance of automated shading systems (i.e., fewer override actions).

- Apply an acceptable range of established shade control thresholds per each facade of the building. Based on the current study findings, it is recommended to consider high irradiance thresholds (above 400 W/m^2) for blind activation in north and west elevations, while low irradiance thresholds (250-400 W/m^2) in south and east elevations.

- Use high-quality and accurate shading light sensors during the operation phase of the building.

- Quiet operation and delayed reactions are recommended while designing an automated shading system to increase occupant acceptance.

Moreover, lessons relevant to the facade design can be learned from shade behavioural patterns. Small window size or fixed shade might be more robust design solutions in east and south elevations, while moderate window size is more appropriate in north and west elevations. Further research is recommended to explore various building designs in different locations and climatic zones to develop comprehensive guidelines for occupant-centric shading design.

5.6 Limitations of the study

The developed regression models have some obvious limitations, as summarized below:

- In the logistic regression analysis, workplane illuminance measurements were not recorded during the study period, which is one of the primary triggers behind shade adjustments as defined before in previous studies [119, 82, 48].

- The study period was over 66 working days during summer in 2019. The number of occupant-related events and corresponding predictors might be not sufficient to build a representative statistical model. Therefore, future research on a long-term data logging period is suggested to develop a stochastic occupant model.

- The monitored dataset was collected during the summertime in 2019, from June until mid-September, before the COVID-19 pandemic. However, the questionnaire was conducted under similar thermal and visual condition during the pandemic, July 2021.

- The representative sample size was 92 subjects out of 140 employees. Instead, 32 responses were completed -out of 42 participants- since the questionnaire was only issued to those working from offices.

- Monitored datasets included different types of occupancy level (single-occupancy, shared, open-plan offices), while the questionnaire was performed in single-occupancy offices due to COVID-19 constraints.

Chapter 6

Conclusions and future work

6.1 Conclusions and recommendations

With the aim of improving automated shading design and operation in terms of occupants' comfort and satisfaction as well as energy performance in existing and new buildings, three main phases are performed in this research. First, a thorough investigation of automated shading systems' current practice in existing buildings was set. Then, an experimental-based study was carried out in a full-scale test cell to evaluate the performance of an external automated shading system in terms of user interaction and acceptance, thermal and visual comfort under different scenarios. Finally, an in-situ monitoring study was performed in a mid-rise office building to derive occupant-centric rules for optimal shading design solutions. The following summarizes the main conclusions drawn from each phase of this research and proposes recommendations for building designers and operators.

Phase 01: Current practice of automated shading systems

This study investigate the current practice of automated shading systems' configuration in 19 case studies using a written questionnaire issued via email or printed copy to the building operators or managers. The questionnaires' analysis determined the commonly-used setpoints and commercial shading control devices. Thus, the performance of "the used" commercial shading control devices was evaluated in one of the case studies (Luxembourg building). Besides, two commercial devices (SOLEXA II and WAREMA) were tested in an experimental-based study for their accuracy and quality. The findings of the experimental study reveal a low performance of commercial devices compared to simulation-based algorithms (accurate reference). To conclude, commercial devices' limited quality and accuracy for automatic shading control can be due to economic constraints and sensors' positions or inclinations. However, the Luxembourg case study findings indicate that high-quality and accurate shading light sensors were considered during the operation phase of the building.

To evaluate the energy performance of the commonly-used shading setpoints, a parametric analysis using simplified simulation tools was conducted. Different design parameters (e.g., window size, space orientation), climatic zones (Luxembourg and Jerusalem), and shade behavioural patterns (Low, medium, and high expectations) were used for the analysis. The simulation-based analysis findings show a significant difference in the annual heating and cooling demand as well as shade operating hours (disturbing view-to-the outside) between small and large window sizes, Mediterranean and temperate climatic zones, with high and low user expectations.

Phase 02: Experimental study of an external automated shading system

In phase 02, an experimental study was conducted in a full-scale test cell to assess the robustness of automated shading systems to occupant behaviour and evaluate their thermal and visual comfort under different scenarios (e.g., shading control strategies, window size, cooling system, time of the day, and sky conditions). Indoor environmental parameters, weather data parameters, user-shade and system-triggered adjustments were recorded. Different performance indicators were used to evaluate the indoor thermal and visual conditions, blind occlusion, and user-shade override actions. Then, a paired t-test statistical analysis was performed on paired groups of different scenarios to find significant differences. After each scenario, a self-reported questionnaire about occupants' interaction with automated shading systems, satisfaction, preferences, and perceived thermal and visual comfort were collected.

Based on *shade behavioural patterns'* results and occupants' feedback, approximately 60% of the participants tend to raise the blind very often to achieve a better view-to-the outside and sufficient daylighting. However, high occupants' satisfaction and fewer user-shade override actions were achieved by:

(a) Using a multi-objective control strategy since 86% of the respondents reported that they never or rarely adjust the blind. The multi-objective control strategy with an intermediate position could balance solar heat and glare protection as well as daylight availability and view-connection to the outside, improving user satisfaction with the automated shading system.

(b) Using a high irradiance threshold (450 W/m^2) in controlling shading systems, where the number of user-shade raising actions is reduced by 49% compared to the low irradiance threshold (300 W/m^2).

(c) Providing occupants a decent level of adaptive control options over their workplaces (e.g., window opening, turning on/off artificial light, adjusting the blind, and using the ceiling fan) might improve user satisfaction with indoor environment including shade operation.

The results of *thermal comfort evaluation*, based on predicted mean vote (PMV) model and adaptive model, indicate that using active cooling or ventilation system (e.g., radiant cooling system, mechanical ventilation by exhaust air, operable window, and ceiling fan) kept the indoor operative temperature within the comfort range during the different scenarios in the experiment. Moreover, approximately 40-45% of participants prefer no changes in the indoor thermal conditions when (a) the cooling system is active or (b) when they are permitted to open the window and adjust the ceiling fan. The *visual comfort* evaluation using Simplified Daylight Glare Probability (DGPs) metrics predicted a high probability of glare discomfort when shade lowering irradiance threshold exceeded 450 W/m^2. This result is in line with occupants' feedback, where 35% are disturbed by glare due to direct sunlight and bright desk. However, 82% of the respondents perceived the overall lighting conditions as comfortable. Additionally, 60% are satisfied with view-to-the outside under the same conditions. This result confirms that people may tolerate some glare discomfort since they feel comfortable and have a view-out connection.

Due to the "the Hawthorne effect", participants may alter their normal behaviour towards interacting with the test room devices and systems due to their awareness of the study. Therefore, phase 03 represents an in-situ monitoring study performed in a real office building to overcome this limitation.

Phase 03: Learning from shading design and utilization in Luxembourg building

A comprehensive field study, including design investigation, data monitoring, a questionnaire, and simulation-based analysis, was performed in a real office building, Luxembourg case study. The study focused on the buildings' automated shading activation and the interaction between the occupants and the shading systems with the aim of identifying occupant-centric rules for optimal shading design solutions. The case study is a five-story office building located in Niederanven, Luxembourg. First, a written interview with the designer, who was involved in the design and operation phase of the system, was conducted to investigate the shading system design and selection criteria. Based on the designers' feedback, the double external/internal shading systems were proposed from the early building design stage. The designer conducted a simulation-based analysis to select the optimal shading systems considering different design and environmental parameters, while none occupant-related assumptions was checked.

Second, a monitoring campaign was conducted in 47 offices over 66 working days in the summer 2019. These offices are located on three floors, including 2-6 workers per office. Occupants' interactions with automated shading systems as well as environmental conditions were collected using built-in sensors, local weather stations, and data loggers. Contrary to expectations and previous studies' findings [101, 84, 119], the study found relatively few interactions between the occupants and the shading systems_an average of 0.184 blind adjustments per day and per office. The statistical analysis of the monitored data showed the limited approach of the regression model used in this study, while data mining techniques showed advantages in exploring occupant behavioural patterns. Under similar conditions, a web-based questionnaire was conducted in 2020 to reveal subtle and non-physical triggers behind blind use and better understand the findings of the monitored datasets. Similar results are found since more than 50% of the occupants rarely or never adjust the automated external shading systems. Similarly, 57% are satisfied with the performance of automated shading systems.

Finally, a simulation-based study was conducted using IDA Indoor Climate and Energy (IDA ICE) software to evaluate different shading control strategies' visual performance and energy efficiency compared to the original design simple strategy. The simulation results indicate that the established control strategy (250 W/m^2) could provide view maximization to the outside while keeping the energy use close to the minimum compared to other simple control strategies (100 and 450 W/m^2). Based on the aforementioned findings of the three phases, general guidelines is recommended to building designers and operators as follows:

(a) Due to the limited application of simulation-based control in current building practice, designers may use other design strategies such as an intermediate blind position and combined internal/external shading systems (double approach). However, high-quality and accurate shading light sensors should be considered during the operation phase.

(b) Building designers should perform a parametric analysis in the early stage of building design, considering different design parameters (e.g., space orientation and window size), climatic zones, and behavioral patterns while selecting the optimal shading control strategy in terms of user acceptance and energy performance.

(c) Building designers should consider the visual and thermal stimuli while selecting the optimal shading control strategy to ensure a comfortable indoor environment and less disturbing hours to the view outside.

(d) Multi-objective shade control strategy based on combined indoor and outdoor environmental parameters with intermediate shade position is promoted for shading system activation.

(e) Providing a good cooling and ventilation system can improve user satisfaction with the indoor environment, including shade operation. However, energy-saving adaptive measures or alternatives to guarantee user satisfaction beyond active cooling (e.g., personalized comfort systems, increasing air velocity...etc.) are recommended to avoid further challenging energy resources and increasing climate change.

(f) Designers should consider deploying a high degree of control options, easy-to-access user interfaces, and the ability to override the automated system while designing and operating shading systems.

(g) Robust and simple shade control strategies are promoted. For instance, low irradiance thresholds (250-400 W/m^2) is recommended for shade control in the south and east-facing offices with moderate window size or fixed shade. In contrast, high irradiance lowering threshold (above 400 W/m^2) can be adapted in north and west-facing offices.

(h) Quiet and not too frequent movements are promoted while operating the automated shading systems to increase occupant satisfaction.

6.2 Research contributions

The findings of this research are expected to contribute to the existing literature and provide valuable insights to the designers and practitioners through the following points:

(a) The findings of automated shadings' current practice in existing buildings can inform the designers and operators about the necessity to consider the hardware quality of shading control devices during the operation phase or balance their limitations by using other design strategies (e.g., double internal/external shading, intermediate blind position).

(b) The experimental-based study introduce a comprehensive evaluation of automated shading systems using a wide range of performance indicators. The findings of this study fill a gap in the literature since most previous studies focused on the evaluation of the shading system's visual performance and neglected occupants' thermal comfort and acceptance.

(c) A multi-objective control strategy was developed and tested in this research. The developed algorithm can be applied and implemented inside a commercial controller for further evaluation. It represents a promising solution for improving indoor thermal and visual comfort, saving energy, and view-out maximization.

(d) Learning from shade operation: This successful example of a real office building provides valuable insights and guidelines for building designers and operators in shading system design decision-making to find optimal solutions with less override actions. This study is published in the Journal of Physics: Conference proceedings of CISBAT 2021 in Lausanne, Switzerland. The case study is accepted in a book chapter "detailed case studies" in a book "Simulation-aided occupant-centric building design: Theory, methods, and detailed case studies." The book is a result of Subtask 3 activities of IEA EBC Annex 79 and will be published in Autumn 2022.

6.3 Future work

Further analysis and evaluation related to the use of automated shadings systems remained uncovered in this study and are recommended for further research. The recommendations for future research are listed below:

(a) The performance of automated shading systems is evaluated in terms of user behaviour, thermal and visual comfort, while the energy performance is uncovered in this study. Therefore, future studies should perform a simulation-based analysis to evaluate the energy performance of the tested scenarios to provide a comprehensive evaluation of the automated shading system in terms of comfort and energy performance.

(b) The experimental and monitoring studies are conducted in office spaces located in temperate climatic zones (Luxembourg and Germany). Future research should investigate the user-shade interaction with automated shading systems in different types and designs of buildings and climatic zones (tropical and subtropical zones) to verify the findings and provide general guidelines for the building designers and operators.

(c) The in-situ monitoring study explore user interaction with automated shading systems under warm conditions over three months (July-September). Therefore, future work should involve long-term monitoring campaigns over the year (four seasons) to infer comprehensive occupant behavior models that predict user-shade override actions and improve occupant-centric shading design.

6.4 Publications

- Derbas G., and Voss K. "Data-driven occupant-centric rules of automated shade adjustments: Luxembourg case study." Journal of Physics: Conference Series. Vol. 2042. No. 1. IOP Publishing, 2021.
- Abuimara T., O'Brien W., Tahmasebi F., Gosselin L., Rouleau J., Novakovic V., Andras R., Derbas G., de Souza C. B., Jin Q., Wallbaum H., Zhou J., Noguchi M., Sonta A., (2023) '11. Detailed case studies', O'Brien, W., & Tahmasebi, F. (Eds.). (2023). Occupant-centric Simulation-aided Building Design: Theory, Application, and Case Studies. Routledge. The contribution of the author was under the title of "Case study 6: Niederanven, Luxembourg".
- Day, J. K., McIlvennie, C., Brackley, C., Tarantini, M., Piselli, C., Hahn, J. . . . Derbas. G & Pisello, A. L. (2020). A review of select human-building interfaces and their relationship to human behavior, energy use, and occupant comfort. Building and Environment, 178, 106920.
- Derbas, G., & Voss, K. (2023). Optimizing Automated Shading System by Exploring Occupant Behaviour and Comfort in Office Environment: An Experimental Study, MDPI, Journal of Building (submitted).
- Walter, K., Kalpkirmaz Rizaoglu, I., Kirant-Mitic, T., and Derbas, G., (2021) Building 2226 on the Test Bench - Simulation study on the relocated 2226 building by Baumschlager Eberle. Technical report.

Appendix A1

A1.1 Questionnaire: phase 01

b+tga | Faculty of Architecture and Civil Engineering
Department of Building Physics and Technical Building Services
Prof. Dr.-Ing. Karsten Voss | Living Lab Building Performance
Configuration of Shading Devices
October 2018

CONFIGURATION OF SHADING DEVICES IN BUILDING MANAGEMENT SYSTEM(BMS) (not for individual glare protection!)

BUILDING: ___________________

Building General Information

GENERAL INFORMATION	DESCRIPTION	GOOGLE EARTH PICTURE
Building Type		
Location		
Construction Year		
Building Total Area		
User Type (rental/ owner)		
Type of Sunscreen		

b+tga | Faculty of Architecture and Civil Engineering
Department of Building Physics and Technical Building Services
Prof. Dr.-Ing. Karsten Voss | Living Lab Building Performance
Configuration of Shading Devices
October 2018

Shading Devices (SD) Detailed Information

Parameters Settings of Shading Devices in BMS (Total/part of the building/facade with orientation)	Value	Unit	Notes
Operation days per week	☐Mo. ☐Tu. ☐We. ☐Th. ☐Fr. ☐Sa. ☐Su.		
Operation hours per day			
Switching value of **light** for SD closure/occlusion (upper threshold)		lux	
Switching value of **light** to start-up (lower threshold)		lux	
Switching value of hysteresis light (difference between upper and lower thresholds)		lux	
Delay time of light		min	
Installation location(s) descriptions of light sensor(s) (number, alignments, etc.)			
Description of light measurements (interval, if applied averaging of values, etc.)			
Switching value of **wind monitor** (upper threshold)		m/sec	
Switching value of wind monitor (lower threshold)		m/sec	
Switching value of hysteresis wind monitor (difference between upper and lower thresholds)		m/sec	
Delay time of wind switch		min	
Installation location(s) descriptions of wind monitor (numbers, alignments, etc.)			
Description of wind measurements (interval, if applied averaging of values, etc.)			
Description of further input parameters like weather forecast, sky conditions, fire, etc.			

A1.2 Questionnaire: Phase 02

Informed Consent

You are kindly invited to participate in this survey as a part of an experimental research study about "Robustness of building design and solar shading control strategies in terms of user behaviour, thermal and visual comfort". The experimental research design consists of two main parts. Each part includes three sessions (two hours per each) with a total duration of 7 hours from 9:30 am until 4:30 pm (including one-hour lunch break after the first session). The researcher would greatly appreciate your participation in a short web-based survey once time after each session (three times in total per day).

General information

I am Ghadeer Derbas, a PhD student at the Architecture and Civil Engineering Faculty, Wuppertal University. I am working as a doctoral researcher at Civil Safety Research Institute IAS-7, Jülich Research Centre, Germany.

The information on this page is intended to help you understand exactly what the researcher is asking of you, so you can decide whether or not to participate in this study. Please read this consent form carefully before you decide to proceed with the survey. If you decide not to participate, it will not be held against you in any way. You may exit out of the survey at any time.

Privacy and confidentiality

Your participation in this survey is completely voluntary. Your answers will be kept confidential and your identity protected. All data will be transmitted by a secure, encrypted internet connection and stored in a password-protected file.

Potential harms/benefits

There are no known harms associated with your participation in this research. As well, there will be no direct benefit to you for your participation in this study. However, we hope that the information obtained from this study may benefit the scientific community.

Consent form

If you agree to the terms listed above, please proceed to the survey (if you proceed into the next page, that serves as your informed consent). Thank you in advance for your time and support. Please be precise and honest with your answers. Your responses are extremely valuable to our research.

This survey is anonymous (unnamed), so to analyse the questionnaire results, a code for each participant is needed.

If you have any questions, please don't hesitate to ask me.

Best regards,

Ghadeer Derbas
Doctoral Researcher
IAS-7: Civil Safety Research Institute/Jülich Research Centre.

Tel: +49 (0)202 / 439 4060
E-Mail: g.derbas@fz-juelich.de

Section A: Section 1: General Information

A1. Please write down your participant code. Your code consists of the first two letters of your mother's first name (capital letters), then add (-), then add four digits of your year of birth. (example: MA-1993)

A2. What is your Gender?

- Female ☐
- Male ☐
- Other ☐

Other

A3. What is your current professional position?

- student ☐
- employee ☐
- Other ☐

Other

A4. Whats is your Nationality?

- German ☐
- Palestinian ☐
- Other ☐

Other

A5. **Please specify the date of the day?**

☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

A6. **Please specify the current *Time*?**

- 11:30 am ☐
- 14:30 pm ☐
- 16:30 pm ☐

Section B: Section 2: User adaptive control behaviours

B1. **Please indicate the current state of the given options to control the indoor climate at your workspace?**

	Fully closed/adjusted up/turned ON	Partially open/intermediate position	Fully open/adjusted down/turned OFF
Operable window [Right]	☐	☐	☐
Operable window [Left]	☐	☐	☐
External shading system	☐	☐	☐
Artificial lighting	☐	☐	☐

B2. **a. Did you lower the shading device during the previous session?**

- Yes ☐
- No ☐

B3. **b. If yes, how many times?**

☐☐☐☐☐☐☐☐☐☐

B4. **c. What was the reason behind lowering the blind?**

- To reduce overall brightness of the workspace. ☐
- To reduce glare on my computer screen. ☐
- To reduce glare from the sun (directly into my eyes). ☐
- To increase visual privacy. ☐
- To reduce the heat from the sun. ☐

Other ☐

Other

[ ]

B5. **a. Did you raise the shading device during the previous session?**

Yes ☐

No ☐

B6. **b. If yes, how many times?**

[ ]

B7. **c. What was the reason behind raising the blind?**

To maintain visual contact to the outside. ☐

To increase the amount of daylight in the workspace. ☐

To get heat from the sun. ☐

To get a fresh air. ☐

Other ☐

Other

[ ]

B8. **d. If *No action*, what was the reason that you decided not to change the position of the blind?**

Too much effort. ☐

I am too busy to adjust the blind. ☐

Not needed. ☐

Not easy to access the blind control. ☐

I don't know. ☐

Other ☐

Other

[ ]

B9. **a. Did you adjust the electrical lights during the previous session?**

- Yes. ☐
- No. ☐

B10. **b. If yes, what was the reason behind that?**

- To reduce overall brightness of the workplace. ☐
- To reduce glare on computer screen. ☐
- To reduce heat from electrical light. ☐
- To save energy. ☐
- To increase the amount of light in the workspace. ☐
- Other ☐

Other

Section C: Section 3: Thermal Comfort Evaluation

C1. **How do you feel about the room air temperature at the moment? [ASHRAE 7-point scale].**

- Cold. ☐
- Cool. ☐
- Slightly cool. ☐
- Neutral. ☐
- Slightly warm. ☐
- Warm. ☐
- Hot. ☐

C2. **Using the list below, please check each item of clothing that you are wearing right now. [Clothing level assessment /ASHARE 55-2017]**

- Short-sleeve shirt. ☐
- Long-sleeve shirt. ☐
- T-shirt. ☐
- Long-sleeve sweatshirt. ☐
- Sweater. ☐
- Vest. ☐

Jacket. ☐

Knee-length skirt. ☐

Ankle-length skirt. ☐

Dress. ☐

Shorts. ☐

Athletic sweatpants. ☐

Trousers. ☐

Undershirt. ☐

Long underwear bottoms. ☐

Long sleeve coveralls. ☐

Overalls. ☐

Slip. ☐

Nylons. ☐

Socks. ☐

Boots. ☐

Shoes. ☐

Sandals. ☐

Other: please note if you are wearing something not described above, or if you think something you are wearing is especially heavy. ☐

Other ☐

Other

C3. How do you rate the following indoor air quality parameters at your workspace?

	Very uncomfortable.	2	3	4	Very comfortable.
Temperature.	☐	☐	☐	☐	☐
Humidity.	☐	☐	☐	☐	☐
Air movement.	☐	☐	☐	☐	☐

C4. **How do you prefer the air temperature at the moment in your workspace?**

- Much cooler. ☐
- Cooler. ☐
- No change. ☐
- Warmer. ☐
- Much warmer. ☐

Section D: Section 4: Visual Comfort Evaluation

D1. **Please describe the current lighting condition at your workspace?**

- Very dark. ☐
- Dark. ☐
- Slightly dark. ☐
- Neutral. ☐
- Slightly bright. ☐
- Bright. ☐
- Very bright. ☐

D2. **How comfortable are you with the current amount of light at your workspace?**

Note:

1- Not comfortable.

5- Very comfortable.

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

D3. **a- Were you disturbed by glare (brightness) in the previous session?**

- Yes ☐
- No ☐

D4. **b- If yes, please specify the reason behind the glare?**

- Direct sunlight. ☐
- Bright sky. ☐
- Bright wall. ☐

Bright desk. ☐

Bright screen. ☐

Other ☐

Other

D5. **Please specify the magnitude of the glare? [Glare sensation vote scale (GSV)]**

Imperceptible (little). ☐

Noticeable. ☐

Disturbing. ☐

Intolerable (too much). ☐

D6. **How do you rate your satisfaction with the following current light conditions at your workspace?**

	Very dissatisfied.	2	3	4	Very satisfied.
Daylight lighting.	☐	☐	☐	☐	☐
Artificial lighting.	☐	☐	☐	☐	☐
Overall lighting.	☐	☐	☐	☐	☐
View connection to the outside.	☐	☐	☐	☐	☐

Section E: Section 5: User-blind satisfactions and preferences.

E1. **Was the automated shading system moved during the previous session?**

Yes ☐

No ☐

E2. **How satisfied are you with the performance of the automated shading system during the previous session?**

1- Very dissatisfied.

5- Very satisfied.

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Thank you very much for your support and cooperation.

A1.3 Questionnaire: Phase 03

English version

Dear Golav employees,

You are invited to participate in this survey as part of a Ph.D. dissertation on "Function and Use of Automated Solar Shading Systems". I would appreciate your participation in a short (15-20) minutes survey about your control options and satisfaction with the shading system, the context, and the environmental conditions in your office. The company's administration has agreed to do the survey.

Please participate only if you have been working from the office.
Please click on "submit" when you are done!
The survey will be open for responses until the end of July 2021.

General information

The information on this page is intended to help you understand exactly what the researcher is asking of you, so you can decide whether or not to participate in this study. Please read the consent form carefully before you decide to proceed with the survey. If you decide not to participate, it will not be held against you in any way. You may exit out of the survey at any time.

Your participation in this survey is VOLUNTARY!

There will be no direct benefit to you for your participation in this study. However, we hope that the information obtained from this study may benefit the scientific community.

This survey is ANONYMOUS!

We will not ask you to share any personal information. However, please be mindful not to include any information that could identify you in the responses. Any information that could identify you will be anonymized after the survey closes, before data analysis being carried out. To compare the questionnaire results with the measurement findings, a code for each participant is needed at the beginning of the survey.

Consent form

By moving on to the survey, you confirm that you have been informed about the study, that you have read the information provided in full, that you feel sufficiently informed and that you have understood what the survey is about. You also agree with the data processing described above – all data will be anonymized and it will not be possible to assign the data to you in any way.

Thank you for your time and cooperation. Please be precise and honest with your responses. Your answers are extremely valuable to my research! If you have any questions, please do not hesitate to contact me.

Contact person

Ghadeer Derbas
Doctoral researcher in a joint project of Wuppertal University and Jülich Research Centre.
Institute for Advanced Simulation, Civil safety research/ IAS-7
E-Mail: g.derbas@fz-juelich.de

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Section A: Participant code and the date

A1. **Please write down your participant code. Your code consists of the first two letters of your father's first name (capital letters), then add (-), then add four digits of your year of birth. (example: GD-1984)**

A2. **Please select the date when you start filling out the questionnaire.**

Section B: Your current state of mind

B1. **In the following scale, please select which one is your current state of mood.**

1- very bad mood

5- very good mood

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

Section C: Section A: General questions about your work activity and workplace

C1. **How long have you been working in this place in this room?**

- less than 1 year ☐
- between 1 to 2 years ☐
- More than 2 years ☐

C2. **How much time do you usually spend at your workplace per week?**

- 20% ☐
- 40% ☐
- 60% ☐
- 80% ☐
- 100% ☐

LimeSurvey

C3. Do you have a full-time or part-time job?

- Full-time ☐
- Part-time ☐
- Other ☐

Other

C4. During a typical workday, when are you usually at your workplace?

- all day ☐
- mornings only ☐
- afternoons only ☐
- mixed (some mornings, some afternoons) ☐

C5. On which floor is your office located?

- Ground floor ☐
- 1st floor ☐
- 2nd floor ☐
- 3rd floor ☐

C6. Considering that number (4) in the graph is the main entrance of the building, which number represents the location of your office? (for offices at the corner you can say 1,2 or 2,3 or 3,4 or 1,4).

- (1) East ☐
- (2) South ☐
- (3) West ☐
- (4) North ☐
- Other ☐

Other

LimeSurvey

C7. What is the percentage of your work activity in the following areas?

Note: The total sum is 100%

Desk work (including PC work and telephoning) % ☐

Meetings / client meetings in the same office % ☐

Working time elsewhere in the building % ☐

Other (incl. working time outside the building) % ☐

Section D: Section B: Questions about your workplace context

D1. <u>Before the COVID-19 pandemic</u>, what type of office do you have?

Private single office (1 person) ☐

Shared office (2-3 people) ☐

Open-plan office (more than 3 people) ☐

D2. How far are you sitting from the nearest window?

up to 1 metre ☐

up to 2 metres ☐

up to 3 metres ☐

4 metres and more ☐

D3. Regarding your workspace, the window is located:

directly in front of me ☐

On my left ☐

on my right ☐

behind me ☐

LimeSurvey

D4. What is approximately the total area of the windows on the exterior wall at your workplace?

- 25% of the wall area ☐
- 50% of the wall area ☐
- 75% of the wall area ☐
- 100% of the wall area ☐
- Other ☐

Other

D5. How far is your workplace from the manual switch of the external blinds?

- up to 1 meter ☐
- up to 2 metres ☐
- up to 3 metres ☐
- 4 metres and more ☐

D6. Please select how important do you consider the listed factors below for your working environment satisfaction?

	Unimporta nt	Less important	Neutral	Important	Very important
A comfortable room temperature	☐	☐	☐	☐	☐
A pleasant humidity	☐	☐	☐	☐	☐
Sufficient fresh air	☐	☐	☐	☐	☐
Adequate daylight	☐	☐	☐	☐	☐
Good artificial light	☐	☐	☐	☐	☐
View connection to the outside (through a window)	☐	☐	☐	☐	☐
Visual privacy	☐	☐	☐	☐	☐
Acoustic privacy	☐	☐	☐	☐	☐

LimeSurvey

Section E: Section C: Thermal and visual comfort at your workplace

Note: You can consider this week as a reference for your answers to the following section.

E1. How do you feel the temperature at your workplace?

- Often too cool ☐
- Sometimes too cool ☐
- Comfortable ☐
- Sometimes too warm ☐
- Often too warm ☐

E2. How do you feel about the amount of daylight at your workplace?

- very little ☐
- little ☐
- neutral ☐
- much ☐
- Very much ☐

E3. How often do you face glare from direct sunlight at your workspace?

1- Almost always 5- Almost never

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

E4. How satisfied are you with the following conditions at your workplace?

	very unsatisfied	unsatisfied	neutral	satisfied	very satisfied
Room temperature	☐	☐	☐	☐	☐
Daylight conditions	☐	☐	☐	☐	☐
Artificial lighting conditions	☐	☐	☐	☐	☐
View Connection to the outside	☐	☐	☐	☐	☐

E5. Please select which of the following is a major source of thermal discomfort at your workplace?

- I do not feel this kind of discomfort ☐

LimeSurvey

Work area hotter than other areas ☐

Direct sunlight through the window ☐

Individual room temperature control not possible or not effective ☐

Surfaces around me are too warm ☐

Draught (window and/or mechanical ventilation) ☐

Other ☐

Other

E6. Please select which of the following is a major source of visual discomfort at your workplace?

I do not feel this kind of discomfort ☐

Glare through window ☐

Not enough artificial lighting ☐

Not enough natural lighting ☐

Too much artificial lighting ☐

Too much natural light ☐

Lack of or poor view connection to the outside ☐

Other ☐

Other

Section F: Section D: User interaction with automated shading system

Note: You can consider this week as a reference for your answers to the following section.

F1. At your workspace, how are the external blinds kept most of the time?

Fully open ☐

Fully closed with open slat angle ☐

Fully closed with closed slat angle ☐

Partially open ☐

LimeSurvey

F2. How often do you open the external blinds?

- Never ☐
- Once or twice a week ☐
- More than twice a week ☐
- Once or twice a day ☐
- More than twice a day ☐
- Other ☐

Other

F3. When do you usually open the external blinds?

- Upon arrival ☐
- During the workday, in the morning ☐
- During the workday, in the afternoon ☐
- After lunch ☐
- Upon departure ☐
- When the blinds are automatically closed ☐
- Other ☐

Other

F4. Why do you usually open the external blinds?

- More daylight into the office ☐
- To have a view to the outside ☐
- More solar heat gain ☐
- Arrival/Departure to the office ☐
- To save energy ☐
- For the desire of an employee/manager ☐

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Other ☐

Other

[ ]

F5. How often do you close the external blinds?

- Never ☐
- Once or twice a week ☐
- More than twice a week ☐
- Once or twice a day ☐
- More than twice a day ☐
- Other ☐

Other

[ ]

F6. When do you usually close the external blinds?

- Upon arrival to the workspace ☐
- During the workday, in the morning ☐
- During the workday, in the afternoon ☐
- After lunch ☐
- Upon departure ☐
- Other ☐

Other

[ ]

F7. Why do you usually close the external blinds?

- To avoid direct sun on my work surfaces ☐
- To avoid overheating ☐
- to block the view to the outside (privacy) ☐

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Arrival/Departure to the office ☐

To save energy ☐

For the desire of an employee/manager ☐

Other ☐

Other

F8. Why did you decide not to overrule the position of the external blinds?

I don't know ☐

Too much effort ☐

Not needed ☐

Too busy ☐

Other ☐

Other

F9. <u>Before the COVID-19 pandemic</u>, how many people in your workplace share (with you) the control of the external blinds?

Only me ☐

Another employee ☐

Two or more employees ☐

I don't know ☐

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F10. **<u>Before the COVID-19 pandemic</u>, do you avoid adjusting the external blinds for fear of bothering your colleagues?**

- Never ☐
- Rarely ☐
- Sometimes ☐
- Frequently ☐
- Always ☐

Section G: Section E: User interaction with inner glare protection

Note: You can consider this week as a reference for your answers to the following section.

G1. **At your workplace, how are the inner glare protections kept most of the time?**

- Fully open ☐
- Fully closed ☐
- Partially open ☐

G2. **How often do you adjust the inner glare protection at your workplace?**

- Never ☐
- Once or twice a week ☐
- More than twice a week ☐
- Once or twice a day ☐
- More than twice a day ☐
- Other ☐

Other

G3. **Are you more likely to adjust the inner glare protection when you feel uncomfortable about the lighting or the temperature at your workspace?**

- Temperature ☐
- Lighting ☐
- Both ☐
- None of them ☐

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Section H: Section F: User preferences and satisfaction with the external blinds and inner glare protection

Note: You can consider this week as a reference for your answers to the following section

H1. Which position do you usually prefer for the external blinds?

- Fully open ☐
- Fully closed with open slat angle ☐
- Fully closed with closed slat angle ☐
- Partially open ☐

H2. How do you usually experience the movement of the external blinds?

1- very annoying

5- absolutely not annoying

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

H3. How satisfied are you with the performance of the automated shading system at your workspace?

1- Very dissatisfied 5- Very satisfied

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

H4. How satisfied are you with having the ability to control two shading devices (the external blind and the inner glare protection) at your workplace?

1- Very dissatisfied 5- Very satisfied

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

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H5. **Which system do you prefer to use at your workplace? and why?**

- Inner glare protection ☐
- External blinds ☐
- Both ☐
- None of them ☐

H6. **Were you ever taught/ trained how to override the automatic blinds at your workplace? (e.g. verbally, through a meeting, training, email...etc.)**

- Yes ☐
- No ☐

Section I: Section G: Individual control options at your workplace

I1. **Which of the following control options can you adjust at your workplace?**

	Yes	No
Heating thermostat	☐	☐
Cooling thermostat	☐	☐
Air volume ventilation system	☐	☐

Section J: Section H: Demographic data

J1. **What is your Gender?**

- Female ☐
- Male ☐
- Other ☐

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J2. What is your age range?

- less than 25 years ☐
- 26 - 35 ☐
- 36 - 45 ☐
- 46 - 55 ☐
- older than 55 years ☐

J3. Which one of the following categories fits with your job position?

- Managerial and decision-making powers (e.g. director, managing director, member of the board) ☐
- Professional (e.g. engineer, draftsman, specialist planner) ☐
- Clerical/administration employee ☐
- Other ☐

Other

Section K: Remarks

K1. If we forgot something important for you or if you would like to tell us something about your workplace, the building in general, or this questionnaire, please feel free to note it here:

Workplace:

Building:

Questionnaire:

Thank you very much for your support!

German version

Sehr geehrte Mitarbeiterinnen und Mitarbeiter von Golav,

Sie sind eingeladen, an dieser Umfrage als Teil einer Dissertation zum Thema “Funktion und Nutzung automatisierter Sonnenschutzsysteme“. Ich würde mich sehr über Ihre Teilnahme an einer kurzen (15-20) Minuten dauernden Umfrage zu Ihren Steuerungsmöglichkeiten und Ihrer Zufriedenheit mit dem Beschattungssystem, dem Arbeitsplatzkontext und den Umgebungsbedingungen in Ihrem Büroraum freuen.Die Geschäftsführung hat der Befragung zugestimmt.

Bitte nehmen Sie nur teil, wenn Sie vom Büro ausgearbeitet haben.

Bitte klicken Sie auf "absenden", wenn Sie fertig sind!

Die Umfrage wird nur bis Ende Juli 2021 für die Beantwortung zugänglich sein.

Allgemeine Informationen

Die Informationen auf dieser Seite sollen Ihnen helfen zu verstehen, was genau der Forscher von Ihnen verlangt, damit Sie entscheiden können, ob Sie an dieser Studie teilnehmen möchten oder nicht. Bitte lesen Sie die Einverständniserklärung sorgfältig durch bevor Sie sich entscheiden, mit der Umfrage fortzufahren. Wenn Sie sich entscheiden nicht teilzunehmen, wird dies in keiner Weise gegen Sie verwendet. Sie können die Umfrage jederzeit abbrechen.

Ihre Teilnahme an dieser Umfrage ist freiwillig

Sie haben keinen direkten Nutzen von Ihrer Teilnahme an dieser Studie. Wir hoffen jedoch, dass die aus dieser Studie gewonnenen Informationen für die wissenschaftliche Gemeinschaft von Nutzen sein können.

Diese Umfrage ist anonym

Wir werden Sie nicht auffordern persönliche Informationen preiszugeben. Bitte achten Sie jedoch darauf, dass Sie in den Antworten keine Informationen angeben, die Sie identifizieren könnten. Alle Informationen, die Sie identifizieren könnten, werden nach Abschluss der Umfrage anonymisiert, bevor die Datenanalyse durchgeführt wird. Um die Umfrageergebnisse mit den Messergebnissen vergleichen zu können, wird zu Beginn der Befragung ein Code von jedem Teilnehmer benötigt.

Einverständniserklärung

Mit dem Fortfahren der Umfrage bestätigen Sie, dass Sie über die Studie informiert wurden, dass Sie die bereitgestellten Informationen vollständig gelesen haben, dass Sie sich ausreichend informiert fühlen und dass Sie verstanden haben, worum es in der Umfrage geht. Sie erklären sich auch mit der oben beschriebenen Datenverarbeitung einverstanden - alle Daten werden anonymisiert und es wird nicht möglich sein, die Daten in irgendeiner Weise Ihnen zuzuordnen.

Vielen Dank für Ihre Zeit und Mitarbeit. Bitte seien Sie präzise und ehrlich mit Ihren Antworten. Ihre Antworten sind extrem wertvoll für meine Forschung! Wenn Sie irgendwelche Fragen haben, zögern Sie bitte nicht, mich zu fragen.

Kontaktperson:

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Teil A: Ihr Teilnehmercode und das Tagesdatum

A1. **Bitte schreiben Sie Ihren Teilnehmercode auf. Dieser besteht aus den ersten beiden Buchstaben des Vornamens Ihres Vaters (in Großbuchstaben), gefolgt von (-), und den vier Ziffern Ihres Geburtsjahres. (Beispiel: GD-1984).**

A2. **Bitte schreiben Sie das Datum auf, an dem Sie den Fragebogen ausfüllen.**

Teil B: Ihre momentane Befindlichkeit

B1. **Bitte kreuzen Sie in den nachfolgenden Zeilen jeweils das Kästchen an, das am besten zu Ihrem momentanen Befinden passt.**

1- sehr schlecht gestimmt

5- sehr gut gestimmt

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Teil C: Abschnitt A: Allgemeine Fragen zu Ihrer Arbeitstätigkeit und zu Ihrem Arbeitsplatz

C1. **Seit wann arbeiten Sie an diesem Platz in diesem Raum?**

weniger als 1 Jahr ☐
zwischen 1 und 2 Jahren ☐
Mehr als 2 Jahren ☐

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C2. Wie viel Zeit verbringen Sie normalerweise pro Woche an Ihrem Arbeitsplatz?

- 20% ☐
- 40% ☐
- 60% ☐
- 80% ☐
- 100% ☐

C3. Haben Sie einen Vollzeit- oder einen Teilzeitjob?

- Vollzeit ☐
- Teilzeit ☐
- Sonstiges ☐

Sonstiges

C4. Während einer typischen Arbeitswoche, wann sind Sie normalerweise an Ihrem Arbeitsplatz?

- ganztägig ☐
- nur vormittags ☐
- nur nachmittags ☐
- mal vormittags / mal nachmittags ☐

C5. In welchem Geschoss befindet sich Ihr Arbeitsplatz?

- Erdgeschoss ☐
- 1.OG ☐
- 2.OG ☐
- 3.OG ☐

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C6. In Anbetracht der Tatsache, dass Nummer (4) in der Abbildung der Haupteingang des Gebäudes ist, welche Nummer bildet die Position Ihres Büros ab? ***(Die Büros in den Ecken können 1,2 oder 2,3 oder 3,4 oder 1,4 benannt werden).***

(1) Ost ☐
(2) Süd ☐
(3) West ☐
(4) Nord ☐
Sonstiges ☐

Sonstiges

C7. Wie verteilt sich in etwa Ihre Arbeitstätigkeit auf folgende Bereiche?

Hinweis: Die Gesamtsumme beträgt 100 %

Schreibtischarbeit (einschließlich Bildschirmarbeit und Telefonieren) %

Besprechungen / Kundengespräche im selben Büro %

Arbeitszeit anderweitig im Gebäude %

Sonstiges (einschl. Arbeitszeit außerhalb des Gebäudes) %

Teil D: Abschnitt B: Fragen zu Ihrer Arbeitsplatzumgebung

D1. Vor COVID-19 Pandemie, welche Art von Arbeitsplatz haben Sie?

Einzelbüro (1 Person) ☐
Mehrpersonenbüro (2-3 Personen) ☐
Gruppenbüro (mehr als 3 Personen) ☐

D2. Wie weit sitzen Sie vom nächsten Fenster entfernt?

bis zu 1 Meter entfernt ☐
bis zu 2 Meter entfernt ☐
bis zu 3 Meter entfernt ☐
4 Meter und mehr entfernt ☐

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D3. Wo befindet sich das Fenster von Ihrer Sitzposition aus gesehen?

- direkt in Blickrichtung ☐
- links von mir ☐
- rechts von mir ☐
- hinter mir ☐

D4. Wie groß schätzen Sie die Gesamtfläche der Fenster an der Außenwand ungefähr ein?

- 25% der Wandfläche ☐
- 50% der Wandfläche ☐
- 75% der Wandfläche ☐
- 100% der Wandfläche ☐
- Sonstiges ☐

Sonstiges

D5. Wie weit ist Ihr Arbeitsplatz vom An- und Ausschalter der Außenjalousien entfernt?

- bis zu 1 Meter entfernt ☐
- bis zu 2 Meter entfernt ☐
- bis zu 3 Meter entfernt ☐
- 4 Meter und mehr entfernt ☐

D6. Bitte kreuzen Sie an, wie wichtig Ihnen die folgenden Faktoren für Ihr Wohlbefinden und Ihre Zufriedenheit am Arbeitsplatz sind ?

	unwichtig	weniger wichtig	neutral	wichtig	sehr wichtig
Eine angenehme Raumtemperatur	☐	☐	☐	☐	☐
Eine angenehme Luftfeuchtigkeit	☐	☐	☐	☐	☐
Ausreichend frische Luft	☐	☐	☐	☐	☐
Genügend Tageslicht	☐	☐	☐	☐	☐
Gute künstliche Beleuchtung	☐	☐	☐	☐	☐
Sicht Verbindung nach außen durchs Fenster	☐	☐	☐	☐	☐

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	unwichtig	weniger wichtig	neutral	wichtig	sehr wichtig
Visuelle Privatsphäre	☐	☐	☐	☐	☐
Akustische Privatspäre	☐	☐	☐	☐	☐

Teil E: Abschnitt C: Thermisches und Visuelles Empfinden an Ihrem Arbeitsplatz

Hinweis: Sie können diese Woche als Referenz für Ihre Antworten des folgenden Abschnitts betrachten

E1. Wie bewerten Sie die Temperatur an Ihrem Arbeitsplatz?

- Oft zu kühl ☐
- Manchmal zu kühl ☐
- Angenehm ☐
- Manchmal zu warm ☐
- Oft zu warm ☐

E2. Wie empfanden Sie das Tageslichtangebot an Ihrem Arbeitsplatz?

- sehr wenig ☐
- wenig ☐
- neutral ☐
- viel ☐
- sehr viel ☐

E3. Wie häufig erleben Sie Blendung durch Tageslicht an Ihrem Arbeitsplatz?

1- nahezu nie 5- nahezu immer

- 1 ☐
- 2 ☐
- 3 ☐
- 4 ☐
- 5 ☐

E4. Wie zufrieden waren Sie mit den folgenden Bedingungen an Ihrem Arbeitsplatz?

	sehr unzufrieden	unzufrieden	neutral	zufrieden	sehr zufrieden
Raumtemperatur	☐	☐	☐	☐	☐
Tageslichtverhältnissen	☐	☐	☐	☐	☐
künstlichen Beleuchtung	☐	☐	☐	☐	☐

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	sehr unzufrieden	unzufrieden	neutral	zufrieden	sehr zufrieden
Sicht Verbindung nach außen	☐	☐	☐	☐	☐

E5. Bitte kreuzen Sie an, welche der folgenden Punkte eine Hauptquelle für thermisches Unbehagen an Ihrem Arbeitsplatz darstellen?

- Ich empfinde diese Art von Unbehagen nicht ☐
- Arbeitsbereich heißer als andere Bereiche ☐
- Direkte Besonnung durch das Fenster ☐
- Individuelle Raumtemperaturregelung nicht möglich bzw. nicht wirksam ☐
- Oberflächen um mich herum sind zu heiß ☐
- Luftzug (Fenster und/oder mechanische Lüftung) ☐
- Sonstiges ☐

Sonstiges

E6. Bitte kreuzen Sie an, welche der folgenden Punkte eine Hauptquelle für visuelles Unbehagen an Ihrem Arbeitsplatz darstellen?

- Ich empfinde diese Art von Unbehagen nicht ☐
- Blendung durch Fenster ☐
- Nicht genügend künstliche Beleuchtung ☐
- Nicht genügend natürliche Beleuchtung ☐
- Zu viel künstliche Beleuchtung ☐
- Zu viel natürliches Licht ☐
- Fehlende oder schlechte Sicht nach draußen ☐
- Sonstiges ☐

Sonstiges

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Teil F: Abschnitt D: Nutzer-Außenjalousie Interaktion

Hinweis: Sie können diese Woche als Referenz für Ihre Antworten des folgenden Abschnitts betrachten

F1. Wie sind üblicherweise die Außenjalousien an Ihrem Arbeitsplatz?

- Ganz geöffnet ☐
- Ganz geschlossen mit offenem Lamellenwinkel ☐
- Ganz geschlossen mit geschlossenem Lamellenwinkel ☐
- Teilweise geöffnet ☐

F2. Wie oft öffnen Sie die Außenjalousien?

- Nie ☐
- Ein- oder zweimal wöchentlich ☐
- Mehr als zweimal wöchentlich ☐
- Ein- oder zweimal täglich ☐
- Mehr als zweimal täglich ☐
- Sonstiges ☐

Sonstiges

F3. Wann öffnen Sie die Außenjalousien normalerweise?

- Bei Ankunft ☐
- Im Laufe des Arbeitstages am Morgen ☐
- Im Laufe des Arbeitstages am Nachmittag ☐
- Nach dem Mittagessen ☐
- Bevor Sie das Büro verlassen ☐
- Wenn die Jalousien automatisch geschlossen sind ☐
- Sonstiges ☐

Sonstiges

LimeSurvey

F4. Warum öffnen Sie die Außenjalousien normalerweise ?

- Mehr Tageslicht im Büro ☐
- Freie Sicht nach Außen ☐
- Mehr solare Wärmegewinne ☐
- Ankunft/Abfahrt zum Büro ☐
- um Energie zu sparen ☐
- Für den Wunsch eines Mitarbeiters/Managers ☐
- Sonstiges ☐

Sonstiges

F5. Wie oft schließen Sie die Außenjalousien?

- Nie ☐
- Ein- oder zweimal wöchentlich ☐
- Mehr als zweimal wöchentlich ☐
- Ein- oder zweimal täglich ☐
- Mehr als zweimal täglich ☐
- Sonstiges ☐

Sonstiges

F6. Wann schließen Sie die Außenjalousien normaleweise?

- Bei Ankunft ☐
- Im Laufe des Arbeitstages am Morgen ☐
- Im Laufe des Arbeitstages am Nachmittag ☐
- Nach dem Mittagessen ☐
- Bevor Sie das Büro verlassen ☐

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Sonstiges ☐

Sonstiges

F7. **Warum schließen Sie die Außenjalousien normalerweise?**

- um die Blendung auf meinem Bildschirm/Arbeitsplatz zu reduzieren ☐
- um Überhitzung zu reduzieren ☐
- um die Sicht nach außen zu versperren (Privatsphäre) ☐
- Ankunft/Abfahrt zum Büro ☐
- um Energie zu sparen ☐
- für den Wunsch eines Mitarbeiters/Managers ☐
- Sonstiges ☐

Sonstiges

F8. **Warum haben Sie sich entschieden, die Position der Außenjalousien nicht zu überstimmen?**

- Ich weiß nicht ☐
- Zuviel Aufwand ☐
- Nicht erforderlich ☐
- Zuviel beschäftigt ☐
- Sonstiges ☐

Sonstiges

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F9. **<u>Vor COVID-19 Pandemie</u>, wie viele Personen an Ihrem Arbeitsplatz teilen sich (mit Ihnen) die Steuerung der Außenjalousien?**

- Nur ich ☐
- Ein anderer Mitarbeiter ☐
- Zwei oder mehr Mitarbeiter ☐
- Ich weiß es nicht ☐

F10. **<u>Vor COVID-19 Pandemie</u>, vermeiden Sie die Außenjalousien einzustellen, damit Sie Ihre Kollegen nicht stören?**

- Nie ☐
- Selten ☐
- Manchmal ☐
- Oft ☐
- Immer ☐

Teil G: Abschnitt E: Nutzer-Blendschutzrollo Interaktion

Hinweis: Sie können diese Woche als Referenz für Ihre Antworten des folgenden Abschnitts betrachten

G1. **Wie sind üblicherweise die Blendschutzrollos an Ihrem Arbeitsplatz?**

- Ganz geöffnet ☐
- Ganz geschlossen ☐
- Teilweise geöffnet ☐

G2. **Wie oft stellen Sie die Blendschutzrollos ein?**

- Nie ☐
- Ein- oder zweimal wöchentlich ☐
- Mehr als zweimal wöchentlich ☐
- Ein- oder zweimal täglich ☐
- Mehr als zweimal täglich ☐
- Sonstiges ☐

Sonstiges

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G3. Passen Sie eher die Blendschutzrollos am Arbeitsplatz an, wenn Sie sich mit der Temperatur unwohl fühlen oder mit der Beleuchtung?

Temperatur ☐

Beleuchtung ☐

Beide ☐

Keine ☐

Teil H: Abschnitt F: Nutzerpräferenzen und Zufriedenheit mit den Außenjalousien und Blendschutzrollos

Hinweis: Sie können diese Woche als Referenz für Ihre Antworten des folgenden Abschnitts betrachten

H1. Welche Position für die Außenjalousien bevorzugen Sie normalerweise ?

Ganz geöffnet ☐

Ganz geschlossen mit offenem Lamellenwinkel ☐

Ganz geschlossen mit geschlossenem Lamellenwinkel ☐

Teilweise geöffnet ☐

H2. Wie erleben Sie normalerweise die Bewegung der Außenjalousien?

1- sehr lästig

5- absolut nicht lästig

1 ☐

2 ☐

3 ☐

4 ☐

5 ☐

H3. Wie zufrieden sind Sie mit der Automatisierung der Außenjalousien an Ihrem Arbeitsplatz?

1- Sehr unzufrieden 5- Sehr zufrieden

1 ☐

2 ☐

3 ☐

4 ☐

5 ☐

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H4. **Wie zufrieden sind Sie mit der Möglichkeit, zwei Beschattungssysteme (die Außenjalousien und die Blendschutzrollos) an Ihrem Arbeitsplatz zu steuern?**

1- Sehr unzufrieden 5- Sehr zufrieden

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

H5. **Welches System verwenden Sie bevorzugt an Ihrem Arbeitsplatz? *und warum?***

Innenjalousie (Blendschutzrollo) ☐
Außenjalousie ☐
Beide ☐
Keine ☐

H6. **Wurde Ihnen jemals beigebracht, wie Sie die automatischen Jalousien in Ihrem Büro außer Kraft setzen können? (z.B.mündlich, durch eine Besprechung, eine Schulung, eine E-Mail oder anderes)**

Ja ☐
Nein ☐

Teil I: AAbschnitt G: Individuelle Anpassung des Raumklimas

I1. **Welche der folgenden Bedienelemente für das Raumklima können Sie in Ihrem Büro einstellen nutzen?**

	Ja	Nein
Thermostat Heizung	☐	☐
Thermostat Kühlung	☐	☐
Luftmenge Lüftungsanlage	☐	☐

LimeSurvey

Teil J: Abschnitt H: Persönliche Angaben

J1. Bitte geben Sie Ihr Geschlecht an.

- weiblich ☐
- männlich ☐
- divers ☐

J2. Bitte geben Sie Ihre Altersgruppe an.

- bis 25 Jahre ☐
- 26 bis 35 Jahre ☐
- 36 bis 45 Jahre ☐
- 46 bis 55 Jahre ☐
- über 55 Jahre ☐

J3. Welche der unten aufgeführten Kategorien entspricht am ehesten Ihrer Stelle?

- Führungskraft mit umfassenden Führungsaufgaben und Entscheidungsbefugnissen (z. B. Direktor/-in, Geschäftsführer/-in, Mitglied des Vorstandes) ☐
- Leitungs Ingenieur/-in, Bauzeichner/-in, Fachplaner/-in ☐
- Mitarbeiter/in in der Verwaltung ☐
- Sonstiges ☐

Sonstiges

Teil K: Anmerkungen

K1. Wenn wir etwas für Sie Wichtiges vergessen haben oder Sie uns zu Ihrem Büroarbeitsplatz, zum Gebäude allgemein oder zu diesem Fragebogen noch etwas mitteilen möchten, können Sie dies hier gerne notieren:

zum Arbeitsplatz:

zum Gebäude:

zum Fragebogen:

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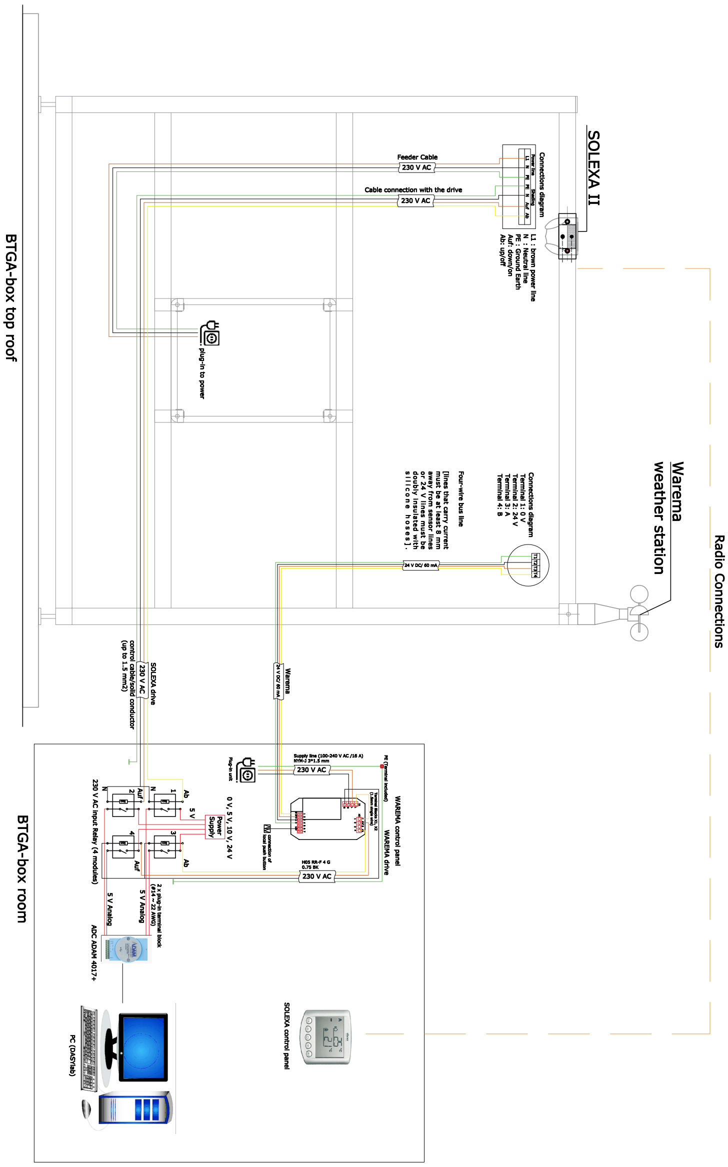
Herzlichen Dank für Ihre Unterstützung!

A1.4 Miscellaneous

Electrical connection plan of SOLEXA and WAREMA devices.



Garment insulation according to ANSI/ASHRAE standard 2017

Table 5.2.2.2B Garment Insulation I_{clu}

Garment Description [a]	I_{clu}, clo	Garment Description [a]	I_{clu}, clo
Underwear		Dress and Skirts [b]	
Bra	0.01	Skirt (thin) mm	0.14
Panties	0.03	Skirt (thick)	0.23
Men's briefs	0.04	Sleeveless, scoop neck (thin)	0.23
T-shirt	0.08	Sleeveless, scoop neck (thick), i.e., jumper	0.27
Half slip	0.14	Short-sleeve shirtdress (thin)	0.29
Long underwear bottoms	0.15	Long-sleeve shirtdress (thin)	0.33
Full slip	0.16	Long-sleeve shirtdress (thick)	0.47
Long underwear top	0.20	Sweaters	
Footwear		Sleeveless vest (thin)	0.13
Ankle-length athletic socks	0.02	Sleeveless vest (thick)	0.22
Panty hose/stockings	0.02	Long-sleeve (thin)	0.25
Sandals/thongs	0.02	Long-sleeve (thick)	0.36
Shoes	0.02	Suit Jackets and Vests [c]	
Slippers (quilted, pile lined)	0.03	Sleeveless vest (thin)	0.10
Calf-length socks	0.03	Sleeveless vest (thick)	0.17
Knee socks (thick)	0.06	Single-breasted (thin)	0.36
Boots	0.10	Single-breasted (thick)	0.44
Shirts and Blouses		Double-breasted (thin)	0.42
Sleeveless/scoop-neck blouse	0.12	Double-breasted (thick)	0.48
Short-sleeve knit sport shirt	0.17	Sleepwear and Robes	
Short-sleeve dress shirt	0.19	Sleeveless short gown (thin)	0.18
Long-sleeve dress shirt	0.25	Sleeveless long gown (thin)	0.20
Long-sleeve flannel shirt	0.34	Short-sleeve hospital gown	0.31
Long-sleeve sweatshirt	0.34	Short-sleeve short robe (thin)	0.34
Trousers and Coveralls		Short-sleeve pajamas (thin)	0.42
Short shorts	0.06	Long-sleeve long gown (thick)	0.46
Walking shorts	0.08	Long-sleeve short wrap robe (thick)	0.48
Straight trousers (thin)	0.15	Long-sleeve pajamas (thick)	0.57
Straight trousers (thick)	0.24	Long-sleeve long wrap robe (thick)	0.69
Sweatpants	0.28		
Overalls	0.30		
Coveralls	0.49		

a. "Thin" refers to garments made of lightweight, thin fabrics often worn in the summer; "thick" refers to garments made of heavyweight, thick fabrics often worn in the winter.
b. Knee-length dresses and skirts
c. Lined vests

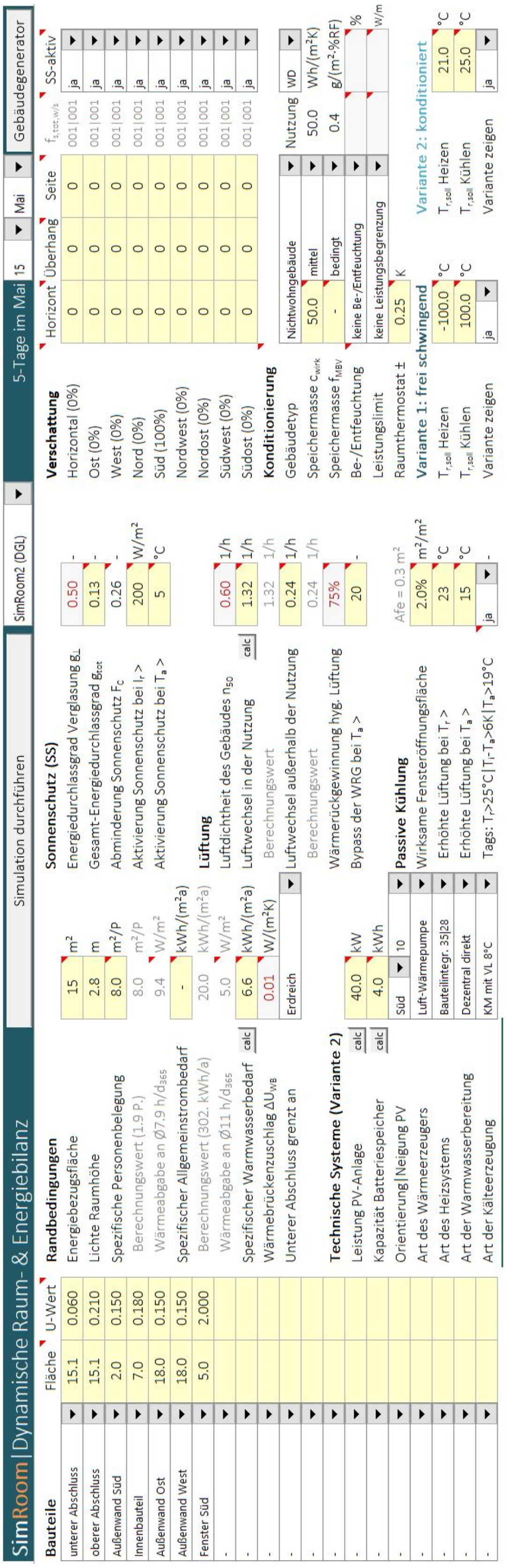
Metabolic rates for typical tasks (ASHRAE standard 2017)

Table 5.2.1.2 Metabolic Rates for Typical Tasks

Activity	Metabolic Rate Met Units	W/m²	Btu/h·ft²
Resting			
Sleeping	0.7	40	13
Reclining	0.8	45	15
Seated, quiet	1.0	60	18
Standing, relaxed	1.2	70	22
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	37
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	48
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	70
Office Activities			
Reading, seated	1.0	55	18
Writing	1.0	60	18
Typing	1.1	65	20
Filing, seated	1.2	70	22
Filing, standing	1.4	80	26
Walking about	1.7	100	31
Lifting/packing	2.1	120	39
Driving/Flying			
Automobile	1.0 to 2.0	60 to 115	18 to 37
Aircraft, routine	1.2	70	22
Aircraft, instrument landing	1.8	105	33
Aircraft, combat	2.4	140	44
Heavy vehicle	3.2	185	59
Miscellaneous Occupational Activities			
Cooking	1.6 to 2.0	95 to 115	29 to 37
House cleaning	2.0 to 3.4	115 to 200	37 to 63
Seated, heavy limb movement	2.2	130	41
Machine work			
sawing (table saw)	1.8	105	33
light (electrical industry)	2.0 to 2.4	115 to 140	37 to 44
heavy	4.0	235	74
Handling 50 kg (100 lb) bags	4.0	235	74
Pick and shovel work	4.0 to 4.8	235 to 280	74 to 88
Miscellaneous Leisure Activities			
Dancing, social	2.4 to 4.4	140 to 255	44 to 81
Calisthenics/exercise	3.0 to 4.0	175 to 235	55 to 74
Tennis, single	3.6 to 4.0	210 to 270	66 to 74
Basketball	5.0 to 7.6	290 to 440	90 to 140
Wrestling, competitive	7.0 to 8.7	410 to 505	130 to 160

6 ANSI/ASHRAE Standard 55-2017

SIMRoom input parameters



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