Human-Window Interaction in open-plan offices

Guiding occupants to improve window operation through window feedback systems

Serhan Yuksel

Title
Human-Window Interaction in open-plan offices:
Guiding occupants to improve window operation through window feedback systems

Author

Name:	Serhan Yuksel
Student number:	5461596

Date
Friday, June 16th, 2023

Graduation committee

First mentor:	Dr. A. Luna Navarro | Façade and Product design
Second mentor:	Prof.dr.ir A.C. Boerstra | Climate design
Board of examiners:	Ir. M.H. Meijs

TU Delft
Delft University of Technology
Faculty of Architecture
and the Built Environment

AR3B025_Building Technology Graduation Studio

Acknowledgements

This report will end my journey as a student of the master track Building Technology. The past period has been a great adventure filled with invaluable experiences in which I gained new knowledge and developed a diverse range of skills that will undoubtedly be helpful in future endeavours. I would like to express my appreciation to all the individuals who supported me during this period.

First and foremost, I would like to thank my first and second mentor, Alessandra Luna Navarro and Atze Boerstra. Your guidance, expertise and support throughout this journey have been invaluable and shaped my research and understanding of the subject. Moreover, your dedication and passion for your work have been a source of inspiration. I am truly grateful for your mentorship.

In addition, I would like to extend my appreciation to Pedro de la Barra whose assistance was invaluable in making the measurement setup possible. Pedro, your technical knowledge, critical insights and willingness to share your expertise have been enlightening and have played a significant role in enhancing the quality of this research. Thank you for your time and contributions.

I would also like to express my gratitude to Isabella Gaetani for her role as an external advisor. Your support and insightful feedback enriched my research journey. Thank you for your time and council.

Lastly, I want to extend my appreciation to all my friends and family for their support throughout this journey.

Abstract

Occupants are often unaware of window opening strategies that can enhance their well-being and reduce energy consumption. Window feedback systems that indicate when to manually operate a window have become a strategy for enhancing the indoor climate, occupant's satisfaction and energy efficiency. These systems are recognized for providing the comfort benefits of manual window controls while providing the efficiency benefits of completely automated windows (Bordass et al., 2007; Day et al., 2020). However, there is a lack of evidence to what extent window feedback systems are able to provide a successful cooperation between occupants and windows which enhances energy efficiency, satisfaction levels and their well-being.

This research investigated the influence that ambient light window feedback systems can have on the indoor climate and occupants' satisfaction in open-plan workplaces. The research focused on determining the effectiveness of these systems and on establishing design guidelines for further developments. To do so, an experiment was carried out which assessed an existing and new situation of an open-plan workplace. The existing situation served as a benchmark for the new situation in which an ambient light window feedback system was implemented.

The methodology is divided into two parts and consists of literature research and research by experimentation. The literature research formed the initial part of the study and provided important considerations for the experiment. In addition, it formed guidelines for designing the window feedback system. The research by experimentation part provided objective and subjective data to determine the effectiveness of the implemented window feedback system. In addition, the data helped in determining design recommendations for the further development of the window feedback system and its algorithm. The outcome of the research shows that ambient light window feedback systems can be promising inside open-plan workplaces.

Table of contents

INTRODUCTION

LITERATURE RESARCH

LITERATURE RESARCH

EXPERIMENTAL RESEARCH

CONCLUSION

REFERENCES

APPENDIX

INTRODUCTION

1 Introduction

1.1 Problem statement

Energy efficiency has been recognised as an important strategy to minimise climate change (IEA, 2022). One significant barrier for energy-efficient buildings is the lack of understanding about the real functioning of a building once it is built. The predicted energy use of buildings does frequently not match the real energy use and is caused by several factors such as the construction and weather conditions. Several studies argue that the occupant's behaviour could also be a reason for this mismatch (Buso et al., 2015; Mahdavi et al., 2021). It appears that occupants influence the energy consumption by using different interfaces such as windows, window shades, thermostats and lighting controls (Day et al., 2020).

Especially window opening behaviour can have a significant impact on the energy consumption, since it is directly related to the thermal environment, indoor air quality, energy efficiency and the occupant's satisfaction. Despite the importance of window operation, occupants are often unaware of window opening strategies that can enhance their well-being and reduce energy consumption. Both manual and automated window control have their flaws. Automated window control provides more energy efficiency but comes at the expense of occupants' comfort, satisfaction and productivity. Manual window control can provide a wider comfort band but bears the risk of inefficient energy use. A feedback system for manual window control could be a compromise in which occupants get the ability to satisfy their comfort while being informed about the impact of window operation on the indoor climate and energy efficiency to enhance their behaviour (Bordass et al., 2007; Day et al., 2020). However, there is a lack of evidence to what extent window feedback systems are able to provide a successful cooperation between occupants and windows which enhances energy efficiency, satisfaction levels and their well-being.

1.2 Objective

The objective of this research is to investigate the influence of window feedback systems on the indoor climate and occupants' satisfaction. This research will determine the effectiveness of window feedback systems and will provide design guidelines for further developments. As part of the study, a window feedback system will be developed and implemented in an open-plan workplace. Due to time constraints, the research will only focus on ambient light window feedback systems in open-plan workplaces without an air-conditioning system.

1.3 Research Questions

Main question

To what extent do ambient light window feedback systems provide energy savings, human multi-domain comfort and indoor air quality in open-plan workplaces?

Sub questions

Literature study:

1. What are the drivers for window operation?
2. What is the current evidence on window feedback systems and its impact on the indoor environment, energy efficiency and the occupants' behaviour?
3. How can we measure and evaluate the impact of occupant-window interaction strategies on energy efficiency, human multi-domain comfort and indoor air quality?

4. How can we define an algorithm that is satisfactory for energy efficiency, human multi-domain comfort and indoor air quality?

Experiment:

5. How is the energy efficiency, human multi-domain comfort and indoor air quality affected with and without a feedback system?
6. How do occupants perceive the window feedback system and its effect on the indoor environment?

1.4 Methodology

The methodology to conduct the research is divided into two parts and consists of literature research and research by experimentation. Figure 1 gives a visualisation of the approach and methodology.

1.4.1 Literature research

The literature review is the initial part of the research and will be used as the base for the experiment. It will help in identifying the most important drivers which can be used for creating a survey and the logic behind the window feedback system. The literature review will also provide important parameters to measure and evaluate during the experiment regarding energy efficiency, thermal comfort and indoor air quality. Furthermore, it will help in creating a window feedback system by providing design considerations. The experiment is only valid to start when the literature review is complete and finished.

1.4.2 Research by experimentation

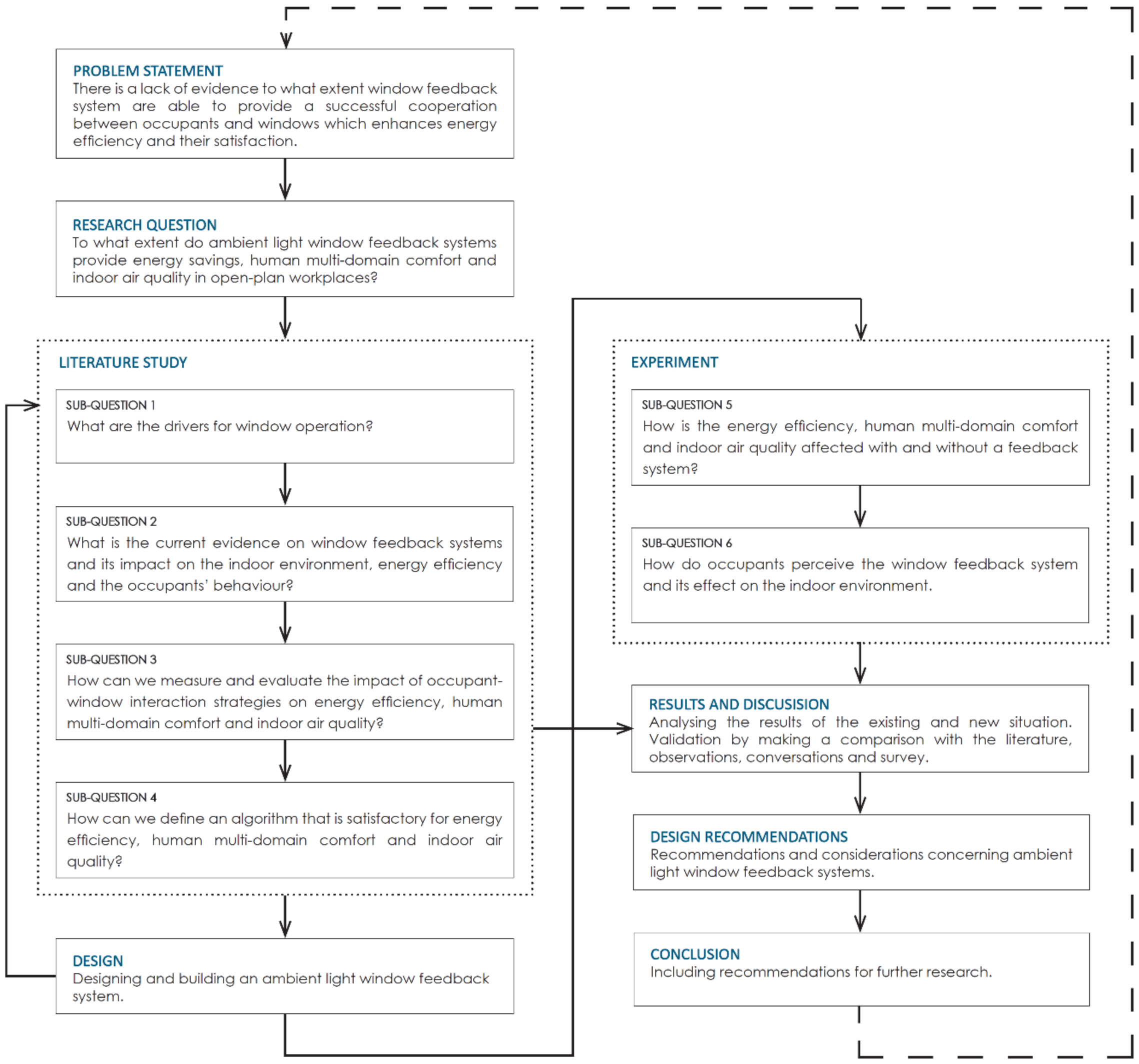
The second part of the methodology will consist of research by experimentation in which both quantitative and qualitative data will be measured. The experiment will be conducted in an open-plan workplace in which two situations will be examined and include:

1. An existing situation which serves as a benchmark.
2. A new situation in which an ambient light window feedback system is implemented.

In these two situations, both objective and subjective measurements will be conducted and include surveys, informal interviews, observations and indoor and outdoor environmental measurements. Both situations will be compared with each other to determine the influence of the window feedback system. Each situation will be conducted for 3 weeks.

The surveys will serve to identify personal factors (e.g., age, gender), reasons for window operation, the satisfaction levels of the indoor environment and the perception regarding window feedback systems. The surveys will be conducted by all the occupants to measure the average satisfaction and comfort levels. This will also help in identifying the social impact of the window operations. The outcome of the survey will be compared with the literature.

Regarding the indoor and outdoor environmental measurements, several parameters will be measured and include the indoor and outdoor air temperature, indoor carbon dioxide, indoor and outdoor particulate matter, indoor and outdoor relative humidity, window opening state and if the radiators are working. These parameters will be used to assess the thermal environment, indoor air quality, energy efficiency and window operation. The assessment will be validated by comparing the results with the literature and the outcome of the survey.



PROBLEM STATEMENT
There is a lack of evidence to what extent window feedback system are able to provide a successful cooperation between occupants and windows which enhances energy efficiency and their satisfaction.

RESEARCH QUESTION
To what extent do ambient light window feedback systems provide energy savings, human multi-domain comfort and indoor air quality in open-plan workplaces?

LITERATURE STUDY

SUB-QUESTION 1
What are the drivers for window operation?

SUB-QUESTION 2
What is the current evidence on window feedback systems and its impact on the indoor environment, energy efficiency and the occupants' behaviour?

SUB-QUESTION 3
How can we measure and evaluate the impact of occupant-window interaction strategies on energy efficiency, human multi-domain comfort and indoor air quality?

SUB-QUESTION 4
How can we define an algorithm that is satisfactory for energy efficiency, human multi-domain comfort and indoor air quality?

DESIGN
Designing and building an ambient light window feedback system.

EXPERIMENT

SUB-QUESTION 5
How is the energy efficiency, human multi-domain comfort and indoor air quality affected with and without a feedback system?

SUB-QUESTION 6
How do occupants perceive the window feedback system and its effect on the indoor environment.

RESULTS AND DISCUSISION
Analysing the results of the existing and new situation. Validation by making a comparison with the literature, observations, conversations and survey.

DESIGN RECOMMENDATIONS
Recommendations and considerations concerning ambient light window feedback systems.

CONCLUSION
Including recommendations for further research.

Figure 1: Visualisation of the research approach and methodology

LITERATURE RESEARCH

2 Literature research methodology

Different literature has been examined to get a better understanding of window feedback systems and their effect on the occupants' satisfaction and indoor climate. Depending on the desired knowledge different search queries have been used as shown in Table 1. These queries were used to search through literature databases including Scopus, Research Gate and Google Scholar. The assessment of the relevancy was based on the title, abstract, author and year. Literature based on only simulations were not assessed. In some cases, relevant literature was also found through references.

Table 1: Used search queries per topic

Topic	Search Query
Window feedback and operation	(Human OR occupant OR behaviour) AND window AND (interaction OR operation OR strategies OR efficiency) AND (building OR façade) Occupant AND Feedback AND Window AND Building
Thermal comfort	(Thermal comfort OR heat balance OR adaptive approach) AND window AND (operation OR opening OR closing OR interaction)
Indoor Air Quality	(Indoor air quality OR IAQ) AND parameters AND (indoor climate OR offices OR perception)
Energy efficiency	Energy AND (consumption OR savings OR efficiency) AND window AND (opening OR closing OR operation OR behaviour)

The search queries resulted in 42 sources regarding window feedback and operation. From these sources only six case studies were found related to window feedback and were assessed by 11 sources. More literature was found regarding the drivers and motivation of window operation with a total of 16 sources which includes two literature reviews. Other sources were related to window control.

31 sources were found regarding thermal comfort and indoor air quality and served primarily as background knowledge. These sources provided a better understanding of how to measure and evaluate these domains of the indoor environment.

3 Existing studies window feedback

In chapter 2: Literature research methodology, it was shown that the found number of studies related to window feedback is limited. The search queries resulted in the finding of six studies that are more or less relevant for this thesis. This chapter will discuss the methodology, findings and limitations of these studies to get a better understanding of the state-of-the-art.

3.1 Window signalling systems (Ackerly & Brager, 2013)

Ackerly and Brager (2013) did a field study in 16 buildings in the US to understand why and how window feedback signals are implemented, and to investigate the extent in which window signalling systems influence the occupants' behaviour and response. The research was conducted through surveys, interviews and observations in which the survey had 604 respondents with a response rate of at least 60%. The data collection was not supported with objective measurements to validate the survey results and limits this research.

Based on the results, Ackerly and Brager (2013) concluded that a majority of the occupants typically disregard the signals because they generally feel comfortable and easily overlook the signals. This conclusion is understandable when the different buildings are examined more closely since most of the window signal devices were not placed effectively, as shown in Figure 2. So, the conclusion from Ackerly and Brager (2013) doesn't necessarily argue against the effectiveness of window feedback.

The research is relevant for this master thesis since it notes important considerations for designing and implementing window feedback devices, as discussed in section 5.2. In addition, this research is one of the few studies that provide an understanding of occupants' reasoning for window operation.

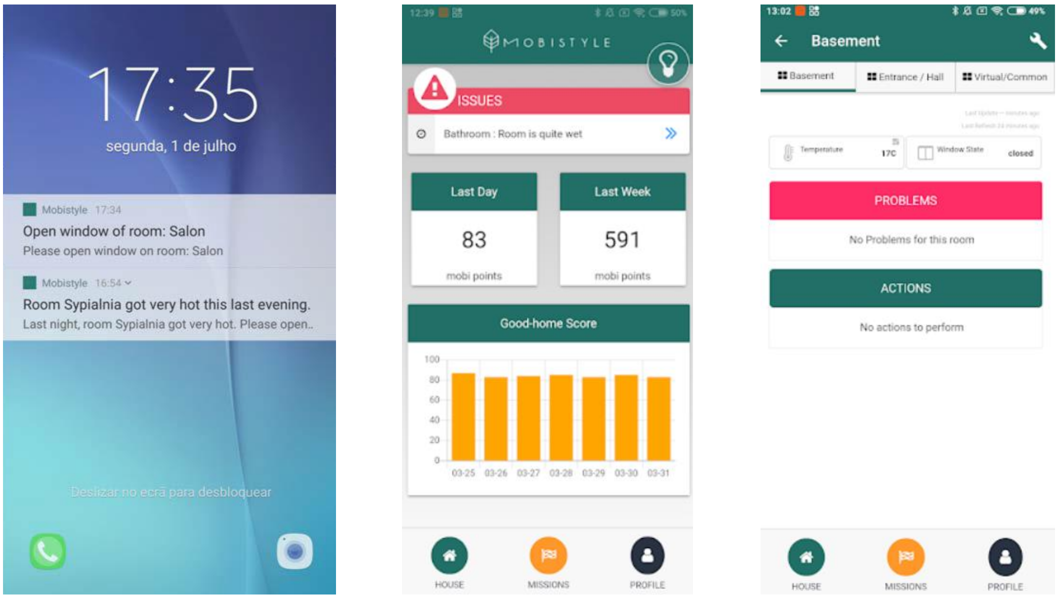
Figure 2: Encountered signalling devices by Ackerly and Brager which are not placed effectively and are easily overlooked when working. The shown signalling devices are placed far from the window and/or on the opposite side of the window (Ackerly & Brager, 2011)

3.2 MOBISTYLE

Mobistyle is a project which is developed to provide occupants with personalised feedback on energy use, indoor environment, health and lifestyle by using ICT-based solutions. The overall aim is to enhance energy efficiency and indoor environmental quality by investigating how behavioural change of occupants can be stimulated with feedback. As part of this project a dashboard and a game were developed and tested in several case studies. Some of these case studies were also related to window operation and will be discussed in this section.

3.2.1 Game interface

The game interface consists of a mobile application and several sensors that can measure different indoor environmental conditions such as indoor temperature, humidity, CO_2 and window state. The sensors are used to track the occupants' actions and to judge the indoor environmental quality in order to provide the occupants with goals and missions. These goals and missions are provided through notifications and serve to create good behaviour that enhances the indoor climate and energy savings. In addition, the game interface encourages good behaviour by rewarding it with 'MobiPoints' which can be compared with other users (Mobistyle, 2019). Figure 3 gives a visualisation of the game interface.



Mobistyle 17:34
Open window of room: Salon
Please open window on room: Salon

Mobistyle 16:54
Room Sypialnia got very hot this last evening.
Last night, room Sypialnia got very hot. Please open..

Bathroom : Room is quite wet

No Problems for this room

No actions to perform

Figure 3: Visualisation game interface Mobistyle (Mobistyle, 2020b)

The game interface was developed to be used in residential buildings and was tested in two case studies which are located in Denmark and Poland. The latter didn't measure enough parameters (temperature and relative humidity) to create a better understanding of window feedback, this is why only the Danish case study will be discussed (Mobistyle, 2020b).

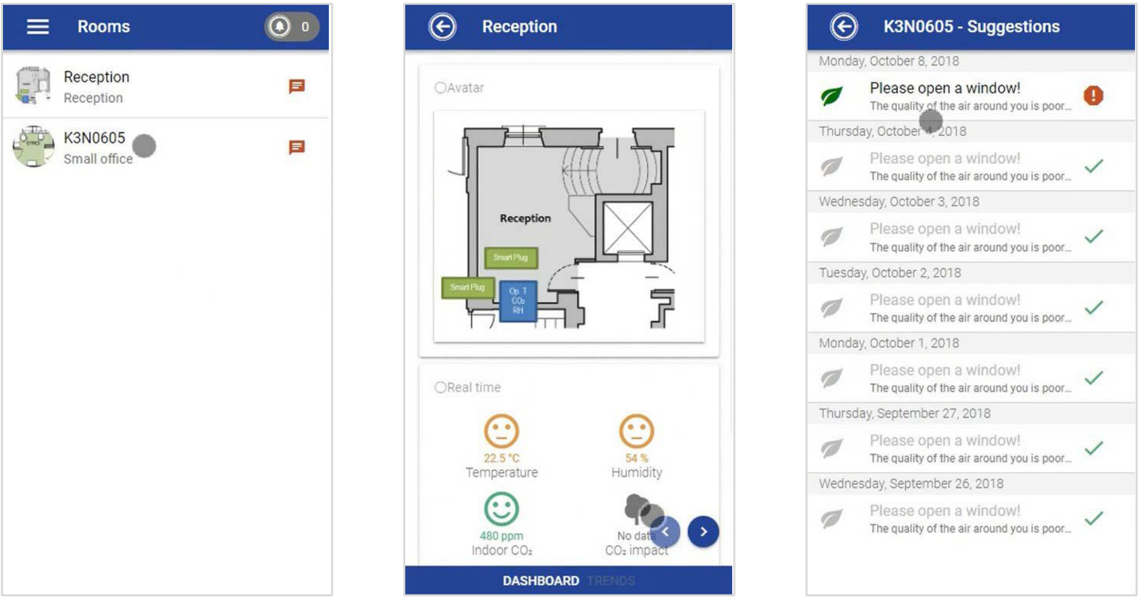
The case study in Denmark tested the game interface in 17 apartments which varied in size from 67-130 m^2 and in occupancy between 1-5 persons. The study measured besides the indoor environmental conditions also the energy consumption related to heating and domestic hot water usage. The experiment lasted two years in which the first year served as a benchmark and the second year for the new situation with the Mobistyle interface. It should be mentioned that the game interface did not work as desired during the new situation since the feedback was always delayed by 45 minutes. The results of the case study show that in the new situation the indoor environmental quality was improved while the energy use was increased. The collected data showed the following:

- The CO_2 concentration was decreased by an average of 417 ppm;
- The temperature was decreased by an average of 0.5ºC;
- The window opening time increased by an average of 3% - 6%
- The relative humidity was kept quite similar;
- The energy use for heating was increased by an average of 6,4%;
- The energy use for hot water was increased by an average of 12%.

This seems to indicate that the indoor air quality was improved at the expense of energy savings, which implies that occupants value the feedback about indoor air quality more than about energy efficiency. However, this is not proven by subjective measurements such as surveys and interviews (Mobistyle 2020a; Mobistyle, 2020b).

3.2.2 Dashboard

The dashboard interface was initially developed to show different parameters of the indoor environmental quality in one platform through different sensors and an application. In the further development, it also incorporated a notification function and made the interface more user-friendly. Figure 4 gives a visualisation of this interface.



Monday, October 8, 2018
Please open a window!
The quality of the air around you is poor...

Thursday, October 4, 2018
Please open a window!
The quality of the air around you is poor...

Wednesday, October 3, 2018
Please open a window!
The quality of the air around you is poor...

Tuesday, October 2, 2018
Please open a window!
The quality of the air around you is poor...

Monday, October 1, 2018
Please open a window!
The quality of the air around you is poor...

Thursday, September 27, 2018
Please open a window!
The quality of the air around you is poor...

Wednesday, September 26, 2018
Please open a window!
The quality of the air around you is poor...

Figure 4: Visualisation dashboard interface MOBISTYLE (MOBISTYLE, 2019)

The dashboard was developed to be used in commercial settings and was tested in two case studies which are a hotel in Italy and a university in Slovenia. The former will not be discussed since the number of guinea pigs was too small, only one hotel guest and a limited number of employees had tested this interface (Mobistyle, 2020b).

The Slovenian case study was conducted inside 4 faculty buildings of the Ljubljana university. All of these buildings had a similar typology and users. Mobistyle (2020b) only described the data of the faculty of Chemistry and Chemical Technology (FKKT) and used the other faculty buildings as a verification and generalisation of their findings. This is why only the study of the FKKT will be described.

Inside the FKKT, 8 offices were measured which were used by teaching staff, researchers and technical staff. In each room an award-winning INAP sensor was placed that could measure the temperature, relative humidity, CO_2 and VOC. In addition, the sensor could show the quality of these parameters through a light indicator, as shown in Figure 5. Besides the measurements of the INAP sensor, the window state, outdoor temperature, outdoor relative humidity, solar illuminance and the efficiency of the HVAC were also measured. The experiment lasted two years in which the first year served as a benchmark and the second year for the new situation with the Mobistyle dashboard. During the second year a campaign was also implemented to promote the use of the dashboard.

Figure 5: Award-winning INAP sensor with a light indicator (Mobistyle, 2020b)

The results of the case study show that in the new situation the energy use was improved while the indoor environmental quality became worse. The exact opposite from the case study in Denmark. The collected data showed the following:

- The CO_2 concentration was increased by an average of 300 ppm;
- The window opening time decreased by an average between 28 – 37%;
- The temperature stayed quite similar by an average decrease of 0.04°C;
- The air conditioning use was decreased by an average of 13%;
- The relative humidity was kept quite similar;

From this data it stands out that in the new situation the CO_2 concentration is increased and the window opening time is decreased. However, both can be explained by the air conditioning system that stops when the windows are opened. This can also be deduced by Figure 6 which shows the overall measured CO_2 concentration and Figure 7 which shows the window opening time during the cooling season. This conclusion implies that occupants value their comfort more than energy efficiency and indoor air quality (Mobistyle 2020a; Mobistyle, 2020b).

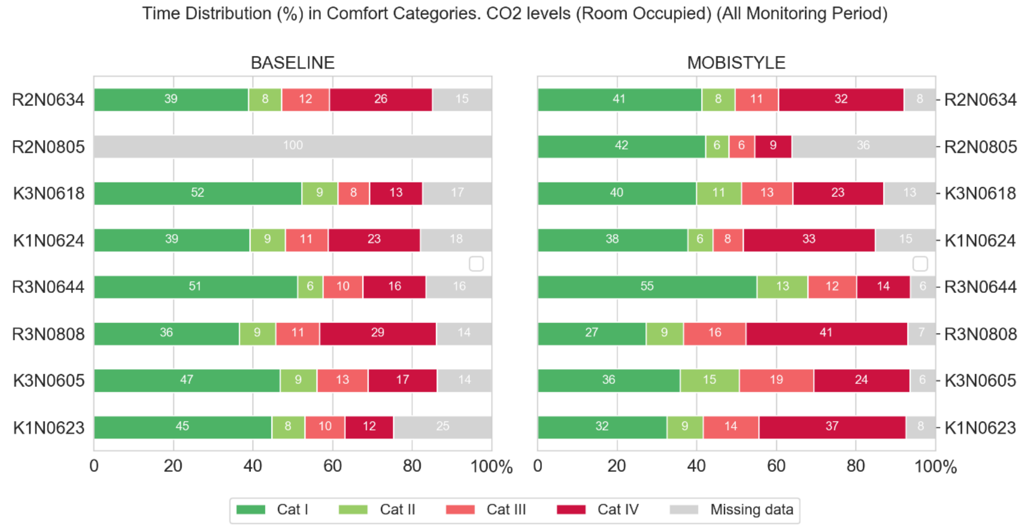


Figure 6: Overall measured CO_2 concentration (Mobistyle, 2020a)

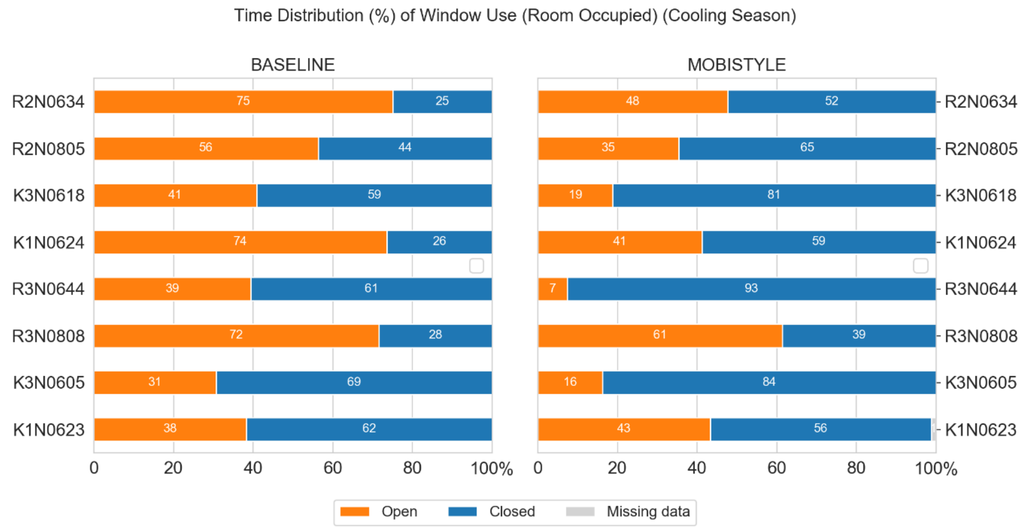


Figure 7: window opening time during the heating and cooling season (Mobistyle, 2020a)

3.3 CO₂ sensors

Avella et al. (2021) did a field study in four schools in Italy to understand how a light indicator affects the window operation which is based on the CO_2 concentration, air temperature and relative humidity. The schools differed in education level and included a kindergarten, a secondary school and two high schools. In each school two classrooms were measured in which one of the two served as a benchmark without a signalling device. The experiment lasted for 3 weeks and was repeated twice. In addition to the aforementioned parameters, the window state was also measured. It should be noted that the measurements were conducted during the COVID-19 pandemic and affected the results of classrooms in the high schools. The pandemic resulted in a lower occupancy halfway through the experiment and limited the possibility of comparing the results. This is why only the results of the secondary school and kindergarten can be discussed (Avella et al., 2012).

The study showed that the light indicator was effective for the secondary school. The signalling device resulted in a decrease of CO_2 concentration with a reduction of 28%. It also resulted in a decrease of window operation by 50%, implying that the window operation was more effective. The study also showed that the device had no effect for the kindergarten despite the high CO_2 concentrations inside the classrooms. This is probably due to the young age of the pupils and the busy schedule of the teacher which resulted in a lower interaction with the device. It should be mentioned that the study also conducted informal interviews with the teachers and school staff to get a better understanding of the results and usability of the device. However, it didn't do subjective measurement to understand the reasoning for window opening which forms a limitation for this study (Avella et al., 2021).

3.4 Overview studies

This chapter explained the methodology, findings and limitations of the found studies related to window feedback systems. A total of six studies were found in which two were not useful due to the small test group and the limited number of measured parameters. The other studies were found relevant but had limitations regarding the contextual factors, a summary of these studies is provided in Table 2.

Table 2: Summary of existing studies related to window feedback system that has been found relevant

	Window signalling systems (Ackerly & Brager, 2013)	**Apartments, Denmark (Mobistyle, 2020b)**	**University, Slovenia (Mobistyle, 2020b)**	**Schools, Italy (Avella et al., 2012)**
Interface	Light indicator	Game interface + notification	Dashboard + notification & light indicator	Light indicator
Methodology *Measurements:* *Building type:* *Period:*	Subjective 16 office buildings -	Objective 17 apartments 2 years	Objective 4 faculty buildings 2 years	Objective 4 schools 6 weeks
Limitations	The visibility of the light indicators was in several buildings limited	Delay in the feedback of 45 minutes	Occupants' behaviour was affected by the AC system that stops when the windows are opened	COVID-19 pandemic, the young age of the test group, not measuring energy efficiency
Parameters	-	T_{in}, relative humidity, CO_2, window state, energy use heating + hot water	T_{in}, T_{out}, relative humidity, CO_2, VOC, solar illuminance, window state, HVAC efficiency	T_{in}, relative humidity, CO_2
Findings	Occupants' reasoning for window operation Considerations for designing and implementing window feedback devices generic values like 'saving energy' seldom motivate occupants to change their behaviour	Indicates that indoor air quality was improved at the expense of energy savings	Implies that occupants value their comfort more than energy efficiency and indoor air quality	Improved the air quality and reduced the window operation

3.5 Conclusion

The studies that have been found relevant, suggest that occupants value their comfort more than energy efficiency and indoor air quality. None of these studies conducted both objective and subjective measurements to validate the results. Only one study was found that conducted subjective measurements to identify the occupants' reasoning for window operation. Two of the four studies measured the energy consumption but had their limitations as shown in Table 2. These studies were not able to provide strong evidence regarding the energy efficiency of window feedback systems. None of these studies compared the effectiveness of different window feedback system interfaces such as light indicators and dashboards.

4 Drivers of window operation

According to Buso et al (2015), occupants of a building tend to act according to the adaptive approach theory which is defined as “If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort”. However, this adaptive behaviour can have a negative effect on the indoor climate. Especially window operation can have a big impact on energy consumption, indoor air quality and human comfort. In order to improve window operation, it is important to understand which factors influence window opening behaviour and how this relates to the reasoning and actions of the occupants. Both will be explained in this chapter.

4.1 Drivers

Factors that influence the occupant’s behaviour are also named ‘Drivers’ since these factors drive the occupant to an action. A distinction can be made between external and internal drivers. External drivers relate to physical environmental and contextual aspects. Internal drivers relate to psychological, physiological and social aspects (Fabi et al., 2012). According to the literature review of Liu et al. (2022) significantly fewer studies have been carried out on the internal drivers than the external drivers since it is harder to quantify and to find representative indicators. In the following, factors are given for each aspect of the external and internal drivers (Fabi et al., 2012).

4.1.1 External drivers

<u>Physical environmental:</u>
physical conditions. Examples of drivers are outdoor temperature, indoor temperature, humidity, air velocity, CO_2 concentrations, $PM_{2.5}$ concentrations, solar radiation, noise and odour (Day et al., 2020; Fabi et al., 2012; Liu et al., 2022).

Among all the physical environmental drivers, the outdoor temperature and indoor temperature are the most influential ones for window opening and closing behaviour (Day et al., 2020; Fabi et al., 2012; Liu et al., 2022). This is also according to the literature review of Liu et al. (2022) in which the limitations of research on occupants’ window opening behaviour were investigated. The research shows that the indoor temperature and outdoor temperature are the most associated drivers with window opening behaviour in existing literature, as can be seen in Figure 8. Furthermore, Warren and Parkins (1984) found in a field study of five naturally ventilated office buildings in the UK that the outdoor temperature explained 76% of the window operation. In addition, different studies show that window opening is the highest in summer, lowest in winter and intermediate in autumn and spring. However, some researchers question whether this variation is due to the difference in outdoor temperature or by the ‘season’ itself (Fabi et al., 2012; Liu et al., 2022).

Other important drivers, with a less significant influence, are CO_2 concentrations, $PM_{2.5}$ concentrations, relative humidity, air velocity and solar radiation (Day et al., 2020; Fabi et al., 2012). The first two drivers are important parameters for quantifying indoor air quality which appears to be a main reason for opening windows. However, most studies didn’t find a significant correlation between CO_2 concentrations or $PM_{2.5}$ concentrations and window opening behaviour (Liu et al., 2022). Relative humidity has an indirect effect on the window opening behaviour since humans are insensitive to relative humidity between a range of 30% to 70%. However, it does affect the thermal sensation of humans which can influence the opening/closing behaviour of occupants (Fabi et al., 2013). Air velocity is an important driver for closing windows, since the sensation of draft produces discomfort. In a field study to residential buildings, all the windows were closed at wind speeds above 8 m/s. Finally, it should be mentioned that solar radiation is closely related to the outdoor temperature and indoor temperature. However, studies didn't find a direct correlation between solar radiation and window opening behaviour (Fabi et al., 2012).

Contextual

This aspect refers to the external surroundings and has an indirect influence on the occupant. Examples of drivers are installations (HVAC), thermal mass, opening and closing of interior doors, design of the building envelope, rainfall, occupancy and the function of the building (Day et al., 2020; Fabi et al., 2012; Liu et al., 2022; Yun & Steemers, 2008).

Another driver is the window design itself. Characteristics such as the window size, the location within the façade, the shape, the window opening type and the opening angle influence the occupant's interaction and its affect on the indoor air quality (Day et al., 2020). Concerning the window opening type, it appears that occupants use small open windows and large open windows differently. Small open windows are mainly used to satisfy indoor air requirements and are less frequently opened, but remain open for a longer period. Large open windows are mainly affected by the outdoor temperature and solar gain and are opened more frequently, but for a shorter period (Fabi et al., 2012). Also the distance from the window to the occupant's workplace effect the human-window interaction. Occupants that sit farther away from the window have a lower perceived control and will most likely use the window less often (Boerstra, 2016). Other drivers are the window safety and façade orientation. It appears that security is the main reason for closing windows in offices. When safety can be ensured, occupants will most likely make use of night ventilation to create a more comfortable thermal climate during the summer period. The façade orientation is closely related to the amount of solar radiation and therefore to the indoor temperature (Liu et al., 2022).

4.1.2 Internal drivers

Psychological

This aspect refers to the human mind. Examples of drivers are the tendency of occupants to satisfy their needs (thermal comfort, acoustical comfort, health, safety, etc.), expectations and concerns they have (expectations about the indoor climate, financial concerns, etc.), habits, lifestyle and the knowledge they have (Fabi et al., 2012).

Concerning habits and lifestyle, most studies in offices have shown that window operation is often driven by the schedule of arrival and departure. Most of the occupants will open the window at arrival and close the window at departure unless a state of discomfort arises in between. As mentioned before, occupants act according to the adaptive approach theory in which they only take action when they perceive discomfort. As a result, window actions between arrival and departure are relatively low (Day et al., 2020; Liu et al., 2022; Yun & Steemers, 2008;). Concerning knowledge, it appears that some people open the windows at the same time everyday regardless of the physical environment. This behaviour is driven by the knowledge that opening a window everyday helps with creating a better indoor air quality (Fabi et al., 2012).

Physiological

This aspect refers to how humans function. Examples of drivers are age, gender, health, clothing, activity level and intake of food and beverages (Fabi et al., 2012).

Concerning age, research has shown that elderly people operate the window differently than younger people, since they ventilate much less (Fabi et al., 2013). Gender can also influence the window opening and closing behaviour of occupants. A survey which was taken in office buildings in the USA showed that females feel to have less control over the indoor environment than males (Amasyali & El-Gohary, 2016). Another research by Schweiker et al. (2016) suggests even that personality traits could influence the window opening and closing behaviour of occupants. However, the research didn't consider other explanations than personality traits and the conclusions of the research are therefore questionable.

Social

This aspect refers to how the behaviour of an occupant is affected by others. Different studies have shown that the window operation behaviour in offices is affected by social norms and interrelationships between co-workers. This includes besides window operation also for example the social norms around what kind of clothing is appropriate (Day et al., 2020, Fabi et al., 2012). When looking at the existing literature, there seems to be in particular a lack of knowledge about the social impact a window action can have. No literature has been found that has measured the satisfaction levels of all the occupants after the window operation by one occupant.

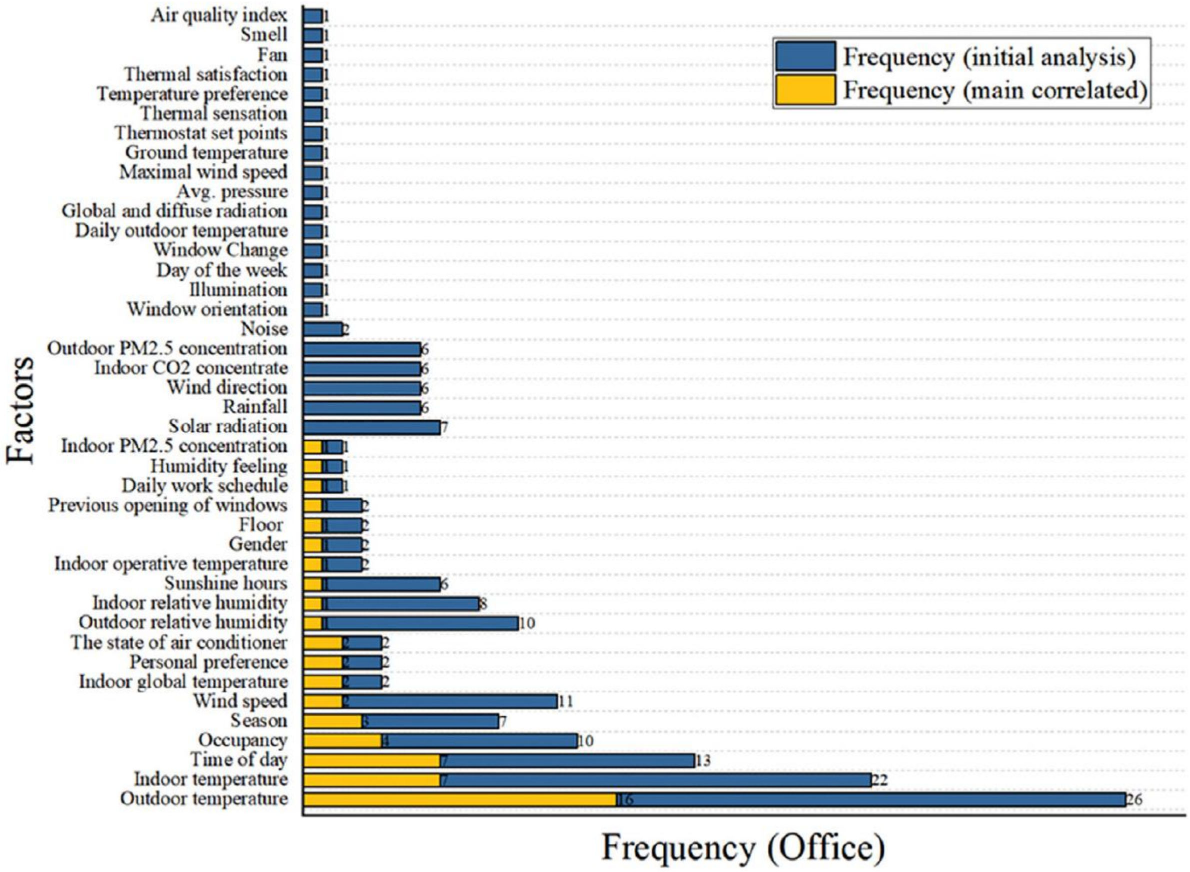


Figure 8: Frequency of factors associated with window opening behaviour in offices in the existing literature by Liu et al. (2022)

4.1.3 Overview of drivers

Table 3 shows the most important drivers that affect the window opening behaviour in offices. The table makes a distinction between external and internal drivers. The former includes drivers related to physical and contextual factors. The latter includes drivers related to psychological, physiological and social factors

Table 3: Drivers that have a significant affect on the window opening behaviour in offices

External		Internal		
Physical	**Contextual**	**Psychological**	**Physiological**	**Social**
Outdoor temperature Indoor temperature Air velocity Relative humidity Solar radiation CO_2 concentration $PM_{2.5}$ concentration Outdoor noise	Occupancy Window Design Distance to façade Façade orientation Thermal mass Safety/security Installations (HVAC) Interior doors Rainfall	Expectations Concerns Habits Lifestyle/schedule Knowledge/education Perceived control Stress	Age Gender Health Clothing Activity level Food and beverages	Social norms Interrelationships

4.2 Reasons for window operation

Occupants react consciously or unconsciously to the internal and external drivers in order to restore their comfort conditions. When the right comfort conditions have been created in a work environment, occupants become more productive which is beneficial for the employer (D'Oca et al., 2017).

Fabi et al. (2012) made a diagram in which the relation between the drivers and action scenarios can be seen, as shown in Figure 9. The diagram shows that drivers affect the occupant 'stimulus' which results in a reason to open or close a window. The main reasons for window opening are to have more fresh air and to 'keeping cool' during summer (Warren & Parkins, 1984). This is in agreement with the field study of Ackerly and Brager (2013) in which 604 occupants were surveyed. In addition, this research shows that an increased air movement and a connection with the outdoors are other important reasons for window opening. Rain, wind and heat loss appear to be important factors for window closing (Fabi et al., 2012).

A reason that occupant mainly don't consider in offices are energy savings (Amasyali & El-Gohary, 2016). This is in agreement with the field study of Boerstra (2016) in which 80% of the respondents indicated not to take energy effects into account when using their controls such as thermostats and operable windows. This is most likely because employees don't have to pay the bill.

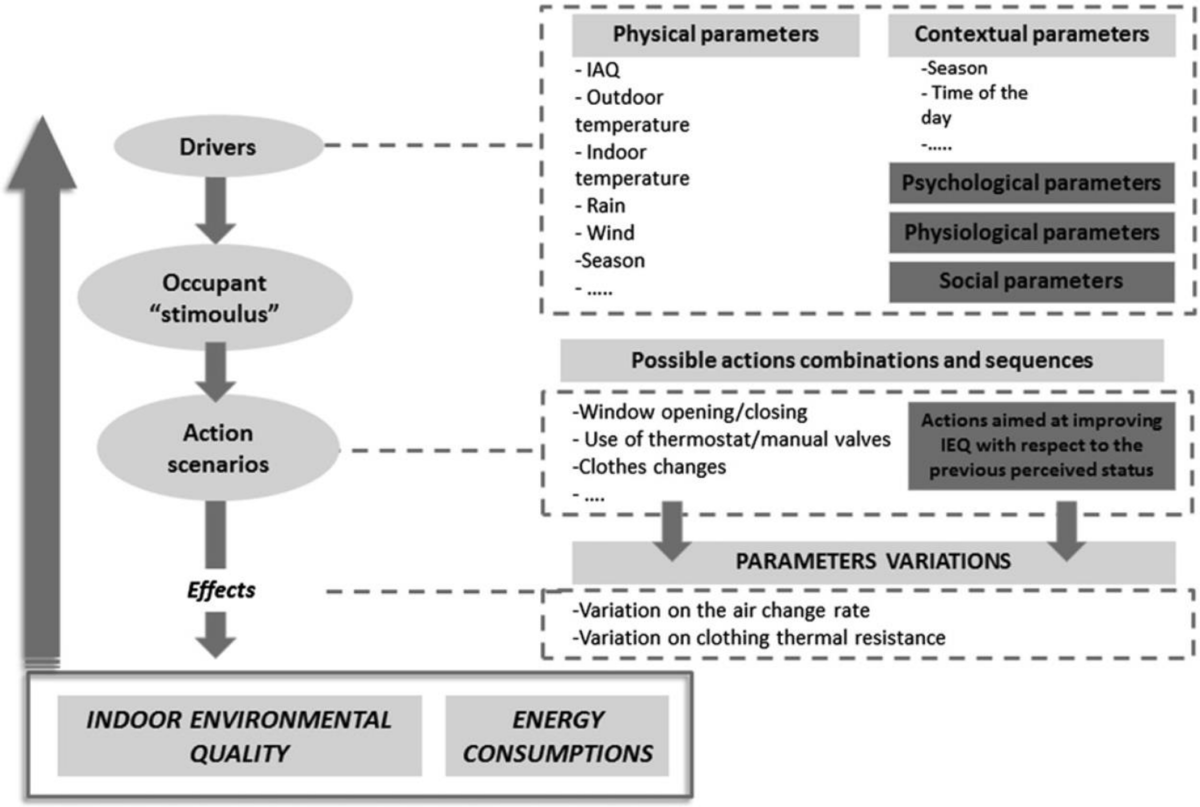


Figure 9: Diagram from drivers to energy consumption and the indoor environment by Fabi et al. (2012)

4.3 Conclusion

This chapter explained which factors influence window opening behaviour and how this relates to the reasoning and actions of occupants. As a conclusion, Table 3 shows the most important drivers that affect the window opening behaviour in offices. It appears that among all the physical environmental drivers, the outdoor temperature and indoor temperature are the most influential ones for window opening and closing behaviour (Day et al., 2020; Fabi et al., 2012; Liu et al., 2022).

The most common reasons for window opening are to have fresh air, to create a cooler indoor environment, to create an increased air movement and to have a connection with the outdoors (Ackerly & Brager, 2013; Warren & Parkins, 1984). Rain, wind and heat loss appear to be important factors for window closing (Fabi et al., 2012). It is important to note that occupants, mainly don't consider energy savings in offices (Amasyali & El-Gohary, 2016; Boerstra, 2016).

Finally, significantly fewer studies have been carried out on the internal drivers than the external drivers since it is harder to quantify and to find representative indicators (Liu et al., 2022). There seems especially to be a lack of evidence concerning the social drivers.

5 Window control and feedback

As mentioned in the previous chapter, there are many factors that drive occupants to interact with openable windows which can result in energy losses. Informed and intentional window operation can help in achieving energy savings and a better indoor climate. The design of window interfaces and the corresponding feedback could play an important role in this. Think for example about a window interface and feedback that could reduce the need for mechanical installations (HVAC) by enhancing the efficiency of window operations. To achieve this, it's important to understand how the window control and feedback relate to the human behaviour. Both will be explained in this chapter.

5.1 Control

For openable window controls, a distinction can be made between fully manual and completely automated windows. Manual windows require occupants to function, while completely automated windows function by using technologies in which occupants don't have the possibility to override the system. The latter is able to collect data which can be used to create a more energy efficient building. However, a completely automated window comes at the expense of occupant's comfort, satisfaction and productivity. This is because of the occupant's inability to open and close windows as desired (Day et al., 2020). Some of the common shortcomings of completely automated windows mentioned by occupants are (Ackerly et al., 2011):

- draughts that are caused by window opening to remove heat on cool days;
- The lack of ability to close windows which are letting in insects or noise;
- The lack of ability to trade off between different types of discomfort such as overheating versus a higher noise level.

As the aforementioned suggests, occupants prefer to maintain a certain level of manual control in which they can change the indoor environment and satisfy their comfort. This is one of the reasons why manual windows play an important role in the adaptive approach theory. This theory suggests that occupants have a wider comfort band when they have direct control over their environment. In addition, manual windows have several characteristics that are beneficial for the perceived control of the environment. They are easy and intuitive to use, have a clear purpose, are easy to access and give direct result/feedback to the window operation. The latter often becomes clear when there is a cooling requirement in a space. Instead of lowering the thermostat, occupants prefer to open a window to lower the temperature. This is because of the delayed effect of the thermostat in which the occupants don't experience a direct improvement in their comfort, leading to energy waste (Bordass et al., 2007; Day et al., 2020).

Manual window control by occupants bears the risk of inefficient energy use, which puts unpredictable and unnecessary extra load on the HVAC installations. This risk of extra load on the installations becomes more significant in buildings that lack thermal mass to prevent fluctuations of the temperature. Occupants are unlikely to respond early and frequently enough to prevent these extra loads while maintaining their comfort levels. This is mainly because occupants aren't knowledgeable about the impacts of the window operation on the indoor environment. Window feedback could help in creating more energy efficient and comfortable buildings, as explained in the next section (Ackerly et al., 2011; Day et al., 2020).

5.2 Feedback

Manual window opening with feedback functions as a compromise between completely manual and automated windows. Occupants get the ability to satisfy their comfort while being informed about the impact of the window operation on the indoor climate and energy efficiency to enhance their behaviour. The information can be expressed by feedback mechanisms such as indicator signals, dashboards and real-time monitors. Other kinds of feedback are the experienced outcomes of the window operation by the occupants and the communication between persons (Day et al., 2020). This section focuses primarily on understanding the interaction between occupants and feedback mechanisms. It appears that window feedback has the most influence when it is clearly visible, the logic behind it is understandable and when it is linked with motivational factors that promote comfort and energy efficiency (Ackerly & Brager, 2013).

5.2.1 Occupant engagement

Window feedback could play an important role in the perception, interaction and engagement with the sustainability strategies in buildings. It influences, in combination with the drivers and the context of the interface, how occupants control the window. The resulting window operation changes the indoor environment and energy efficiency which can be experienced by the feedback of the space and/or interface. A visualisation of this engagement is given in Figure 10 (Day et al., 2020; Ackerly et al., 2011).

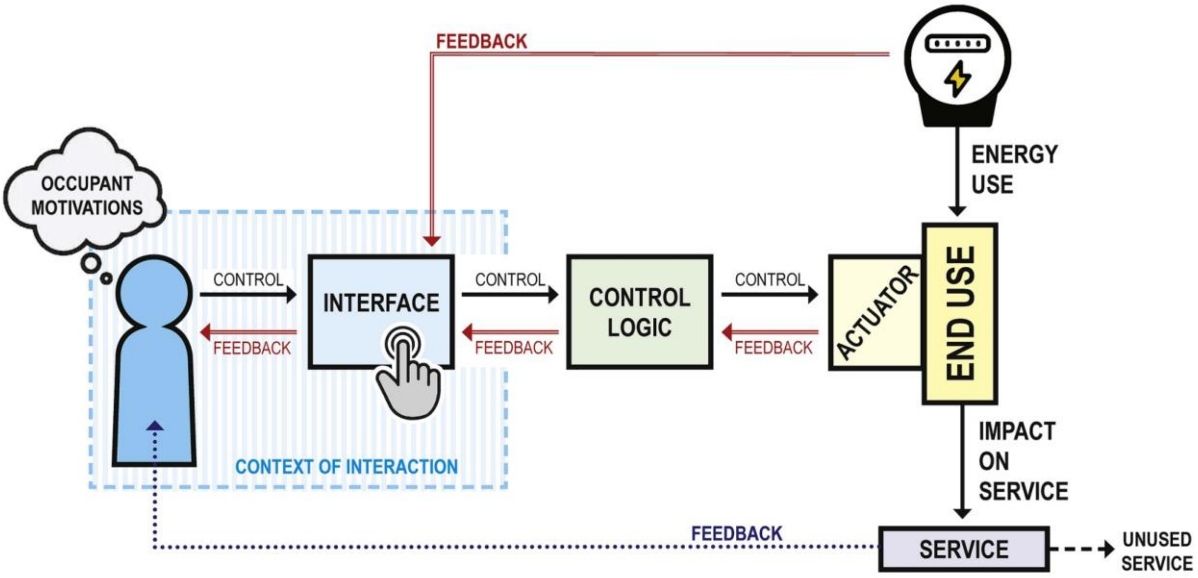


Figure 10: Conceptual model for understanding the occupant engagement with building interfaces by Day et al. (2020)

5.2.2 Visibility

A visible window feedback system functions as a reminder for the window operation and acts as a 'neutral third party' between occupants that have different preferences in window state (Ackerly & Brager, 2013). Abrahams et al. (2005) did a review of 38 field studies in which an energy monitor was used in different households. She concluded that education itself is not enough to change behaviour without a device to act as a reminder. However, it appears that occupants have the tendency to ignore the feedback from a device until they are uncomfortable, at which it matters little what the signal indicates.

Ackerly and Brager (2013) did a field study in 16 buildings in the US to investigate the extent in which window signalling systems influence the occupants' behaviour and response. They concluded that a majority of the occupants typically disregard the signals because they generally feel comfortable and easily overlook the signals. During their field study they encountered different window signalling designs, as shown in Figure 11. Note that in some cases the window signalling system were easily overlooked because of the placement in the room. A good example is Figure 12 in which the signalling system is attached to the ceiling and far from the window. In another case, see Figure 13, the window signalling system did consist out of a computer taskbar icon. Although this solution is highly accessible and low cost, the occupants indicated that it was easily overlooked because of the other desktop icons. The occupants also mentioned that they would react more to the signals if they had direct visual access.

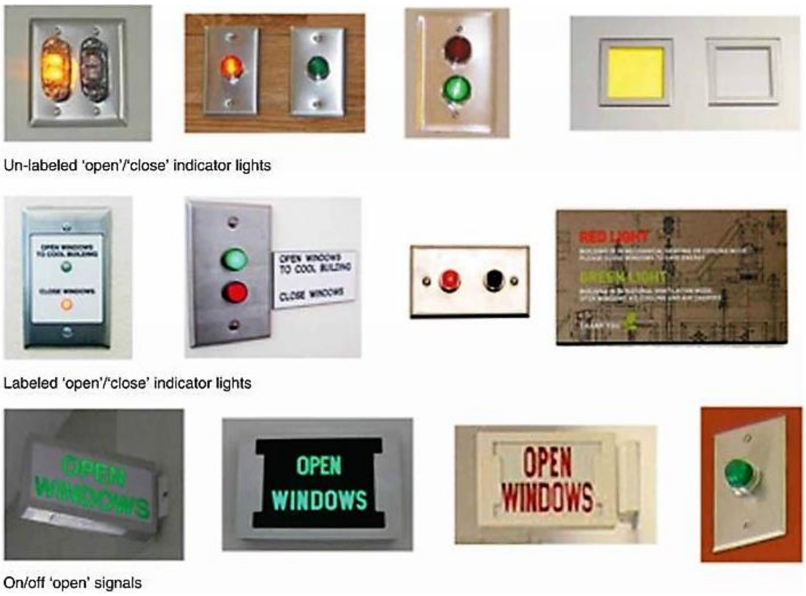


Figure 11: Different types of window signalling systems by Ackerly and Brager (2013)

Figure 12: Window signalling system that is easily overlooked (Ackerly & Brager, 2011)

Outside temp is too cool to open the windows: 50° F

1:34 PM

Figure 13: Computer taskbar icon as window signalling system (Ackerly & Brager, 2011)

Besides visibility, occupants are also affected by the kind of display a window signalling system has. Depending on the technical knowledge of occupants, people prefer more or less detailed information on a display. Occupants with more technical knowledge are likely to prefer a monitor with 24-hour display of data. On the other hand, occupants with less technical knowledge are likely to prefer a light signalling device that has a simple and clear message. Finally, the type (parameters, units) and frequency of the feedback display should also be considered (Ackerly et al., 2011; Fabi et al., 2013).

5.2.3 Understandable

It's likely that the window operation feedback will not always coincide with the comfort levels of the occupants due to the limited number of drivers that are taken into account and/or the underlying design intent (energy savings). This also becomes clear in the field study of Ackerly and Brager (2014) in which the occupants indicated that the window feedback was not always the same as their own sense of opening and closing windows. This difference can be explained by the simple algorithms that were used for the window feedback systems. Most of the algorithms were only based on the outdoor temperature, which is not sufficient enough to take the indoor comfort into account. In a few cases additional drivers such as CO_2, humidity and wind speed were taken into consideration.

In order to be able to make rational decisions, it is for occupants important to understand the underlying logic of the window feedback. There are several ways to make this logic clear to the occupants. It can be by a well thought window interface design in which occupants rely on their own notice and/or by an explanation from an office manager. For the latter, it should be noted that frequently send e-mails could be seen as spam and ignored. Instead, it is recommended to arrange personal discussions with the office manager (Ackerly & Brager, 2013).

5.2.4 Motivational factors

Occupants in commercial settings are less likely to act in order to save energy consumption since they don't benefit from the energy campaigns defined by the top level of the organisation (Barthelmes et al., 2018). It has been found that generic values like 'being green' or 'saving energy' seldom motivate occupants to change their behaviour (Ackerly & Brager, 2013). Therefore, it is important to involve motivational factors along the window feedback system to stimulate good behaviour. A field study about energy feedback showed that occupants with feedback and additional goals save on average approximately 20% more energy (Fabi et al., 2013).

Occupants could be motivated by starting a competition among colleagues or by using computer games to educate people on how to save energy in an enjoyable manner (Fabi et al., 2016). Another example is provided by researchers at Carnegie Mellon University. They created a virtual polar bear on an ice floe that shrinks with poor energy choices and grows with energy efficient behaviour. The study showed that occupants were more likely to save energy when occupants formed an emotional attachment with the polar bear (Fabi et al., 2013).

5.3 Conclusion

For openable window controls, a distinction can be made between fully manual and completely automated windows. Automated windows are more energy efficient but come at the expense of occupants' comfort. Manual windows can provide a wider comfort band but bears the risk of inefficient energy use. Manual window opening with feedback could function as a compromise between completely manual and automated windows. Occupants get the ability to satisfy their comfort while being informed about the impact of the window operation on the indoor climate and energy efficiency to enhance their behaviour (Day et al., 2020). It appears that window feedback has the most influence when it is clearly visible, the logic behind it is understandable and when it is linked with motivational factors that promote comfort and energy efficiency (Ackerly & Brager, 2013).

6 Thermal Comfort Parameters

The indoor climate is a dynamic environment in which occupants try to maintain their thermal comfort by keeping their body around a core temperature of 37 °C. Window operation can have a significant impact on thermal comfort which is defined by ASHRAE 55 as "that condition of mind that expresses satisfaction with the thermal environment". Understanding thermal comfort can help in creating satisfactory conditions for occupants and in controlling the energy consumption of a building. This chapter aims to provide parameters which can be used to measure and evaluate thermal comfort.

There are two approaches that are well known and widely used for predicting the range of temperatures in which occupants feel satisfied with the thermal environment. These are the heat balance approach and the adaptive approach. The former is based on climate chamber tests and the latter on field studies. Both will be explained in this chapter, together with the parameters that influence thermal comfort.

6.1 Heat balance approach

The heat balance approach is based on the assumption that the human body strives towards thermal equilibrium. Based on this assumption different models have been developed in which the Predictive Mean Vote (PMV) of Fanger (1970) is the best known. This model forms the basis for different national and international comfort standards among which ASHRAE 55 and ISO 7730 (Taleghani et al., 2013). This section will elaborate on the PMV-model to get a better understanding of the different parameters that influence thermal comfort. It will also elaborate on the applicability of the heat balance approach.

6.1.1 PMV-model

The PMV-model is based on climate chamber studies in which the thermal sensations of people are measured by asking their comfort vote according to the descriptive scale given in Table 4. The climate chambers were used to produce the desired environmental conditions by adjusting the air temperature, radiant temperature, air velocity and humidity. Other parameters that were considered during the study are the clothing insulation and activity level (metabolism) (Hoof, 2010).

Table 4: 7-point descriptive scale for thermal sensation

Sensation scale	-3	-2	-1	0	+1	+2	+3
Category	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

By doing the climate chamber study, Fanger determined a method for predicting the mean thermal sensation for a group of people which is expressed by the index Predictive Mean Vote (PMV). By assuming that people experience discomfort at PMV ≤ -2 or PMV ≥ +2, Fanger determined also the index Predicted Percentage Dissatisfied (PPD). This index indicates the percentage of people who are dissatisfied with the thermal environment. It appears that even in a neutral situation, 5% of the people are still dissatisfied with the indoor climate as shown in Figure 14 (Hoof, 2010; van der Linden et al., 2018, pp 87-89).

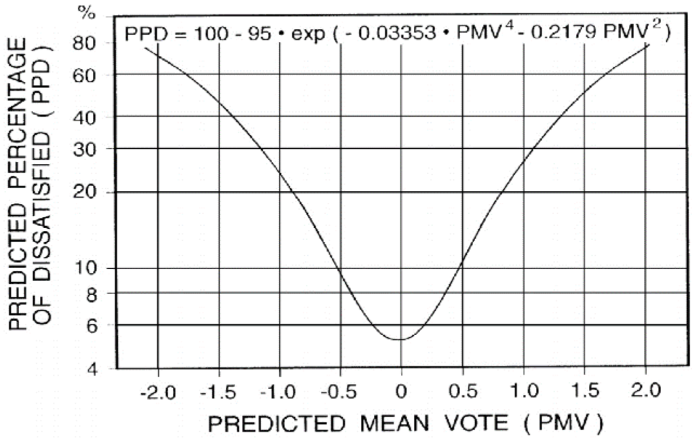


Figure 14: PPD as a function of PMV (ASHRAE 55, 2017, pp 39)

The PMV can be calculated by using the same parameters as measured during the climate chamber study, as shown in Equation 1 (Yau & Chew, 2012). The parameters can be divided into thermal environmental parameters (indoor air temperature, indoor mean radiant temperature, indoor air velocity, indoor air humidity) and personal parameters related to the occupants (metabolism, clothing). Both categories will be explained in the next sections. Note that other factors such as weight, gender and age have an indirect effect on the thermal comfort by influencing the metabolism and clothing insulation (Rupp et al., 2015; Yau & Chew, 2012). Finally, it is good to mention that the PMV-model originates from Fanger's thermal equilibrium equation as shown in Equation 2 (Taleghani et al., 2013).

Equation 1: PMV equation (Yau & Chew, 2012)

$$\text{PMV} = \left| \begin{array}{l} \left(0{,}303 \cdot e^{-0.031M^*} + 0{,}028\right) \cdot [RM^* - 3{,}05 \cdot 10^{-3} \cdot (5733 - 6{,}99 \cdot RM^* - p_i) - \\ 0{,}42 \cdot (RM^* - 58{,}15) - 17 \cdot 10^{-6} \cdot M^* \cdot (5867 - p_i) - 1{,}4 \cdot 10^{-3} \cdot M^* \cdot (34 - T_i) - \\ 39{,}6 \cdot 10^{-9} \cdot f_{kl} \cdot ((T_{kl} + 273)^4 - (T_S + 273)^4) - f_{kl} \cdot a_c \cdot (T_{kl} - T_i)] \end{array} \right. \qquad (1)$$

where,

M^*	Metabolism per m^2 body surface in W/ m^2
RM^*	Metabolism per m^2 body surface minus external work done in W/ m^2
P_i	Vapour pressure of the indoor air in Pa
T_i	Indoor air temperature in °C
T_{kl}	Surface temperature of clothing °C
T_s	Average radiant temperature of the walls in °C
α_c	Heat transfer coefficient for convection in W/m^2K
f_{kl}	Ratio between the surface area of the clothed and unclothed body (-)

in which the formula between […] expresses the difference between internal heat production and heat loss of the body which is the measure for thermal comfort.

Equation 2: Fanger's thermal equilibrium equation (Taleghani et al., 2013)

$$S = M \pm W \pm R \pm C \pm K - E - RES \qquad (2)$$

where,

S	Heat storage	C	Heat exchange by convection
M	Metabolism	K	Heat exchange by conduction
W	External work	E	Heat loss by evaporation
R	Heat exchange by radiation	RES	Heat exchange by respiration

6.1.2 Thermal environmental parameters

Indoor air temperature (T_i)

Air temperature is defined as “the temperature of air around the human body” and will differ depending on the location and time in a room. To get a good indication of the occupants’ thermal sensation, the indoor air temperature is usually measured at three heights with an interval of 3-15 minutes. The measuring heights are ankle level (0,1 m), waist level (0,6 m when seated and 1,1 m when standing) and head level (1,1 m when seated and 1,7 m when standing) (CIBSE, 2022). Note that local discomfort can occur when the vertical temperature gradient is too great. A temperature gradient of 1.5 °C between the head and ankles is found acceptable when seated (van der Linden, 2018).

Indoor mean radiant temperature (MRT)

Mean radiant temperature is defined as “the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform encloser”. It is used to simplify the characterisation of the radiant environment and indicates the heat exchange by radiation between an occupant and a black enclosure which is similar to the actual surroundings. Together with the indoor air temperature, the MRT can be used to approximate the operative temperature which is defined as “the uniform temperature of an imaginary black enclosure, and the air within it, in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment”. The condition for this is that the air velocity must be low (< 0,2 m/s) or the difference between the MRT and the indoor air temperature must be small (< 4 °C) (CIBSE, 2022; Rupp et al., 2015).

The MRT can be divided into short-wave and long-wave radiation. The former origins from solar radiation and the latter from terrestrial objects such as the walls and floor. Short-wave radiation can cause thermal discomfort indirectly when it increases the air and surface temperature of a room, or directly when it is absorbed by the body/clothing of an occupant. It is closely related to the solar transmittance of a building and causes often discomfort during the daytime in summer. Long-wave radiation affects the thermal comfort by influencing the heat exchange between the human body and its surroundings. Especially large cold surfaces such as windows can have a significant impact on the radiation heat loss of occupants and can result in asymmetric radiation. This type of radiation can cause local discomfort in which some parts of the human body are perceived as uncomfortable. These body parts are warmer or colder than the overall body temperature due to the exposure of asymmetric radiation. It appears that occupants are especially sensitive to cool feet and head. Note that occupants can feel thermally neutral for the whole body but can still perceive discomfort at certain body parts. (Huizinga et al., 2006).

The MRT can be measured by using an instrument such as a black-globe thermometer in which the device is placed at the centre height of an occupant. Another possibility for deriving the MRT is by measuring the temperatures of the surrounding walls and the view factor from the position of the occupant to these walls (CIBSE, 2022).

Indoor air velocity

Air velocity is defined by the speed and direction of airflow within a space. It affects the convective heat transfer between an occupant and his environment, and influences the evaporation of perspiration from a person. Concerning thermal comfort, it is common to only consider the air speed since the direction of the airflow is often less relevant (CIBSE, 2022). Air velocity can be experienced as a pleasant breeze or as an unacceptable cold draft depending on the context. It has been found that occupants who feel warmer than neutral at temperatures above 23 °C or at raised activity levels, generally do not feel draughts with air velocities up to 0,4 m/s. When the temperature rises to around 30 °C, air velocities up to 1,6 m/s become acceptable. However, high air velocities can be undesirable for other reasons such as paperwork. As the aforementioned suggests, the thermal comfort can be increased with higher air movements when the occupants feel warm (Huizinga et al., 2006).

Air velocities can also cause local discomfort due to draughts which is defined as an unwanted local cooling of the human body caused by air motion. Occupants experience draught usually when they feel neutral or cold. It appears that occupants are especially dissatisfied when the air velocity fluctuates and when it reaches the neck which is the most sensitive spot. It should be noted that drafts commonly occur near windows due to window opening, ventilation grilles and cold glass planes which causes a downward motion of cool air (Huizinga et al., 2006).

During field studies it can be hard to measure the air velocity accurately because of fluctuations of air flow at different parts in the room. A device to measure the air velocity is an anemometer (CIBSE, 2022).

Air humidity

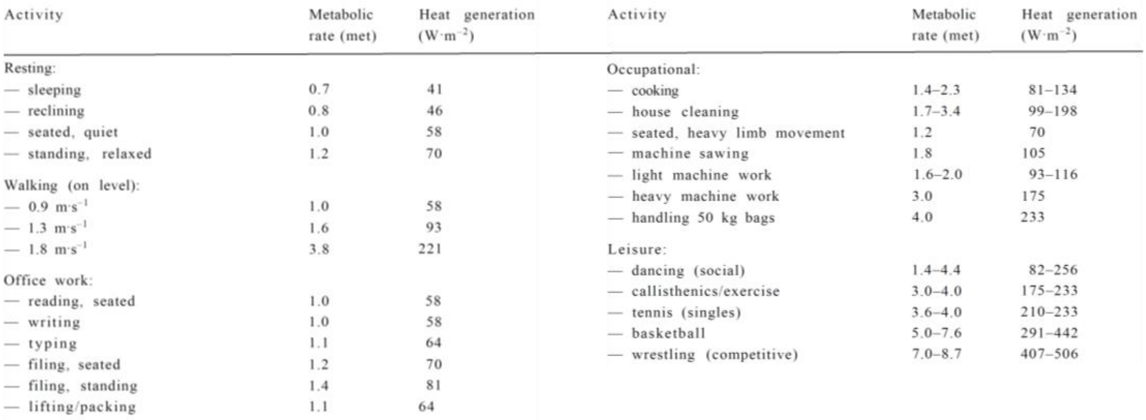
Air humidity relates to the moisture content of the air and is often expressed through the relative humidity. This parameter indicates the amount of water vapour in the air in relation to the maximum amount of vapour that the air can contain at a given temperature and pressure. The air humidity affects the evaporative heat transfer of the human body by perspiration and is therefore part of Fanger's thermal comfort model. A higher moisture content in the air reduces the heat loss of the human body, which can be experienced as unpleasant in warm climates. Generally, a relative humidity between 30-70% has been found acceptable. During field studies, the relative humidity is commonly measured at the centre height of a space (CIBSE, 2022; Yau & Chew, 2012).

6.1.3 Personal parameters

Metabolism

Metabolism is defined as "the rate of transformation of chemical energy into heat and mechanical work by metabolic activities of an individual, per unit of skin surface area" and is expressed in the units of met (1 met = 58,15 W/m^2). The metabolic rate is usually determined by using a published guidance in which different activities are related to their corresponding metabolic rate. See Table 5 for an overview of activities and their metabolic rate. Note that incorrect observations of the activity level can lead to inaccuracy of the PMV (CIBSE, 2022).

Table 5: Typical metabolic rate and heat generation per unit area of body surface for different activities (CIBSE, 1999)

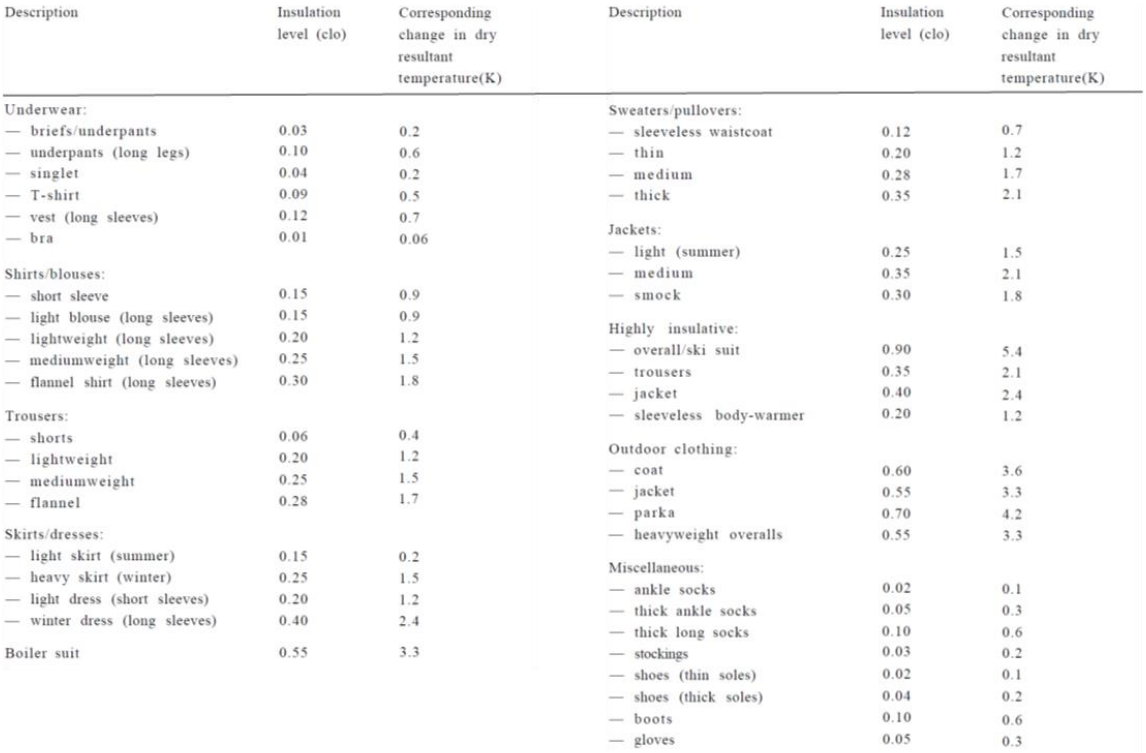


Activity	Metabolic rate (met)	Heat generation $(W\cdot m^{-2})$	Activity	Metabolic rate (met)	Heat generation $(W\cdot m^{-2})$
Resting:			Occupational:		
— sleeping	0.7	41	— cooking	1.4–2.3	81–134
— reclining	0.8	46	— house cleaning	1.7–3.4	99–198
— seated, quiet	1.0	58	— seated, heavy limb movement	1.2	70
— standing, relaxed	1.2	70	— machine sawing	1.8	105
Walking (on level):			— light machine work	1.6–2.0	93–116
— $0.9\ m\cdot s^{-1}$	1.0	58	— heavy machine work	3.0	175
— $1.3\ m\cdot s^{-1}$	1.6	93	— handling 50 kg bags	4.0	233
— $1.8\ m\cdot s^{-1}$	3.8	221	Leisure:		
Office work:			— dancing (social)	1.4–4.4	82–256
— reading, seated	1.0	58	— callisthenics/exercise	3.0–4.0	175–233
— writing	1.0	58	— tennis (singles)	3.6–4.0	210–233
— typing	1.1	64	— basketball	5.0–7.6	291–442
— filing, seated	1.2	70	— wrestling (competitive)	7.0–8.7	407–506
— filing, standing	1.4	81			
— lifting/packing	1.1	64			

Clothing

Clothing insulation is defined as “the resistance to sensible heat transfer provided by a clothing ensemble, expressed in units of clo” in which 1 clo = 0,155 m^2K/W. See Table 6 for different clothing and their representing clo values. Note that these values are an approximation in which the clothing layer is treated as one uniform layer around the human body without uncovered areas. Research has shown that females usually have a lower clothing insulation than men with a difference of 0,1-0,2 clo. It appears also that occupants generally can change their clothing insulation with approximately 0.3 clo to make themselves more comfortable. This could be for example by putting on or taking off a jacket which makes a fluctuation of the indoor climate by PMV = -0.5 or PMV = +0.5 easily acceptable. During field studies it can be difficult to measure the clothing values precisely. Usually, the clothing insulation is determined based on questioners which can have a certain error (CIBSE, 2022; van der Linden et al., 2018; Yau en Chew, 2012)

Table 6: Thermal insulation values of typical clothing and the corresponding change in dry resultant temperature (CIBSE, 1999)



Description	Insulation level (clo)	Corresponding change in dry resultant temperature(K)	Description	Insulation level (clo)	Corresponding change in dry resultant temperature(K)
Underwear:			Sweaters/pullovers:		
— briefs/underpants	0.03	0.2	— sleeveless waistcoat	0.12	0.7
— underpants (long legs)	0.10	0.6	— thin	0.20	1.2
— singlet	0.04	0.2	— medium	0.28	1.7
— T-shirt	0.09	0.5	— thick	0.35	2.1
— vest (long sleeves)	0.12	0.7	Jackets:		
— bra	0.01	0.06	— light (summer)	0.25	1.5
Shirts/blouses:			— medium	0.35	2.1
— short sleeve	0.15	0.9	— smock	0.30	1.8
— light blouse (long sleeves)	0.15	0.9	Highly insulative:		
— lightweight (long sleeves)	0.20	1.2	— overall/ski suit	0.90	5.4
— mediumweight (long sleeves)	0.25	1.5	— trousers	0.35	2.1
— flannel shirt (long sleeves)	0.30	1.8	— jacket	0.40	2.4
Trousers:			— sleeveless body-warmer	0.20	1.2
— shorts	0.06	0.4	Outdoor clothing:		
— lightweight	0.20	1.2	— coat	0.60	3.6
— mediumweight	0.25	1.5	— jacket	0.55	3.3
— flannel	0.28	1.7	— parka	0.70	4.2
Skirts/dresses:			— heavyweight overalls	0.55	3.3
— light skirt (summer)	0.15	0.2	Miscellaneous:		
— heavy skirt (winter)	0.25	1.5	— ankle socks	0.02	0.1
— light dress (short sleeves)	0.20	1.2	— thick ankle socks	0.05	0.3
— winter dress (long sleeves)	0.40	2.4	— thick long socks	0.10	0.6
Boiler suit	0.55	3.3	— stockings	0.03	0.2
			— shoes (thin soles)	0.02	0.1
			— shoes (thick soles)	0.04	0.2
			— boots	0.10	0.6
			— gloves	0.05	0.3

6.1.4 Criticism

As mentioned before, the PMV model has been validated for air-conditioned buildings and forms the basis for different national and international comfort standards among which ASHRAE 55 and ISO 7730. However, studies have shown that the PMV model underestimates the thermal sensations of occupants because of the assumptions made during the derivation of the model in the laboratory. The model does not take the adaptive behaviours of the occupants into account and assumes that people experience thermal comfort when they feel thermal neutrality.

Considering the former, De Dear and Brager (1998) state that the PMV-model is not applicable for naturally ventilated buildings since it doesn’t take the adaptive behaviour of occupants completely into account. Occupants inside naturally ventilated buildings have access to operable windows which is not the case during laboratory studies. They mention that occupants have a wider range of thermal comfort when they can adapt to the indoor climate by for example window opening and the adjustment of clothing insulation. As a response to this criticism, the PMV-model was modified to take additional factors into account. However, Humphreys states that the additional factors introduce more complexity and result in a lower correlation with the subjective warmth. Humphreys also mentioned that the outcomes of the PMV-model have a significant error due to the input of inaccurately measured parameters during field studies such as clothing insulation and metabolism (Hoof, 2017; Yau & Chew, 2012).

Considering thermal neutrality, Humphreys and Hancock showed that thermoneutrality does not always correspond with the desired thermal sensation. It appears that occupants can prefer a slightly cool sensation in warm conditions and a slightly warm sensation in cool conditions. Another study even showed that occupants who vote PMV = -2 or PMV = +2 are not necessarily dissatisfied. So, thermoneutrality is not always the ideal condition as what the PMV model indicates (Hoof, 2010).

The criticism on the PMV-model has led to the development of the adaptive thermal comfort model which is explained in the next section.

6.2 Adaptive approach

As mentioned in the previous section, the adaptive approach has been developed as a response to the limitations of the PMV model. The adaptive approach relies on field studies and is based on the assumption that occupants who expect 'thermal constancy' are more sensitive to slight deviations of the optimal indoor conditions. In this model occupants have the possibility to maintain their comfort through adaptive opportunities such as window operation and the adjustment of clothing insulation (Halawa & van Hoof, 2012). Nicol et al. (2012, sec. 3.5) make a distinction between five basic types of adaptive actions which are:

1. Regulating the rate of internal heat generation (increasing level of activity, beverages)
2. Regulating the rate of body heat loss (clothing insulation)
3. Regulating the thermal environment (thermostat, window opening)
4. Selecting a different thermal environment
5. Modifying the body's physiological comfort conditions (shivering, curling up, sweating)

This section will elaborate more on the adaptative approach and its applicability.

6.2.1 The adaptive model

The adaptive approach is based on one variable which is the outdoor air temperature, see Equation 3. This is fundamentally different from the PMV model which has six variables that are based on thermal environmental parameters and personal parameters. The main reason for using one variable is the simplicity, and the argument that the parameters of the PMV model can be related to the outdoor air temperature or the local climate. There are even studies that question the relevance of some parameters used in the PMV model (Halawa & van Hoof, 2012).

Equation 3: Adaptive approach

$$T_{comf} = A \cdot T_{a,out} + B \tag{3}$$

where,

T_{comf} Comfort temperature
$T_{a,out}$ Monthly mean outdoor air temperature
A & B Constants

The adaptive approach model is incorporated in two internationally used standards which are the ASHRAE 55 and the EN 15251. Both are meant for buildings with operable windows in which occupants are relatively free to adjust their clothing. However, both standards are slightly different from each other. The ASHRAE 55 can only be applied on natural ventilated buildings and is derived from a mean outdoor air temperature. The EN 15251 can be applied on any building which is in free running mode and is based on a more realistic exponentially weighted running mean of the outdoor air temperature. This makes the EN 15251 rely on actual weather data which is an advantage since it has more variability than the monthly mean outdoor air temperature (Halawa & van Hoof, 2012). See Figure 15 for the comfort bandwidths according to the EN 15251, which is based on Equation 4 and Equation 5. Note that the comfort chart is only applicable within a mean outdoor air temperature range of 10-30 °C. Note also the range of acceptability in which a distinction is made between 90% and 80%. The 90% range applies for sensitive occupants with high expectations such as in hospitals, and the 80% range applies for occupants with normal expectations such as in new buildings. Existing buildings have even lower expectations with a range of 65% (Taleghani et al., 2013).

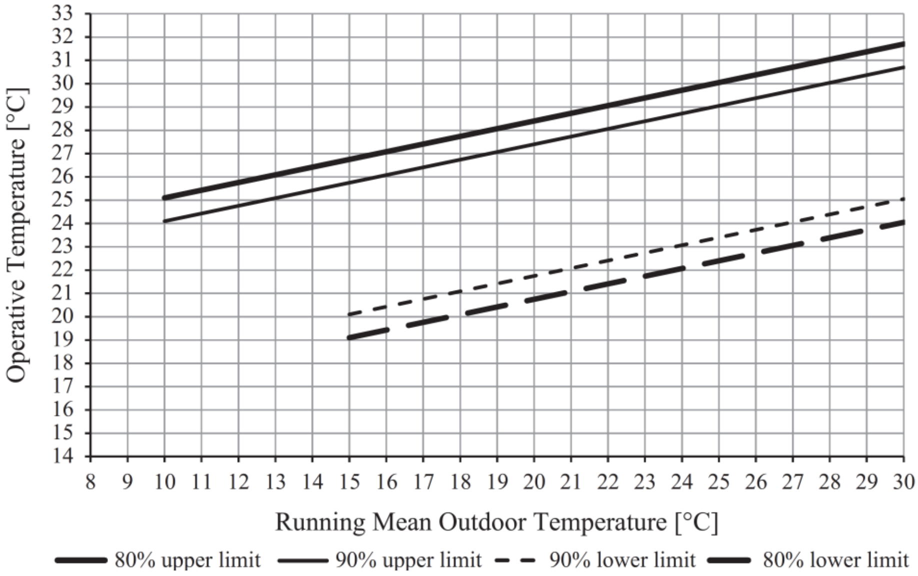


Figure 15: Comfort bandwidths according to the EN 15251

Equation 4: Adaptive approach according to EN 15251

$$T_{comf} = 0{,}33 \cdot T_{rm7} + 18{,}8\ °\mathrm{C} \quad (4)$$

where,

T_{rm7} Exponentially weighted running mean of daily outdoor temperature of the previous seven days based in equation 5

Equation 5: Exponentially weighted running mean of daily outdoor temperature

$$T_{rm7} = \frac{(T_{-1} + 0{,}8T_{-2} + 0{,}6T_{-3} + 0{,}5T_{-4} + 0{,}4T_{-5} + 0{,}3T_{-6} + 0{,}2T_{-7})}{3{,}8} \quad (5)$$

where,

T_{rm7} Exponentially weighted running mean of daily outdoor temperature of the previous seven days based in equation 5

T Mean outdoor temperature of the previous 7 days

6.2.2 Criticism

The adaptive approach has been validated for buildings with operable windows and has been incorporated in the ASHRAE 55 and EN 15251. It is characterised by its simplicity in which only the outdoor temperature is used as a variable. However, this simplicity is also the reason for arguments against this method. According to the adaptive approach, conventional thermal comfort parameters as used in the PMV-model can be related to the outdoor air temperature. This applies to a certain extent to the clothing insulation and activity level (metabolism) that varies with the outdoor conditions. However, the mean radiant temperature and air velocity can hardly be related to the outdoor air temperature. This makes the adaptive approach comparable with a black box in which the relation between the conventional parameters and the outdoor air temperature is not defined (Halawa & van Hoof, 2012).

6.3 Conclusion

This chapter discussed two approaches that can be used to predict the range of temperatures in which occupants feel satisfied with the thermal environment, and concern the heat balance approach and the adaptive approach.

Based on the heat balance approach different thermal models have been developed in which the PMV model is the best known. This model is based on climate chamber studies in which the thermal sensations of people are measured by asking their comfort vote according to the descriptive scale given in Table 4. The PMV model uses four thermal environmental parameters and two personal parameters to predict the thermal comfort. This model was initially not made for adaptive behaviour and was later modified to take additional factors into account. However, this resulted in more complexity and less accuracy.

As a response to the limitation of the PMV-model, the adaptive approach was developed. This model is based on the occupants' adaptive opportunities such as window operation and uses only the outdoor temperature as a parameter. This simplicity and adaptive behaviour make this approach more suitable for the logic of the window feedback system than the PMV model. However, the PMV model provides relevant parameters to measure and evaluate during the experiment and concerns the indoor air temperature, the indoor mean radiant temperature, indoor air velocity, indoor air humidity, metabolism and clothing insulation. In addition, the mentioned descriptive scale can be used to measure the thermal satisfaction of the occupants.

7 Indoor Air Quality Parameters

Achieving good indoor air quality has become more challenging over the years due to new advancements in the building sector. Developments such as more airtight buildings and the increased use of composite materials caused an increased content of pollutants in the indoor environment. These pollutants can influence the health, productivity and window opening behaviour of occupants, as mentioned before in section 4.1. Window operation can help improving the indoor air quality by increasing the air change rate. This will contribute in diluting the pollutants provided that the outside air is cleaner (Nandan et al., 2021; Wei et al., 2020)

The indoor environment can contain various pollutants that have a greater or lesser impact on the window operation and the health of occupants. It would be needless to discuss every type of pollution since some are impractical to measure and don't possess guideline values. This chapter will discuss the most commonly used pollutants to quantify the indoor air quality which are: carbon dioxide, Volatile Organic Compounds, formaldehyde, radon, particulate matter, ozone and carbon monoxide. It will provide information about the most common sources, health effects and maximum threshold values.

7.1 Pollutants

Carbon dioxide (CO_2)

In the indoor environment CO_2 is primarily emitted by occupants and removed by ventilation. For this reason, it is commonly used to provide a rough indication about the ventilation rates and the occupants' densities inside a building (Abdul-Wahab et al., 2015). High levels of CO_2 concentrations could be an indication of poor ventilation levels and the possible accumulation of other pollutants. Note that low concentrations of CO_2 don't exclude the possibility of other pollutants being present (CIBSE, 2022).

As mentioned in section 2.1, CO_2 is a driver for the window opening behaviour of occupants who tend to open the windows at high concentrations (Ackerly et al., 2011). Figure 16 gives an indication of different levels of CO_2 concentrations that represent the indoor air quality according to different standards. Note that all standards refer to outdoor levels. This isn't the case with the CIBSE (2022) which is not included in Figure 16. CIBSE (2022) describes the following levels: Good < 1000 ppm, moderate = 1000-1500 ppm and poor > 1500 ppm. It should be mentioned that occupants could feel discomfort in smelling and breathing when the CO_2 concentration exceeds 1000 ppm (Liu et al., 2022).

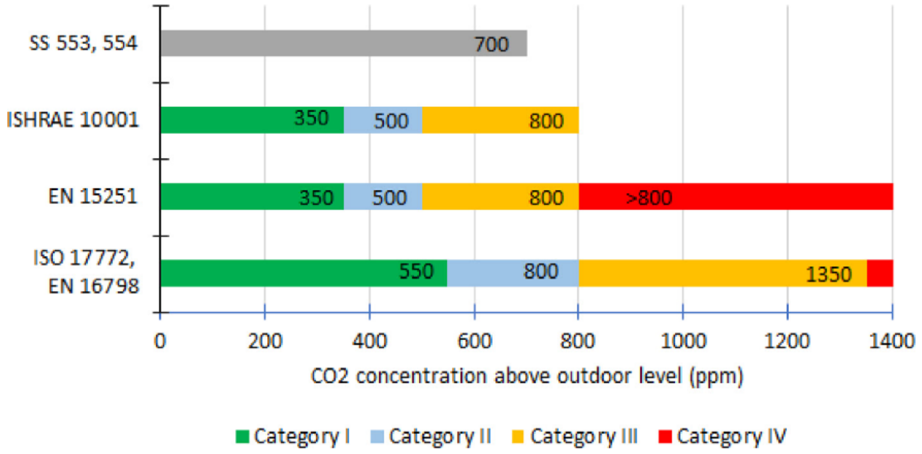


Figure 16: Acceptable CO_2 concentrations for non-residential buildings according to different standards (Khovalyg et al., 2020)

Volatile Organic Compounds (VOC)

Volatile Organic Compounds are carbon-based substances that evaporate at room temperatures such as benzene, toluene, xylenes and formaldehyde. It is emitted by various indoor and outdoor sources such as traffic, carpets, adhesives, household pesticides and paints. The highest concentration of VOCs in the indoor climate can usually be observed in newly built or renovated rooms. VOCs can be responsible for different complaints such as odour complaints and eye irritations (Nandan et al., 2021).

There are standards and guidelines that recommend the acceptable concentration of individual VOCs. However, measuring all the individual VOCs could make the sampling of the indoor air quality complicated. This is why the Total Volatile Organic Compounds (TVOCs) has been introduced which serves as an indication for the different VOCs. There are no guidelines for TVOCs but the CIBSE (2022) recommends an average maximum exposure of 300 µg/m^3 per 8 hours.

Formaldehyde (HCHO)

Formaldehyde is one of the many substances that make up VOCs and is a common element that is used in adhesives to produce for example furniture, wooden panels, cleaning products and paint. Exposure to moderate levels of formaldehyde can cause different symptoms such as burning eyes, an irritated nose and a sore throat (Abdul-Wahab et al., 2015). The World Health Organization recommends a formaldehyde concentration of 100 µg/m^3 per 30 minutes as the maximum limit for occupants (Khovalyg et al., 2020).

Radon (Rn)

Radon is emitted by the radium decay of soil and rocks which includes building materials such as concrete walls. It appears that the decaying radium in the soil under buildings has a bigger impact on the indoor air quality than building materials. This is because the radon can penetrate through the foundation, especially when it is poorly sealed. Emitted radon can attach itself to dust particles in the indoor environment which can cause lung cancer after inhaling it (Nandan et al., 2021). This is why the WHO recommends a maximum concentration of 100 Bq/m^3 (Khovalyg et al., 2020).

Particulate Matter (PM_{10} and $PM_{2.5}$)

Particulate matter are fine particles that are primarily produced by fuel-powered vehicles and a wide range of industrial processes such as mineral processing and steel making. This makes the concentration of particulate matter especially high in urban and industrial environments. Other sources are cleaning products and air fresheners (Abdul-Wahab et al., 2015).

The particles can vary widely in size, shape and composition. A distinction can be made between particles that are smaller than 10 µm in diameter (PM_{10}) and particles that are smaller than 2.5 µm in diameter ($PM_{2.5}$). Both can be inhaled by occupants and can cause health effects such as lung cancer. Note that $PM_{2.5}$ is smaller in size which makes it more likely to be inhaled and cause health effects. The WHO recommends a maximum exposure of 25 µm/m^3 per 24 h for $PM_{2.5}$ and 50 µm/m^3 per 24 h for PM_{10} (Nandan et al., 2021).

Ozone (O_3)

Ozone is well known as an element that is part of the stratosphere to shield us from ultraviolet radiation that is emitted by the sun. However, it can also be part of the ambient air and is characterised by a strong smell. In the indoor environment, ozone is primarily formed when certain pollutants are exposed to solar radiation. It can also be generated by certain devices such as printers and photocopy machines. Ozone can be harmful for occupants at low concentrations and can cause health effects such as a decreased lung capacity, itching eyes and airway irritant (Nandan et al., 2021). The WHO recommends a maximum exposure of 120 µg/m^3 per 8 h (Khovalyg et al., 2020).

Carbon monoxide (CO)
Carbon monoxide is produced by the incomplete combustion of fuels and can originate from various sources such as vehicles and heating systems. It is characterised as a colourless and odourless gas that is capable of reducing the oxygen-carrying capacity in the human body. Carbon monoxide can cause health effects such as nausea, fatigue and can result in death at high concentrations. The WHO recommends a maximum exposure of 7 mg/m^3 per 24 h (Nandan et al., 2021).

7.2 Conclusion

The indoor environment contains a wide range of pollutants which can effect the productivity and health of occupants. This chapter discussed the most commonly used pollutants to quantify the indoor air quality. These pollutants are emitted from various indoor and outdoor sources such as vehicles, industrial processes, cleaning products, carpets, building materials, furniture and devices such as printers and photocopy machines. The pollutants can be responsible for different health effects such as odour complaints, itching eyes, nausea and fatigue.

It turns out that CO_2 in particular could be useful to measure and evaluate the indoor air quality since it can function as an indicator for ventilation levels and the possible accumulation of other pollutants. Particulate Matter ($PM_{2.5}$ and PM_{10}) could be a useful indicator for outdoor air quality since it is primarily produced by fuel-powered vehicles and a wide range of industrial processes.

8 Energy Consumption Parameters

Window operation can have a significant impact on the energy efficiency, thermal comfort, indoor air quality and the occupants' satisfaction. Depending on the requirements and interests of these domains, the window operation can be more or less favourable for the energy consumption which is often in conflict with the requirements of the other domains. This contradiction usually results in energy losses since occupants value their comfort and well-being more than energy efficiency, as mentioned in chapters 3 and 5. Window feedback systems could provide a scenario in which the window operation is satisfactory for all domains, including the energy efficiency. This chapter provides parameters which can be used to calculate and evaluate the energy consumption due to the window operation. Situations with air conditioning are not taken into account.

8.1 Quantifying energy consumption

The energy consumption due to window operation can be approximated in different ways and will most likely be based on Equation 6. In this equation the indoor temperature, outdoor temperature, air flow rate, air characteristics and window opening time are used to calculate the heat loss or gain (Wouters et al., 1987).

For this equation, the air flow rate is usually derived based on the openable window area and the air velocity. However, the air flow rate can also be derived by measuring the decay of a tracer gas such as CO_2. Claude-Alain and Foradini (2002) showed that occupants could be used as the gas source of CO_2 for deriving the air flow rate. This method was probably also used for the Danish and Slovenian Mobistyle projects that are mentioned in chapter 3. When using the tracer gas method, it is important to also take the air infiltration into account (Jack et al., 2016).

Equation 6: Heat loss or gain due to window operation

$$\emptyset_v = q_{vent} \cdot p \cdot c \cdot (T_i - T_e) \cdot t \tag{6a}$$

where,

$\emptyset_v$	Heat losses due to window opening [J]
q_v	Air flow rate [m^3/s]
p	Density of air [Kg/m^3]
c	Specific heat of air [J/Kg K]
T_i	Indoor air temperature [°C]
T_e	Outdoor air temperature [°C]
t	window opening time [s]

for $c = 1000$ J/kg K and $p = 1{,}23$ kg/m^3 the equation can be simplified:

$$\emptyset_v = 1230 \cdot q_{vent} \cdot (T_i - T_e) \cdot t \tag{6b}$$

Note that Equation 6 does not consider weather conditions that can influence the heat gain or loss such as wind speed and wind direction. This simplifies the calculation and measurements but makes it less accurate. Nevertheless, this method provides a good indication of the energy consumption due to window operation (Jack et al., 2016; Wouters et al., 1987).

8.2 Conclusion

This chapter showed that the energy consumption due to window operation could be quantified by using Equation 6. Important parameters to measure are the indoor temperature, outdoor temperature and window opening time. In addition, the CO_2 concentration or the openable window area and air velocity need to be measured

DESIGN

9 Light interface design

Window feedback can be conveyed in different ways such as by light interfaces, game interfaces and dashboards with notifications. The preferred kind of display depends on several contextual factors such as the technical knowledge of the occupants and the function of the room. Concerning open-plan workplaces, light interfaces seem to be the most efficient. Several studies indicate that ambient light feedback can be more easily processed than other kinds of feedback when performing an additional task. This is because occupants need less cognitive capacity to process the feedback than other kinds of feedback that provide complex information such as dashboards (Lu et al., 2016). Despite this potential, the number of studies regarding the design of light interfaces is limited.

Nevertheless, this chapter provides a light interface design that can be used during the experiment. The design is substantiated by different design principles and choices which are based on logic and the limited number of studies.

9.1 Design principles

The study of Ackerly and Brager (2013) indicates that window feedback systems have the most influence when it is clearly visible and the logic behind them is understandable. Based on these considerations several design properties have been recognized as shown in Figure 17. This section will discuss the different design properties in order to create design principles.

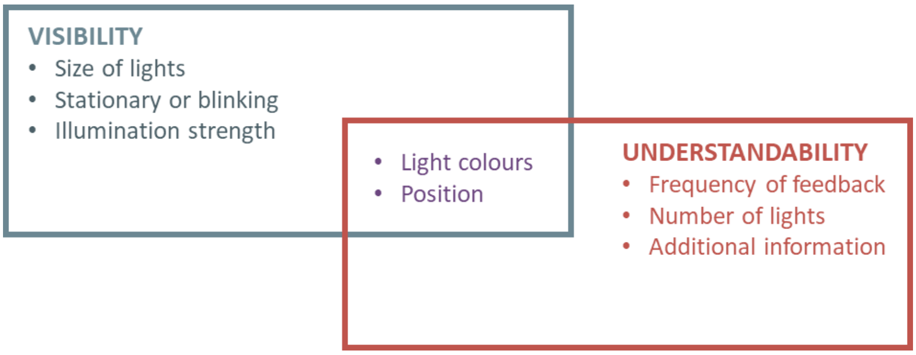


Figure 17: Design properties of ambient light feedback systems

9.1.1 Light colours

Humans can perceive different colours depending on which wavelength of light is reflected to the eyes. These perceived colours can be identified and classified by the hue, tone and saturation (chroma) as shown in Figure 18. Depending on the type of colour, the light of a window feedback system can be more or less visible and understandable for the occupants.

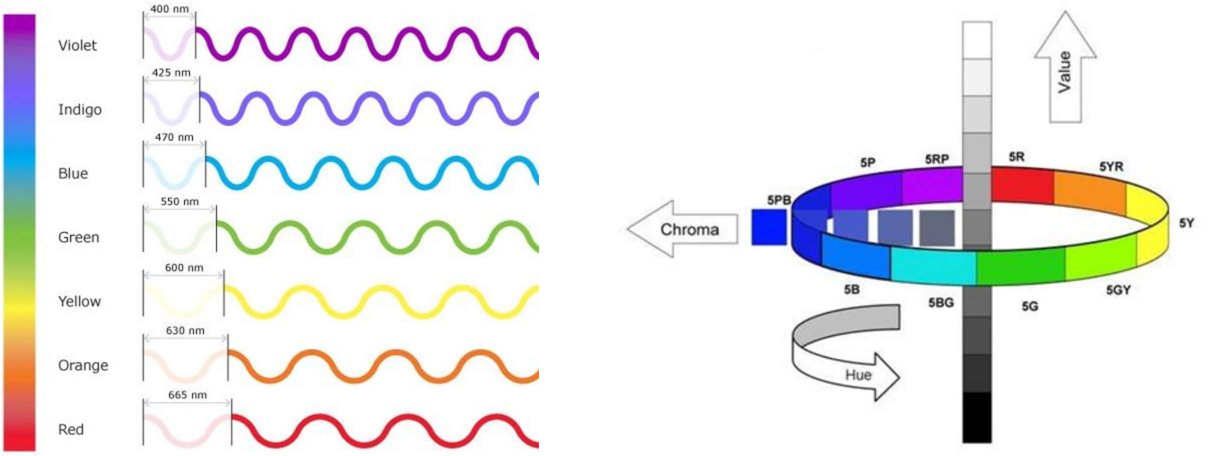


Figure 18: Munsell colour system and the wavelength of colours (CEU, 2019; University of Waikator, 2012).

Concerning the visibility of colours, the ‘arousal’ theory argues that certain colours are more stimulating than others. The theory suggests that colours with a longer wavelength such as red are more arousing than colours with a shorter wavelength such as blue. The theory is supported by several studies that measured the effect of colours on the human body. These studies show that the perception of higher wavelengths (e.g., red) results in higher respiratory movements, blood pressure and frequency of eye blinking, while the perception of lower wavelengths (e.g., blue) results in a decrease of these parameters. Based on the ‘arousal’ theory it can be argued that colours with a higher wavelength are more suitable for the light indicator since occupants will be more likely to be stimulated by the feedback (Buechner & Maier, 2016; Lu, 2017).

Concerning the understandability of colours, the ‘colour-in-context’ theory argues that colours can have different meanings depending on both the physical and psychological situation. Conditions such as gender, age, culture, type of task and setting can change the association occupants have with a colour. An example is the colour red which can be recognized as something negative, while in another setting it can be associated with romance (Buechner & Maier, 2016; Elliot, 2015). Table 7 gives an overview of the different associations that colours can have.

Table 7: Colours and their associations (CEU, 2019)

Colour		Associations
🟥	Red	Love, passion, romance, caution, danger, anxiety, energy, power, excitement
🟧	Orange	Fun, lively, happiness, spirited, warmth, comfort, abundance
🟨	Yellow	Cheerful, friendliness, sincerity, happiness, confidence, extraversion
🟩	Green	Positivity, calm, comfort, harmony, peace, relaxation, nature, hope, prosperity, tender
🟦	Blue	Coolness, intelligence, reliability, relaxation, logic, success, serenity, trust, tranquil
🟪	Purple	Sophistication, spiritual, luxury, quality, exclusive, authenticity, dignified
⬛	Black	Emptiness, toughness, elegance, power, ruggedness, stately
⬜	White	Pure, innocence, honest, heavens, purity, clarity, hygiene, cleanliness

When designing the light interface for a window feedback system it can be useful to choose a light colour that is strongly associated with the corresponding feedback. It appears that highly associated light colours have stronger persuasive effects since it helps users to understand and process the feedback (Lu et al., 2016). Matviienko et al (2015) did a laboratory study about the understandability of certain light patterns in which 30 participants from Western origins were questioned. Despite the limited number of participants, the research provides a better understanding of how light colours are perceived. The research made the following conclusions for ambient light feedback systems:

1. when a light interface has both red and green light colours, red is perceived as something negative and green as something positive. This is not the case when they are used separately;
2. When using red and blue light colours, red can be perceived as warm and blue as cold depending on the context;
3. A green light colour is always perceived as something positive;
4. Red lights are compared to green lights better distinguishable and perceptible;
5. When using a colour fade, the middle colour is less important for the understanding of the feedback than the end colours;
6. When the feedback is not urgent, the colour is less important for the understanding;
7. Traffic light colours are the most suggested light combinations for the feedback of everyday situations;
8. When the feedback is urgent, a red blinking light is the most suitable. This is perceived as the highest grade of urgent information.

Based on the ‘colour-in-context’ theory and the research from Matviienko et al (2015) it can be argued that red and green are the most suitable colours for the light indicator of the window feedback system. This is because red and green are associated with something positive and negative which can be used to indicate the impact of the window state on the indoor environment and occupants’ satisfaction.

9.1.2 Positioning light interface

The positioning of the light interface can affect both the occupant’s visibility and understandability of the window feedback system. Depending on the location, these criteria can be more or less favourable.

Concerning the visibility, the ideal location of the light feedback system can be determined by using the range of the human sight as a base. Figure 19 shows the upper limits of the human sight in which the central vision is represented by the middle segment and the peripheral vision is represented by the outer segments. By using this method and creating two common desk arrangements, the ideal location for the light feedback systems is determined for two scenarios and is shown in Figure 20. In the first scenario, the central vision has more significance than the peripheral vision and in the second scenario, all segments of the vision are equal in significance. In all scenarios, the ideal location of the light feedback system is based on the overlapping between different segments and is shown by grades of blue, in which darker blue represents a higher level of segments that overlap. Note that these scenarios don’t consider vertical obstructions and head movements by the occupants.

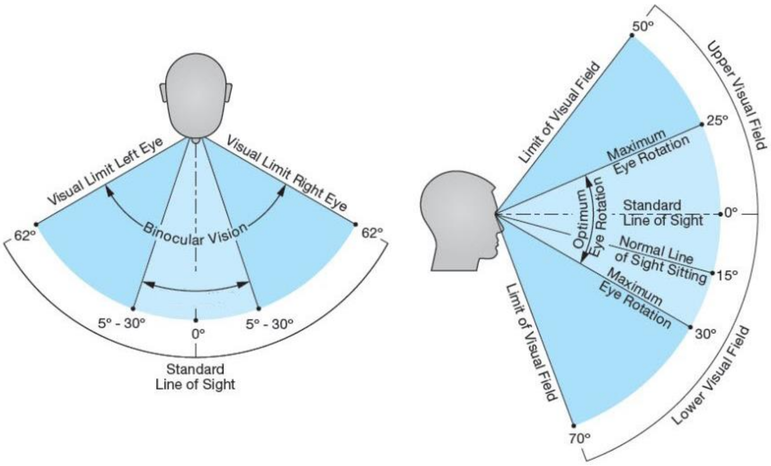
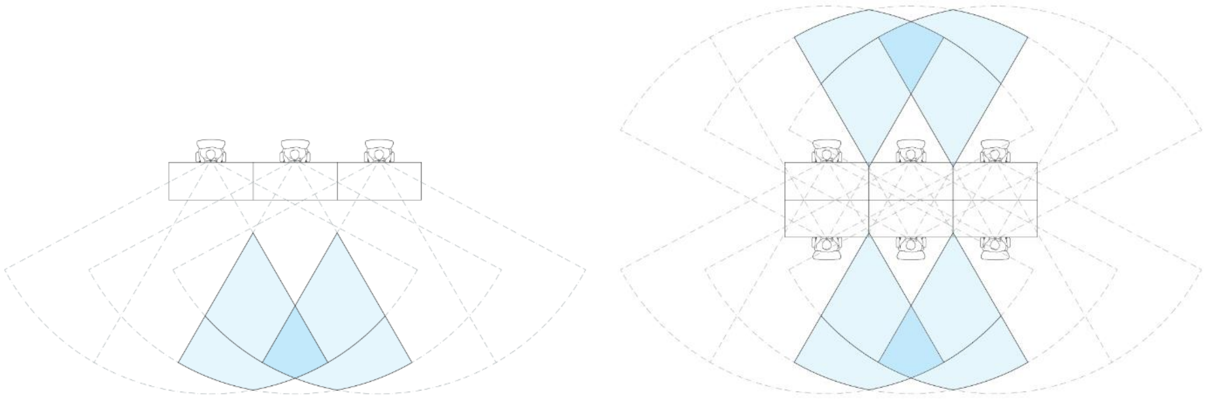


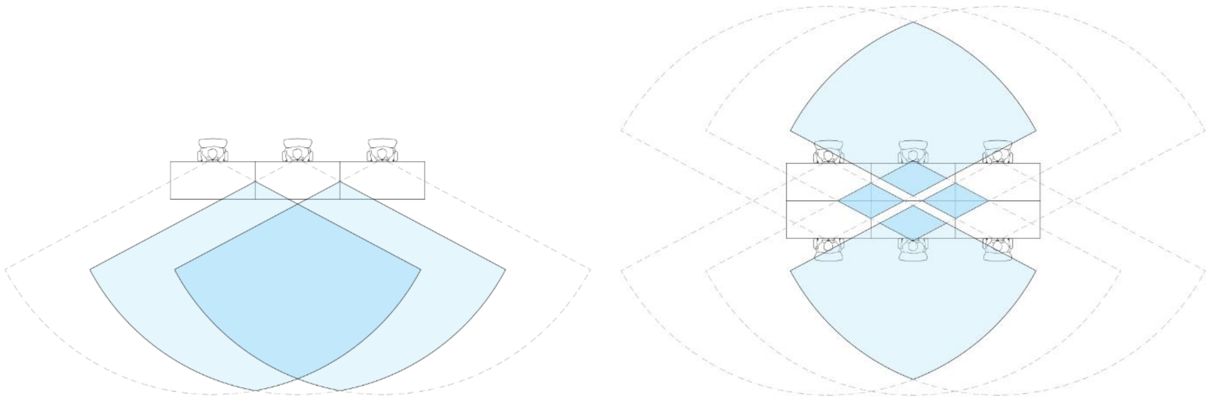
Figure 19: Range of the human sight (Quora, 2016)

Figure 20: Most visible locations of the light feedback system when only the upper limits of the human sight are considered.

Scenario 1: Centre vision has more significance



Scenario 2: All segments of the vision have equal significance



The different scenarios suggest that the ideal location of the window feedback system is located nearby the centre of the table when vertical obstructions and head movements are not considered. Considering these factors could make other positions more interesting, especially when occupants use multiple monitors.

Concerning the understandability, the occupant’s interpretation of a light feedback system can be influenced by how the light interface is positioned in its context. It is conceivable that occupants are more likely to relate the light interface to the window opening when these are positioned closer to each other. So, to create a better understandability of the window feedback system it can be recommended to position the light interface nearby the window opening.

As the aforementioned suggests, finding a visible and understandable light interface position can be contradictory to each other. It seems that the most visible location is near the centre of the table, while the most understandable location is near the window opening when vertical obstructions and head movements are not considered. When placing a light interface, these factors should be considered and if necessary improved by other design aspects.

9.1.3 Visibility

Several design properties related to the visibility of light feedback systems have been recognized and include the position, size, blinking and illumination strength of the lights. For all of these design properties no considerable literature has been found.

Concerning the size, blinking and illumination strength, only two studies have been found that suggest that bigger lights, blinking lights and lights with a higher illumination strength are more perceptible (Lu et al., 2016; Matviienko et al., 2015). However, it is relevant to know how these parameters influence the occupant's satisfaction in a working environment. It is imaginable that these parameters can also be seen as a nuisance under certain circumstances. More research is needed to get a better understanding of these design properties.

9.1.4 Understandability

The design properties that have been recognized for the understandability of light feedback systems are the frequency of feedback, number of lights and additional information. For all of these design properties no considerable literature has been found and more research is needed to get a better understanding.

Concerning the frequency of feedback, only one study has been found which shows that occupants are less likely to act according to the feedback when it doesn't correspond to their perception (Ackerly & Brager, 2013). It is therefore important to provide feedback at the right moments in which the reason is also understandable for the occupants. However, this can be challenging when the feedback is based on parameters that can't be sensed such as certain indoor and outdoor pollutants.

Concerning the number of lights, Matviienko et al (2015) recommend limiting the number of lights as much as possible. They state that too many lights can be overwhelming for the users and decrease the efficiency and understandability of the feedback. However, the understandability of the lights can always be improved by providing additional information such as labels, flyers, campaigns and symbols.

9.1.5 Conclusion design principles

Despite the limited number of studies regarding the design of ambient light feedback systems, the following design principles were found and should be taken into account when making design choices.

<u>Light colour</u>

- When a light interface has both red and green light colours, red is perceived as something negative and green as something positive. This is not the case when they are used separately;
- When a light interface has both red and blue light colours, red can be perceived as warm and blue as cold depending on the context;
- A green light colour is always perceived as something positive;
- Red lights are compared to other colours better distinguishable and perceptible since they have a longer wavelength;
- When using a colour fade, the middle colour is less important for the understanding of the feedback than the end colours;
- When the feedback is urgent, a red blinking light is the most suitable. This is perceived as the highest grade of urgent information.

Positioning

- For the positioning of the feedback system, it is likely that a trade-off must be made between visibility and understandability. It seems that the most visible location is near the centre of the table, while the most understandable location is near the window opening.

Visibility

- Bigger lights, blinking lights and lights with a higher illumination strength are more perceptible, but can also be seen as a nuisance in a working environment.

Understandability

- Too many lights can be overwhelming for the users and decrease the efficiency and understandability.
- The understandability can be enhanced by providing additional information such as labels, flyers, campaigns and symbols.

Note that these design principles are mainly based on general information and experimental studies with a small test group. Nevertheless, these principles form a good base for making design choices.

9.2 Design choices

The previous section provided several design principles which needs to be considered when designing a light interface for a window feedback system. This section substantiates the design choices that have been made based on these principles.

Number of devices

Given the economic and practical preconditions, it has been decided to limit the number of light feedback systems as much as possible. However, this decision will be overruled when it comes at the expense of the visibility and understandability of the light interface.

Positioning

For the positioning, it has been chosen to place the light interface in a central spot which is visible for multiple occupants. This will reduce the number of devices. It has also been decided to place the light interface nearby the window to create a stronger association between the light and the window opening. This will enhance the understandability of the window feedback system. Note that this positioning may lead to a lower visibility in certain scenarios. This needs to be considered when placing the light interface.

Number of lights

It has been chosen to limit the number of lights as much as possible since it can be overwhelming for the occupants and decrease the efficiency and understandability of the feedback. The final design will include a maximum of three light colours.

Additional information

To be able to make rational decisions, it is for occupants important to understand the meaning of the lights and the underlying logic of the window feedback. Providing additional information could help in achieving these goals. It has been chosen to provide additional information on interface level by using labels and a QR code. The labels will explain the meaning of the lights while the QR code will give an understanding of the logic behind the system. Additional information on a bigger scale such as campaigns and flyers is not preferred since its effect is temporary.

<u>Blinking lights</u>
It has been chosen not to use blinking lights since this can be seen as a nuisance in a working environment.

<u>Light size and illumination strength</u>
No literature has been found about the recommended size and illumination strength of ambient light feedback systems. The size and illumination strength will depend on intuition and the possibilities that are available on the market.

<u>Light colour</u>
Based on the design principles, red and green are the most evident choice for the light colours. Depending on the number, colour and meaning of the lights several variations are possible as shown in Table 8. This table provides an overview of the pros and cons for each variation together with a visualisation.

Table 8: Design possibilities in which the number, colour and meaning of the lights vary

Visualisation	Meaning lights	Pros and Cons
1. 	Green = Window should be open No light = Window should be closed	+ Very simple by using one light – Meaning of no light can be unclear – Green is less arousing, distinguishable and perceptible than red
2. 	Red = Window position is wrong No light = Window position is correct	+ Very simple by using one light + Red colour is good visible – Meaning of no light can be unclear
3. 	Green = Window should be open Red = Window should be closed	+ The feedback is always visible + Windows doesn't have to be monitored – The open feedback is less stimulating while it is relatively more important
4. 	Green = Window position is correct Red = Window position is wrong	+ The feedback is always visible + The feedback that indicates an action is more stimulating – It is necessary to monitor all windows
5. 	Green = Window should be open Orange = Window could be open or closed Red = Window should be closed	+ The feedback is always visible + Windows don't have to be monitored + The orange light softens the transition and provides more consistent feedback – The open feedback is less stimulating while it is relatively more important – The orange light has less significance for the understanding

Based on Table 8, it has been decided to use variant 5 for the final design. By eliminating the need to monitor windows, this variant minimizes the costs, complexity and error probability. In addition, this variant improves the feedback accuracy by making the feedback always visible and creating a soft transition with the orange colour. Furthermore, it should be noted that the meaning of the red and green colours corresponds to the window feedback systems in the research of Ackerly and Brager (2011).

9.3 Final design

The different design choices have resulted in the final design as shown in Figure 21. This design consists of three colours as explained by the legend. The QR code provides additional information about the logarithm and its parameters. The designed window feedback system will be placed in a central spot nearby an openable window. Please refer to Figure 40 for a photo of the prototype.

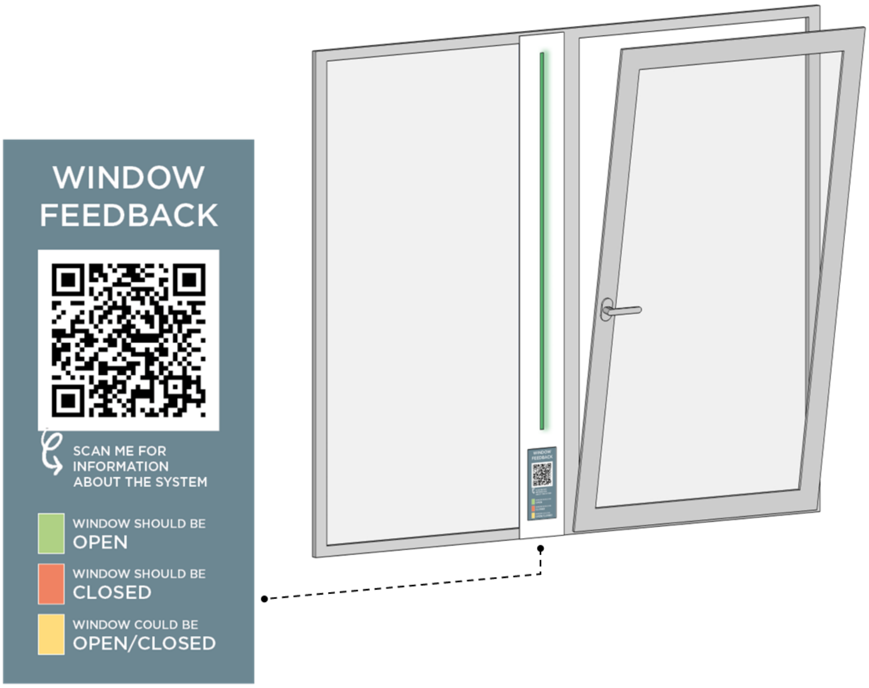


Figure 21: Final window feedback system design with corresponding legend and QR-code

9.4 Limitations

The design of the window feedback system is mainly based on general information and experimental studies with a small test group. As a result, the substantiation of the design is limited and more research is required to validate the design choices. In particular, more research is required concerning the understandability of the light colours, the frequency of the feedback, the positioning of the system and the size, blinking and illumination strength of the lights.

10 Algorithm design

The logic behind a window feedback system is based on an algorithm. The algorithm determines the type of feedback that is conveyed to the occupants based on different parameters such as the indoor temperature and CO_2 concentration. It determines also to a great extent how the window feedback system is perceived and understood by the occupants. Despite this importance, the number of studies regarding the algorithm of a window feedback system is limited. Nevertheless, this chapter provides an algorithm design for the window feedback system which is based on the literature research and own formulated design principles.

10.1 Literature

The literature research in chapter 4 discussed the most important drivers and reasons for window operation in offices. The conclusions in chapter 4 can be used to identify parameters for the algorithm. As a reminder, Table 9 shows again the most important drivers that affect the window opening behaviour in offices. In this table the most influential drivers are highlighted in bold and correspond to the most important reasons for window operation.

Table 9: Drivers that have a significant affect on the window opening behaviour in offices

External		Internal		
Physical	**Contextual**	**Psychological**	**Physiological**	**Social**
Outdoor temperature **Indoor temperature** **Air velocity** Relative humidity Solar radiation **CO_2 concentration** $PM_{2.5}$ concentration Outdoor noise	Occupancy Window Design Distance to façade Façade orientation Thermal mass Safety/security Installations (HVAC) Interior doors **Rainfall**	**Expectations**[1] Concerns Habits Lifestyle/schedule Knowledge/education Perceived control Stress	Age Gender Health Clothing Activity level Food and beverages	Social norms Interrelationships

1 | relates to the reasoning to have a connection with the outdoors

Based on the drivers in Table 9, different parameters can directly or indirectly be selected for the algorithm. When making this selection, careful consideration should be given to the number of parameters that will be used for the algorithm. In general, using more parameters will result in a more accurate, sophisticated and flexible feedback system. However, selecting too many parameters can result in an expensive and complex system that is prone to errors. The following criteria should be at least considered when making the selection of parameters:

- **Relevance:** Parameters that do not directly contribute to the performance or functionality of the feedback system should be avoided.
- **Feasibility:** It should be questioned if the implementation of the parameters is technically feasible with the given practical and financial constraints.
- **Robustness:** Parameters that are not reliable due to for example changing environmental conditions should be avoided.
- **Generalization:** It is desirable to include parameters that can represent different conditions or environments. This will create a more resilient system that is representative for different places around the world.
- **Ethics and legislation:** The selected parameters should not violate any ethical or legal principles such as privacy.

Based on these criteria, different parameters will be selected during the design process

10.2 Design

This section explains the algorithm design by discussing the scope, parameter selection and design choices.

10.2.1 Scope

Depending on the context and desired output, an algorithm may require different parameters and structure. For example, the relative humidity will be more important as a parameter for a residential function than for an office which has in general lower humidity levels. The algorithm design in this section will focus on the implementation in an ambient light window feedback system that will be placed in an open-plan office without an air conditioning system. Including an air conditioning system would require another approach in which the thermal comfort would play a more significant role.

10.2.2 Parameter selection

To create a satisfactory window feedback system, the algorithm should at least include parameters regarding the indoor air quality, energy efficiency, thermal comfort and contextual influences. This section provides a substantiation of the parameter selection per domain. Please refer to Table 10 for an overview of all the selected parameters.

Indoor air quality
The indoor environment contains a wide range of pollutants which can affect the productivity and health of occupants, such as volatile organic compounds, formaldehyde, radon and ozone. From all the air pollutants, CO_2 and $PM_{2.5}$ appear to be the most important drivers for window operation and are for this reason selected as parameters for the algorithm. Selecting other parameters is not necessary since CO_2 functions as an indicator for ventilation levels and the possible accumulation of other pollutants. $PM_{2.5}$ is an indicator for outdoor air quality since it is primarily produced by fuel-powered vehicles and a wide range of industrial processes. It is relevant to measure $PM_{2.5}$ both indoors and outdoors to get a better understanding of the air quality.

Thermal comfort
The heat balance approach and adaptive approach are two well known and widely used models for predicting the range of temperatures in which occupants feel satisfied with the thermal environment. Between these two thermal models, the adaptive approach is more suitable for the algorithm since it takes the adaptive behaviour of occupants into account and has fewer (personal) parameters. The required parameters for this model are the indoor temperature, indoor mean radiant temperature and outdoor temperature. These parameters are also identified as important drivers for window operation as shown in Table 9. Selecting other parameters of the thermal environment such as the air velocity and relative humidity would provide a better understanding of the thermal environment but are not required for the prediction of the thermal comfort. For this reason, only the indoor temperature, indoor mean radiant temperature and outdoor temperature are selected for the algorithm.

Contextual influences
Different contextual drivers influence the window opening behaviour in which a distinction can be made between static and dynamic contextual drivers. The former can influence the desired thresholds of the algorithm but does not change over time and can not function as a parameter. Examples of static contextual drivers are the window design, façade orientation and thermal mass. Dynamic contextual drivers, on the other hand, do change over time and can function as a parameter. Precipitation, wind

velocity, solar radiation, outdoor noise, interior doors and installations are dynamic contextual drivers that influence the window opening behaviour. For this reason, these parameters are selected for the algorithm

Energy

To determine whether a window operation causes energy loss, it is necessary to measure the indoor temperature, outdoor temperature and if the heating is on. These parameters should therefore be included in the algorithm. In addition, the energy consumption could be approximated by measuring the window opening time and the decay of CO_2 concentration. Alternatively, the openable window area and the indoor air velocity could be measured instead of the CO_2 concentration. Depending on the context and available resources, it should be considered whether an approximation of the energy consumption is desirable.

Selected parameters

Table 10 provides an overview of the parameters that are selected for the algorithm per domain. Note that the table does not include parameters regarding the internal drivers due to ethics, legislation and feasibility.

Table 10: Overview of selected parameters for the algorithm per domain

Indoor air quality	Thermal comfort	Contextual influences	Energy
Indoor CO_2 Indoor $PM_{2.5}$ Outdoor $PM_{2.5}$	Indoor temperature Indoor mean radiant temperature Outdoor temperature	Precipitation Wind velocity Solar radiation Outdoor noise Interior doors Heating Ventilation	Indoor CO_2 Indoor temperature Outdoor temperature Heating

10.2.3 Design choices

Several iterations have been made during the design process of the algorithm and resulted in the final design as shown in Figure 22. Please refer to appendix IV for the algorithm code that was implemented in the Raspberry Pi. This algorithm design is based on two principles that served as guidelines throughout the design process and concern:

Principle 1; To enhance the energy efficiency, the window should be closed when the outdoor temperature is colder and should be open when the outdoor temperature is warmer. This principle can be overruled when occupants' comfort or health is on the line.

Principle 2; The health of occupants is more important than energy efficiency and occupants' comfort.

As a result of the first guideline, the domain 'Energy' determines whether the window should be open or closed as a principal and can be overruled by the other domains. The second guideline resulted in a higher importance of the indoor and outdoor air quality than other domains. This is because the air quality can affect the occupants' health directly. In the remainder of this section each domain and the corresponding thresholds will be further substantiated.

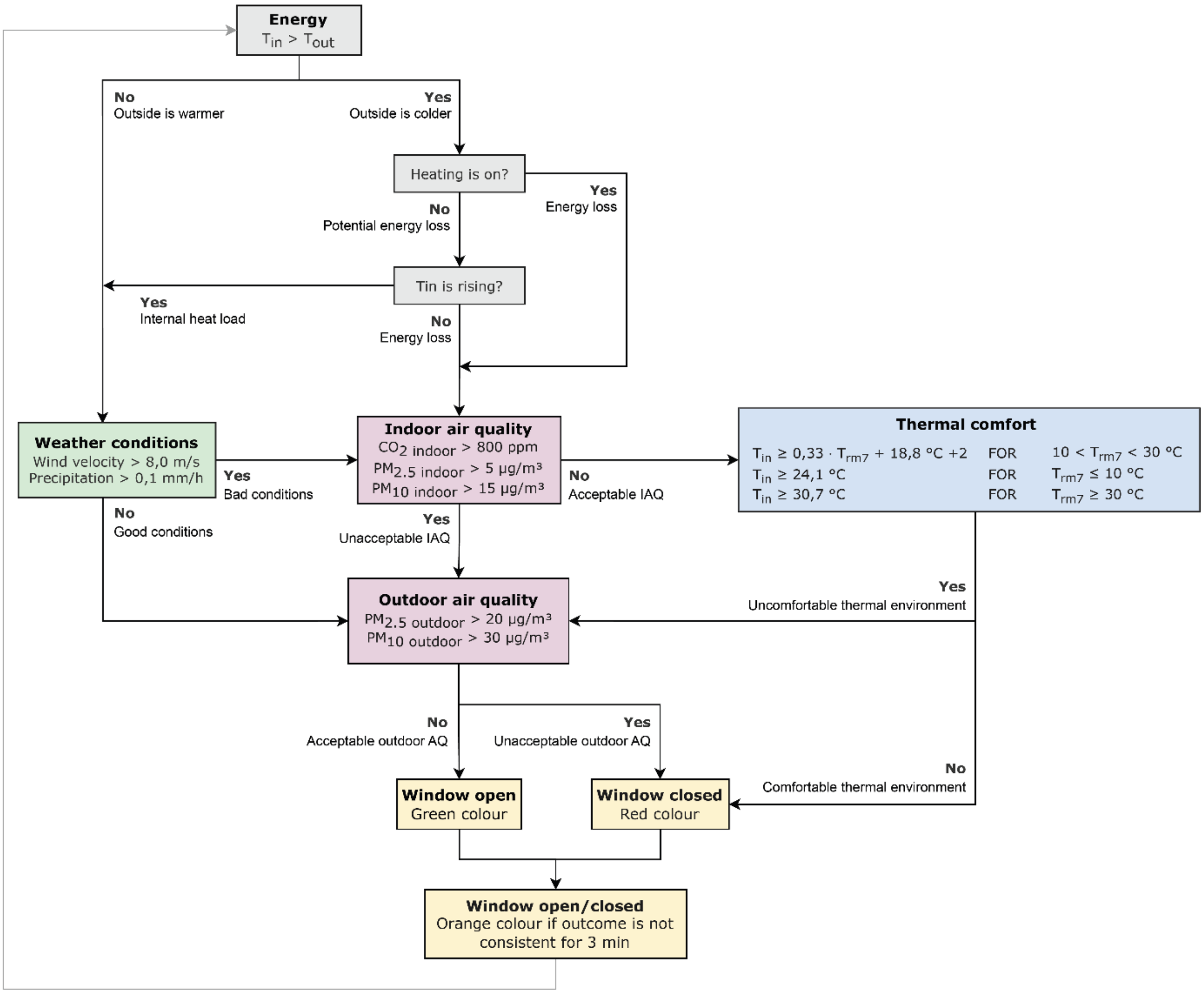


Figure 22: Workflow of final algorithm design

Energy

The goal of this domain is to determine whether the room is gaining or losing thermal energy and is obtained by three questions. The reasoning behind these questions is shown in Figure 23.

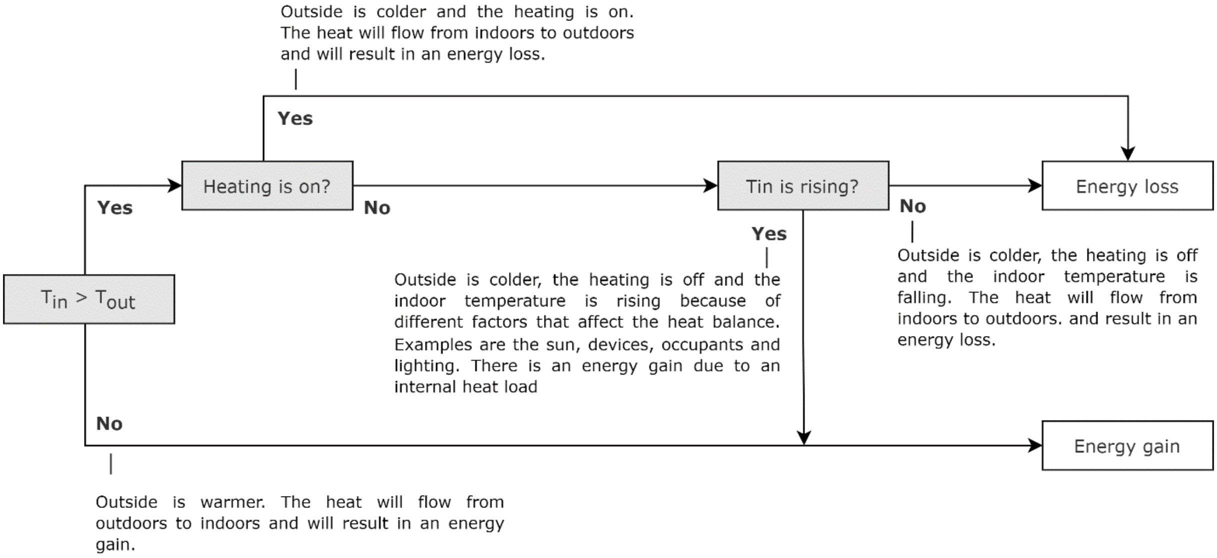


Figure 23: Reasoning behind the workflow of the domain Energy

When the room is gaining energy, it is desirable to open the windows to create higher ventilation rates. When the room is losing energy, it is desirable to close the windows to limit the heat transport.

Weather conditions
This domain determines if the weather conditions are acceptable for opening a window by verifying the amount of precipitation and the wind velocity. The threshold of precipitation is based on own perceptions since no significant literature was found. The threshold for the wind velocity is based on the study of Fabi et al (2012) who indicated that all windows in residential buildings are closed at wind speeds above 8 m/s. Note that this threshold is likely to be higher for tilted windows.

Indoor air quality
This domain determines whether the indoor air quality is acceptable or not. The threshold of the CO_2 concentration is 800 ppm and is according to the recommendations of ISHREA 10001, EN15251 and Frisse Scholen 2021. It is also according to the recommendations of the WHO which states that occupants have lower respiratory movements at concentrations higher than 1000 ppm (Lowther et al., 2021). The thresholds of the $PM_{2.5}$ and PM_{10} concentrations are based on the WHO (2021) which recommends an annual mean of 5 $\mu m/m^3$ for $PM_{2.5}$ and an annual mean of 15 $\mu m/m^3$ for PM_{10}. It should be noted that PM_{10} was not selected as an important parameter but has been included since most sensors on the market measure both $PM_{2.5}$ and PM_{10}.

Outdoor air quality
This domain determines whether the outdoor air quality is acceptable or not. The thresholds are based on RIVM (2018) which recommends a maximum threshold of 20 $\mu m/m^3$ for $PM_{2.5}$ and a maximum threshold of 30 $\mu m/m^3$ for PM_{10}. It should be noted that PM_{10} was not selected as an important parameter but has been included since most sensors on the market measure both $PM_{2.5}$ and PM_{10}.

Thermal comfort
This domain determines if the maximum threshold of thermal comfort is exceeded by using the adaptive model. This model uses the outdoor temperature and operative temperature to make an approximation. The latter will be estimated by measuring only the indoor temperature since it was not feasible to measure the mean radiant temperature. For this reason, stricter thresholds have been implemented in the algorithm by selecting class I of the adaptive model. This class is normally used for sensitive occupants with high expectations such as in hospitals.

Final decision
The last rule of the algorithm determines if the outcome is consistent for 3 minutes. If this is not the case, the algorithm will result in an orange colour as an output. This colour indicates that either open or closed windows are possible and is implemented to prevent the light feedback of switching quickly.

10.2.4 Limitations

The algorithm design has several limitations and are mentioned in the following.

- The indoor mean radiant temperature is not implemented as a parameter due to its feasibility. As a result, the operative temperature is approximated by measuring the indoor temperature which leads to higher inaccuracies of the thermal comfort approximation.
- The outdoor noise is not implemented as a parameter due to the feasibility and ethics. However, this can be an important parameter for window closing depending on the context.

- The algorithm does not include safety and security. Depending on the context these parameters can have a significant importance for window closing.
- The algorithm does not consider parameters related to the internal drives due to the feasibility, ethics and legislation. As a result, the probability of a mismatch between the feedback system and the occupant's feelings becomes higher.
- The algorithm assumes that the heating is off when the outdoor temperature is higher than the indoor temperature. There may be scenarios where this assumption does not hold true.
- The threshold of the precipitation is based on own perceptions and is not validated. Further research is required to validate the threshold.
- The algorithm does not take sun shadings into account which can affect the thermal environment and ventilation rates.
- The outdoor air quality has a higher importance than the indoor air quality. However, this may not be correct in certain scenarios. For example, when both the indoor and outdoor air quality are exceeded and the indoor air quality is more of a concern.
- The domain weather conditions does not take the wind direction and solar radiation into account due to the limitations of web-scraping the internet. Including both would result in a more accurate outcome of the algorithm.

11 Survey design

As mentioned in the methodology, the research by experimentation part will consist of both objective and subjective measurements to create a better understanding of what a satisfactory window feedback system is. For the subjective measurements, different surveys have been designed to record the occupants' perception of the indoor environment and window operation. The results of these subjective measurements will be compared with the results of the objective measurements. This chapter will elaborate on the survey design. It will first discuss the main approach and principles behind the surveys in which after the logic behind the different surveys is explained.

11.1 Approach and principles

Considering that the subjective measurements will be conducted in a working environment, it has been tried to design an approach that keeps the distraction of the occupants to a minimum while it provides a good understanding of the window operation. For this reason, three surveys with different durations have been created that will be conducted at different moments, as explained in the next section. To keep the participants anonymous, the different surveys from each participant will be linked by an ID number without asking for personal sensitive data such as the first name and surname.

Concerning the questions in those surveys, it has been tried to formulate the questions in a simple, clear, positive and objective manner. Furthermore, the aim was to minimize the open questions and to keep the surveys as short as possible. Regarding the sequence, questions with a similar topic were put together and difficult questions were on purpose not placed at the end.

11.2 Survey logic

All the surveys are created and will be answered by using the online software Qualtrics XM, version 2023. In the settings of the software, anonymized responses were enabled to prevent the recording of IP addresses, location data and contact info. The settings were also changed to force responses for every question and to create a back button. In the following the logic behind the three surveys will be explained.

11.2.1 First survey

The first survey is the longest and will be conducted by all the participants at the start of the experiment. The survey consists of 27 questions which are divided into four sections and related to personal factors, window operation, thermal comfort and indoor air quality. Figure 24 shows an overview of the different sections together with the corresponding topic and purpose.

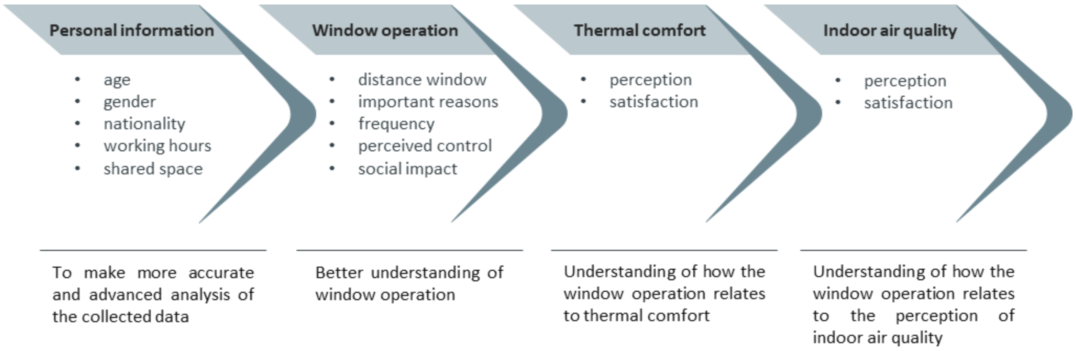


Figure 24: Different sections of the first survey with the corresponding topics and purpose

The overall aim of the first survey is to recognize how different factors relate to the perceived window control and the reasoning for window operation. An overview of all the questions, response possibilities, variables and correlations of the survey is provided in Appendix II.

11.2.2 Second survey

The second survey will be conducted during the experiment and is a short survey of 4 questions to keep the distraction of the participants to a minimum. When occupants operate the window, they will be kindly asked by a QR code to indicate the reason for their window operation, the distance to their workplace and if they considered the comfort of other occupants. Note that the reasoning of the participants that do not operate the window will be recorded during the first survey. An overview of all the questions and response possibilities is provided in Appendix II.

11.2.3 Third survey

The third survey will be conducted at the end of the experiment by all the participants who are seated within a 12-meter radius of the window feedback system. The survey consists of 25 questions and are related to the implemented window feedback system. The questionnaire aims to identify how the window feedback system is understood and how the system can be improved. The legend of the window feedback system will be covered to ensure the own perception of the occupants. Figure 25 shows an overview of the different sections together with the corresponding topic and purpose. An overview of all the questions, response possibilities, variables and correlations of the survey is provided in Appendix II.

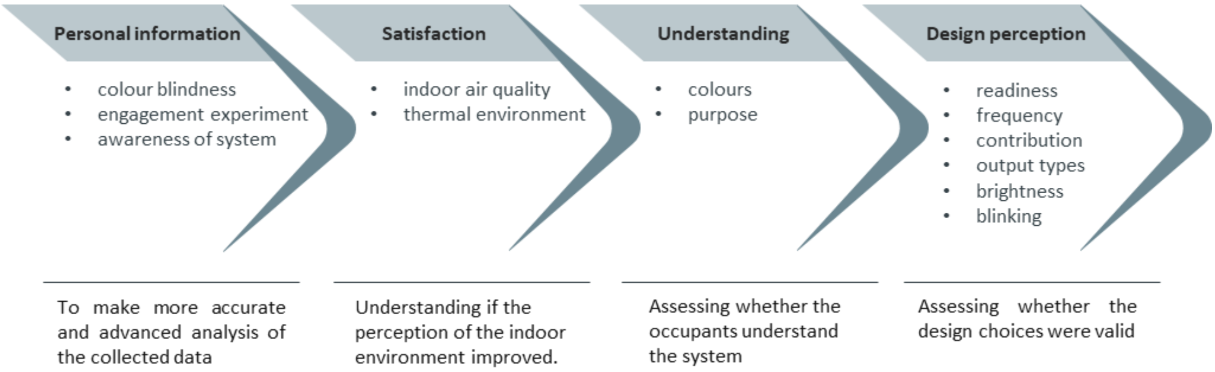


Figure 25: Different sections of the third survey with the corresponding topics and purpose.

EXPERIMENTAL RESEARCH

12 Methodology experiment

The research by experimentation part will consist of both objective and subjective measurements to create a better understanding of what a satisfactory window feedback system is. This section will elaborate on the measurement setup by describing the case study, instrumentations and limitations.

12.1 Description case study

The field study was performed in the building technology studio of the TU Delft's faculty of architecture and the built environment. This studio is located on the West wing of the second floor and functions as an open-plan workspace for both students and professors. The studio is characterized by its narrow plan, multiple façades, many (tilted openable) windows, international-originated occupants and peak periods with high volumes of users. The heating is controlled by radiators and the ventilation is regulated by mechanical in and outlets. The studio does not have an air conditioning system. See Figure 26 to Figure 29 for an overview of the situation.

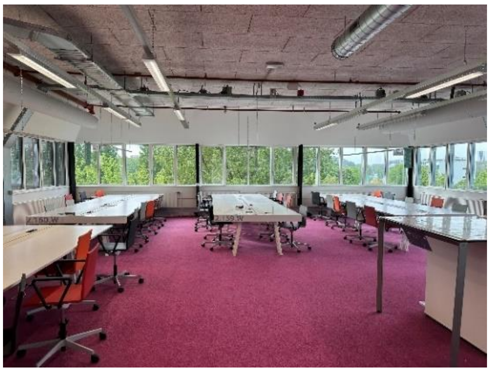


Figure 26: Left side BT-studio

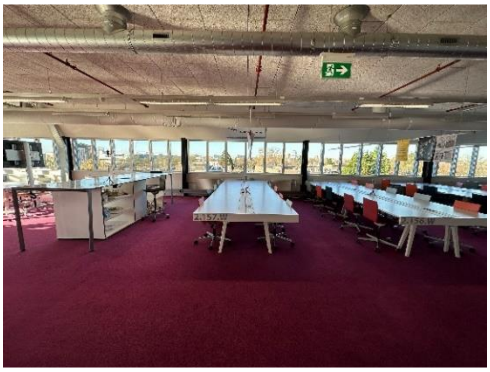


Figure 27: Middle section BT-studio


Figure 28: Right side BT-studio


Figure 29: Tilted openable window

Due to ethical requirements, the measurements were only performed in the middle section of the studio which is the most representative for a typical open-plan workplace. Repeated measurements were taken from 03/04/2023 to 21/04/2023 for the existing situation and from 24/04/2023 to 12/05/2023 for the new situation. This period was characterized by its varying warm and cold weather with sunny and rainy days. Everyday data was collected from 9:00 till 19:00. No data was collected during the weekends, holidays and incidentally other days.

12.2 Instrumentation

In this section the instrumentation for both the objective and subjective measurements are explained.

12.2.1 Objective measurement

Accuracy and reliability

During the experiment, several sensors have been used to monitor different parameters including the temperature, relative humidity, CO_2 concentration, $PM_{2.5}$ concentration, PM_{10} concentration, window position and if the radiators are working. Table 11 provides an overview of the different sensors that have been used with their corresponding parameters and reliability. This table does not include the magnetic sensor that was used to monitor the window position because of its simplicity.

The results of Table 11 show that the indoor sensors are accurate and reliable enough. The measured data with these sensors are also according to the literature and expectations. The opposite is true for the outdoor sensor. The measured temperature and relative humidity have a significant deviation compared to online weather data, even when contextual variations are taken into account. This deviation is most likely caused by the handmade case of the outdoor sensor. As a result of the big deviation, it was decided to exclude the outdoor temperature and relative humidity from the measured data used for the analyses. Instead, these parameters were retrieved from the website www.daggegevens.knmi.nl, location: Rotterdam. The temperature of the outdoor sensor was still used as input for the window feedback systems after corrections because of its topicality. Since the accuracy of the particulate matter from the outdoor sensor seems reasonable, it was used as input for both the analyses and the window feedback system. It should be noted that the outdoor sensor was not installed during the existing situation and data from www.Luchtmeetnet.nl, location: Den Haag-Rebecquestraat was retrieved for the particulate matter.

Table 11: Overview of sensors with corresponding parameters and reliability

Sensor	**CozIR**	**TMP36**	**Sensirion SPS30**	**Sensirion SEN54**
Placement	**Indoor**	**Indoor**	**Indoor**	**Outdoor**
Parameters	CO_2 Temperature Relative humidity	Temperature	$PM_{2.5}$ PM_{10}	$PM_{2.5}$ PM_{10} Temperature Relative humidity
Accuracy manufacturer	± 30 ppm ± 0.5 °C ± 3%	± 2 °C	± 10 % (ratio) ± 25 % (ratio)	± 5 % (ratio) ± 25 % (ratio) ± 0.45 °C ± 4.5%
Measured maximum deviation between identical sensors	23 ppm 0.23 °C 1.51%		0.23 µg/m3 0.27 µg/m3	
Deviation with online (weather) data sources				- ± 4 µg/m3 ± 7.4 °C ± 30 %

Setup

The data of the sensors were collected by a Raspberry Pi 4 model B and was sent through a connector called WeMos D1 mini pro. This connector was attached to each sensor and created its own network together with the Raspberry Pi. See Figure 30 for an overview of the connections between the Raspberry Pi and the sensors. The LED light of the window feedback system was connected in the same way. Please refer to appendix III for the code that was used for these sensors.

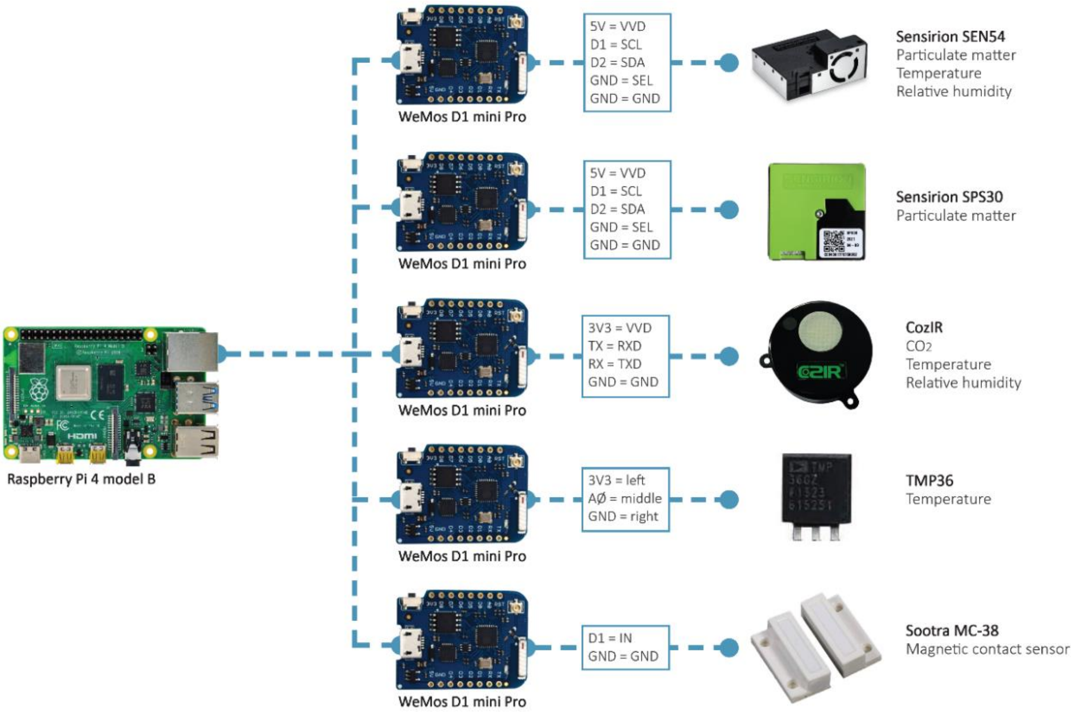


Figure 30: Overview of connections between the Raspberry Pi and the sensors

Please refer also to Figure 31 to Figure 37 for an indicative overview of how the sensors were positioned in the middle section of the BT-studio. During the positioning of the sensors, a deliberate decision was made to measure the CO_2 concentration and indoor temperature at both room and desk levels to enable a comparison between both. In addition, the CO_2 sensors were intentionally placed at breathing height and placed away from the windows to avoid inaccuracies.

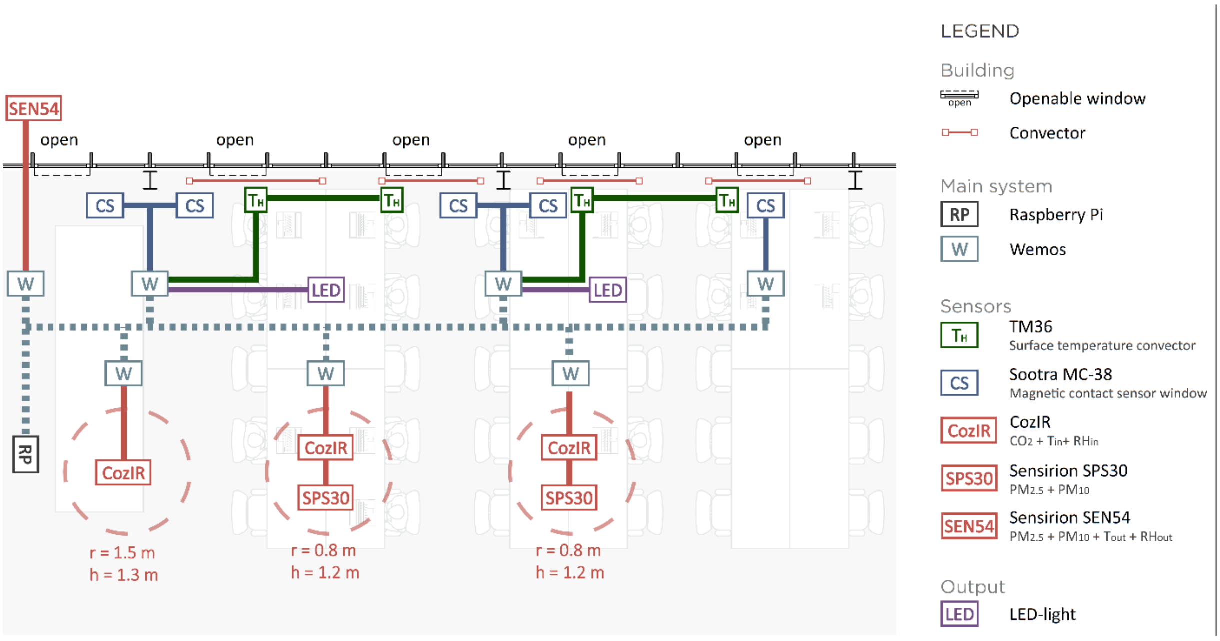


Figure 31: Plan of the middle section of the BT-studio in which the position of the sensors is indicated


Figure 32: CozIR and Sensirion SPS30 on desk level


Figure 33: CozIR on room level


Figure 34: Sootra MC-38 to monitor windows

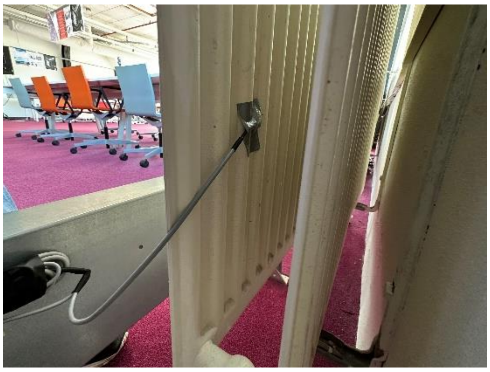


Figure 35: TM36 behind the convector to monitor if the heating is on

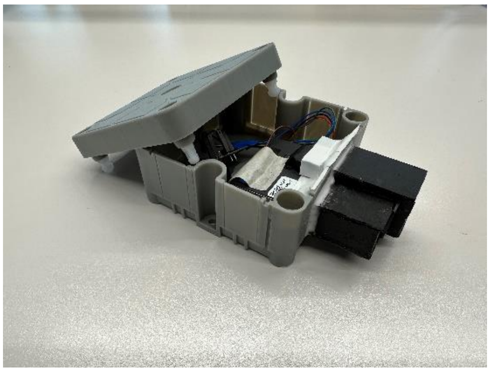


Figure 36: Handmade case for Sensirion SEN54


Figure 37: Outdoor placement of Sensirion SEN54

12.2.2 Subjective measurements

Three surveys were designed in chapter 11. These surveys have been administered in which the first and third surveys have been handed out in person. The second survey was distributed by a QR code placed nearby the window as shown in Figure 38. However, this method for the second survey was not effective and resulted in only 4 respondents. Due to the minimum number of respondents, the results of survey 2 have been excluded for the analyses. The missing information was compensated by the other surveys. Linking the surveys with an ID code was also not effective since none of the volunteers remembered their ID code. As a result, less detailed analyses could be made.

Before the start of the existing situation, occupants were informed about the experiment and the surveys through a WhatsApp message, consent form, personal talks and the infographic as shown in Figure 39. Occupants were also informed about the implementation of the window feedback system before the start of the new situation.


Figure 38: QR-code nearby window for survey 2


Figure 39: Infographics placed on top of the tables and on the edge

12.3 Window feedback system

As part of the experiment, a window feedback system was built according to the design in chapter 9 and was implemented in the middle section of the BT-studio. The system was placed on a visible spot nearby an openable window as shown in Figure 40. The used LED-strip type is ‘WorldSemi WS2812B Digitale 5050 RGB LED Strip - 300 LEDs 5m’

Figure 40: Window feedback system that was built and implemented inside the BT-studio

12.4 Limitations

The measurement setup has several limitations and are mentioned in the following.

- The BT-studio has several aspects that differ from a typical office. Compared to typical offices, the studio has more (openable) windows due to the narrow floor plan and the multiple façades. In addition, the windows cannot open completely and the occupants do not work between specific times. Due to this dynamic behaviour, peak moments of occupancy can occur in which thresholds of the indoor environment get easily exceeded.
- Many occupants inside the BT-studio have an international background. As a result, the perspectives about openable windows and the indoor and outdoor environment can differ based on their background.
- Not all windows and radiators were monitored. The measurement setup assumes the middle section of the BT-studio as a micro-climate that is minimally influenced by its environment. This does not always hold true, for example when multiple windows are opened outside the experiment area.
- The mean radiant temperature was not measured. As a result, the operative temperature was approximated by measuring the indoor temperature.
- The outdoor noise and mechanical ventilation were not monitored. Both would have helped to get a better understanding of the situation.
- The temperature and humidity measurements taken by the outdoor sensor were inaccurate and not properly recorded. As a result, an external source was used to retrieve more reliable data.
- The occupants were observed during the experiment. This could have caused the Hawthorne effect in which the occupant's behaviour changed by observations rather than by interventions.
- The distribution method of survey 2 was not effective since it resulted in only 4 respondents. As a result, the data from survey 2 have been excluded and less detailed analyses could be made.
- Linking the surveys with an ID code was not effective since none of the volunteers remembered their ID code. As a result, less detailed analyses could be made.

13 Results and discussion

The experiment resulted in both objective and subjective data that can be used to analyze the existing and new situation. This chapter analyses both situations and conducts a comparison to determine the effectiveness of the window feedback system. Section 13.1 provides an overview of the results and the corresponding discussions for the existing situation which was conducted from 03/04/2023 to 21/04/2023. Section 13.2 provides an overview of the new situation which was conducted from 24/04/2023 to 12/05/2023. Section 13.3 makes a comparison between both situations and determines the effectiveness of the window feedback system.

13.1 Existing situation

13.1.1 Objective measurements

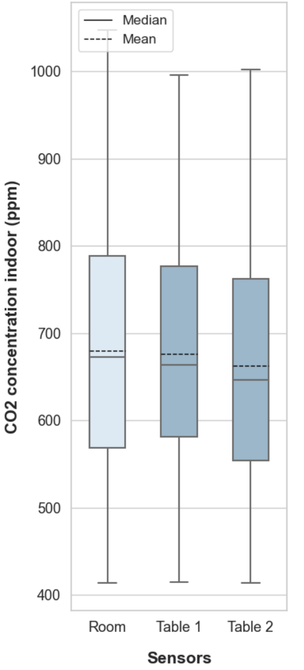


Figure 41: Indoor CO$_2$ concentration boxplot, existing situation

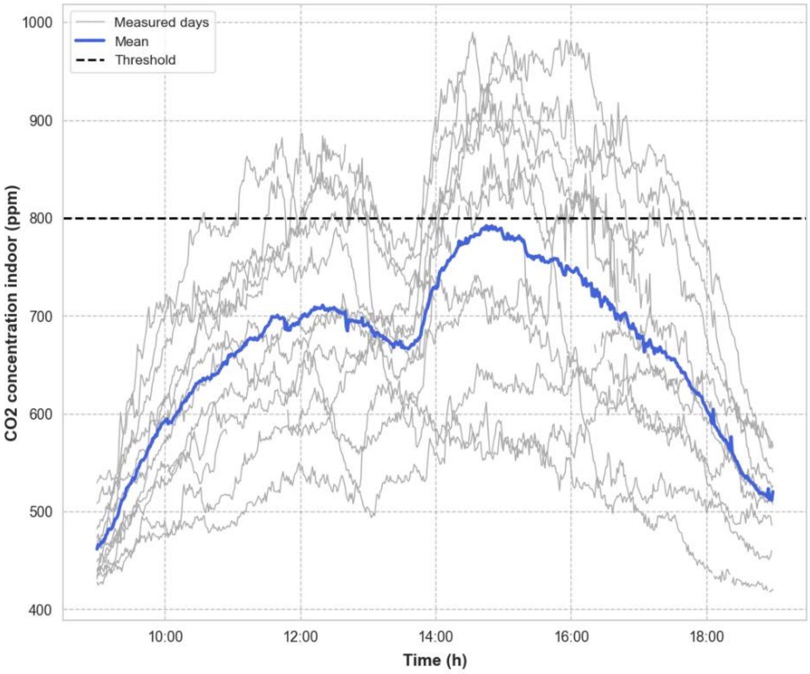


Figure 42: Measured and mean indoor CO$_2$ concentration, existing situation

The upper limit of the CO$_2$ concentration has been exceeded for a total of 1353 min, which averages to 1 hour and 53 minutes per workday. The CO$_2$ concentration is an indicator of occupancy levels and is closely related to their work schedule. Figure 42 indicates that the afternoons tend to be busier and that occupants leave the studio around lunchtime. Higher occupancy levels can contribute directly to higher indoor temperatures and indirectly to lower levels of indoor relative humidity. In the further reading, it can be seen that the maximum indoor temperature and minimum indoor relative humidity are reached during the afternoon.

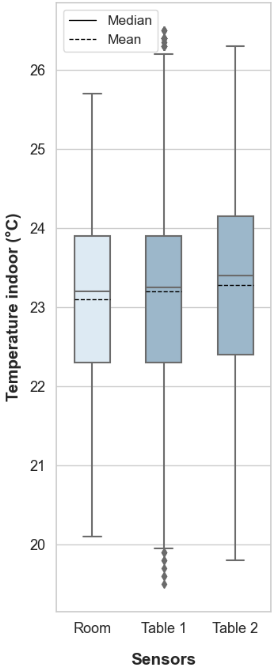


Figure 43: Indoor temperature boxplot per sensor, existing situation

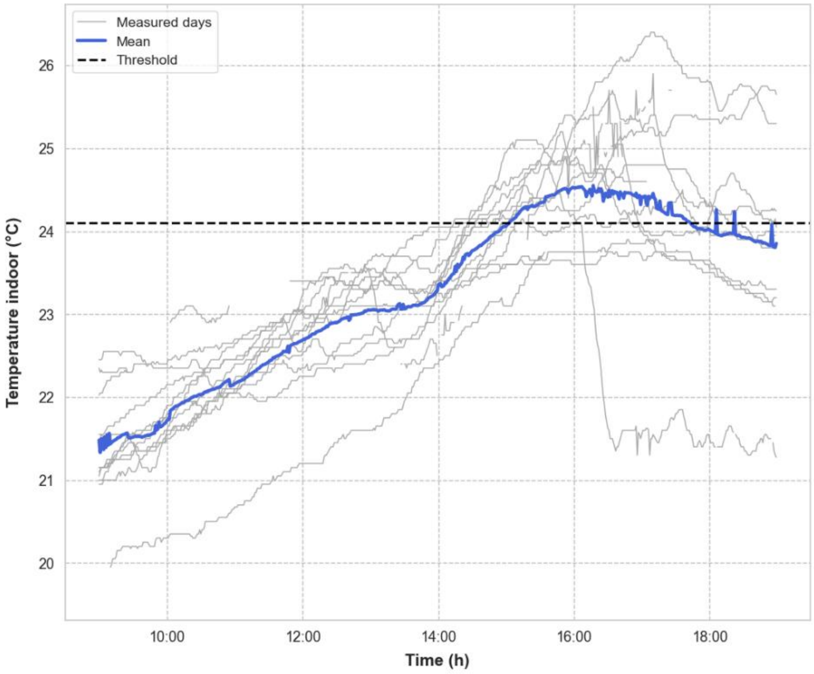


Figure 44: Measured and mean indoor temperature, existing situation

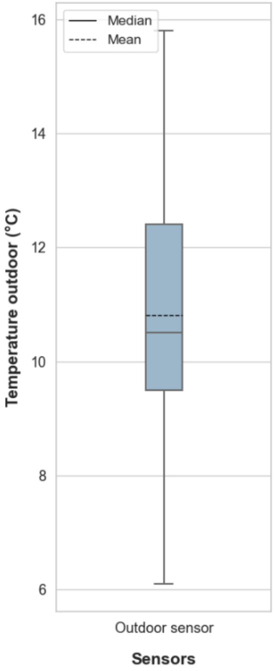


Figure 45: Outdoor temperature boxplot, existing situation

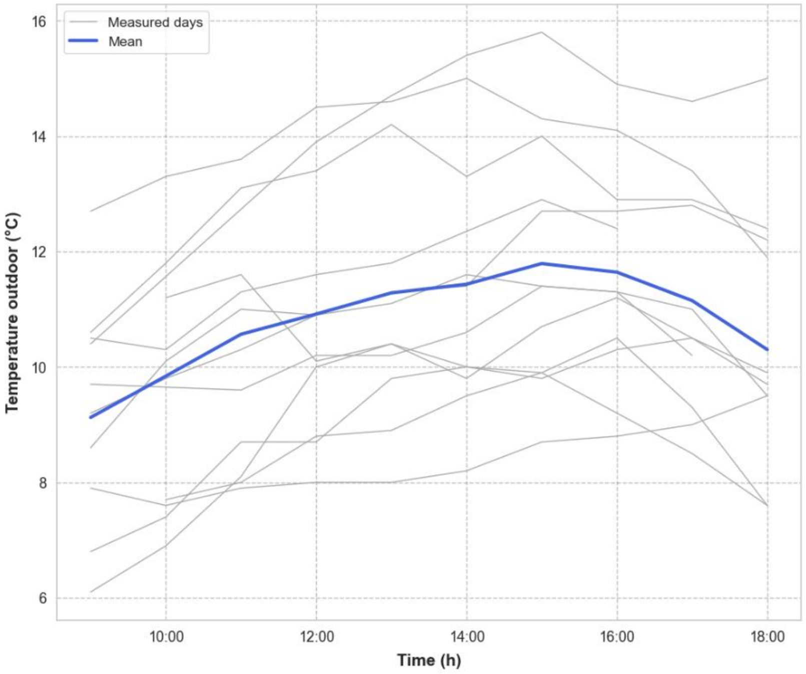


Figure 46: Measured and mean outdoor temperature, existing situation

The upper limit of the indoor temperature has been exceeded for a total of 1664 min, which averages to 2 hours and 19 minutes per workday. According to Figure 44, the exceedance primarily occurs between 14:00 and 18:00, with the peak value being reached around 16:00. This exceedance can be attributed to the outdoor temperature (Figure 46) and the occupancy which is indicated by the CO_2 levels (Figure 42). Both reach their peak value also around 16:00.

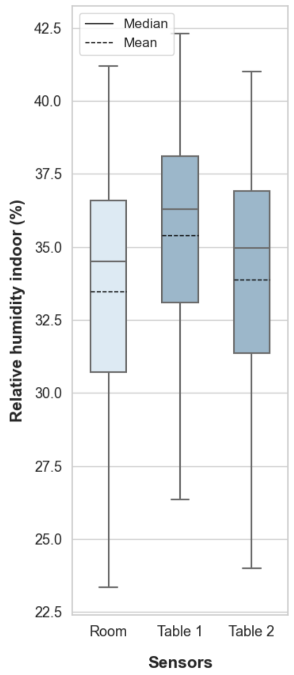


Figure 47: Indoor relative humidity boxplot, existing situation

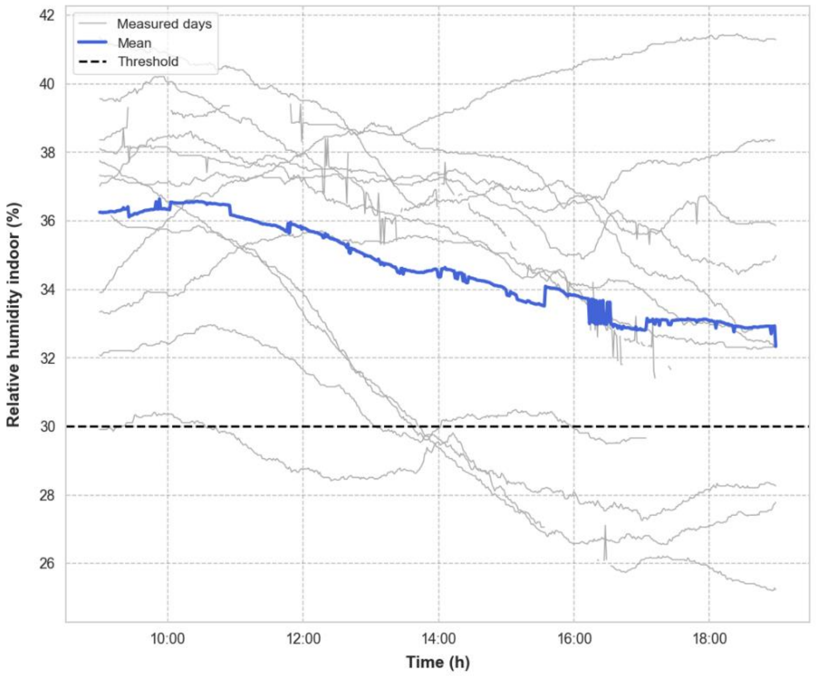


Figure 48: Measured and mean indoor relative humidity, existing situation

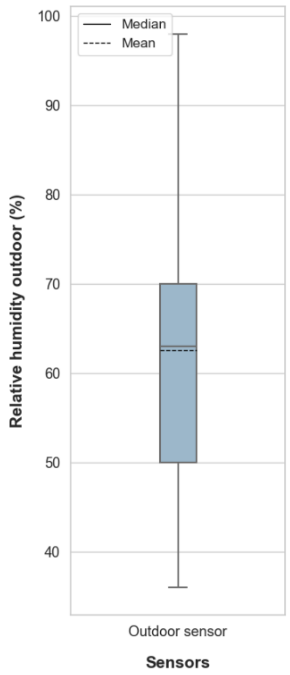


Figure 49: Outdoor relative humidity boxplot, existing situation

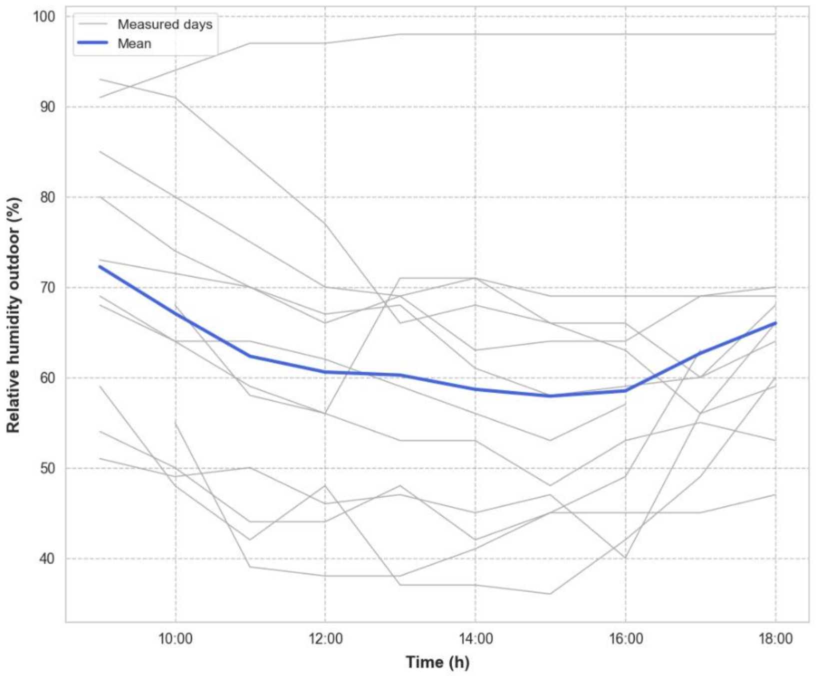


Figure 50: Measured and mean outdoor relative humidity, existing situation

The indoor relative humidity has fallen below the lower limit for a total of 1239 min, which averages to 1 hour and 43 minutes per workday. According to Figure 48, the indoor relative humidity falls primarily below the threshold between 14:00 and 18:00, with the minimum value being reached around 16:00. This pattern can be attributed to the increasing temperature, which leads to a decrease in relative humidity. Both the indoor and outdoor temperature reach their maximum value around 16:00 (see Figure 44 and Figure 46), and as a result the indoor and outdoor relative humidity reach their minimum value also around 16:00 (see Figure 48 and Figure 50). As expected in a work setting, the upper limit of the indoor relative humidity does not get exceeded.

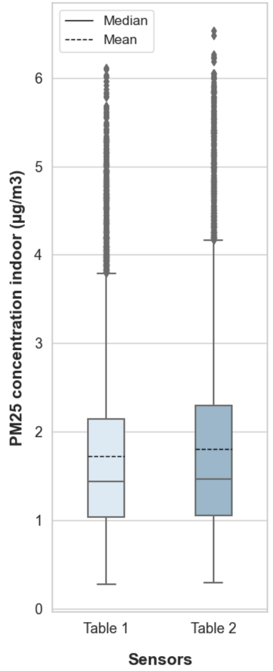


Figure 51: Indoor $PM_{2.5}$ concentration boxplot, existing situation

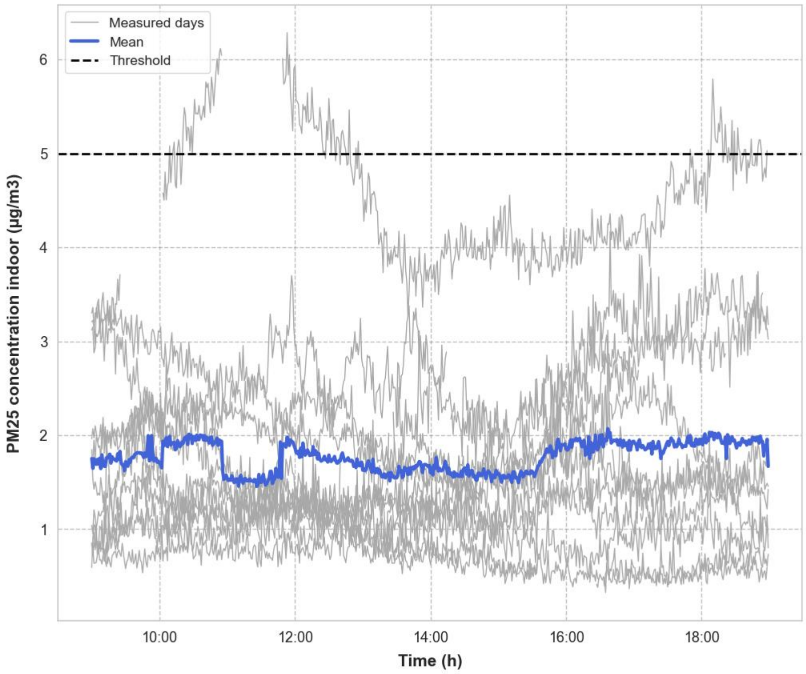


Figure 52: Measured and mean indoor $PM_{2.5}$ concentration, existing situation

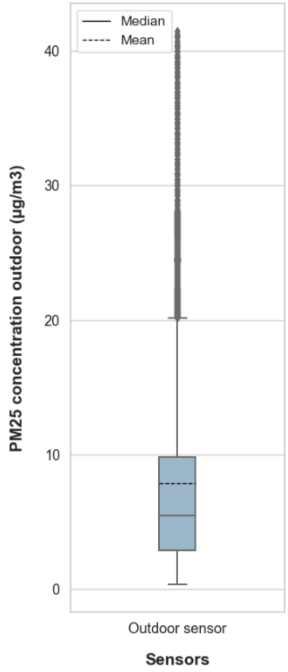


Figure 53: Outdoor $PM_{2.5}$ concentration boxplot, existing situation

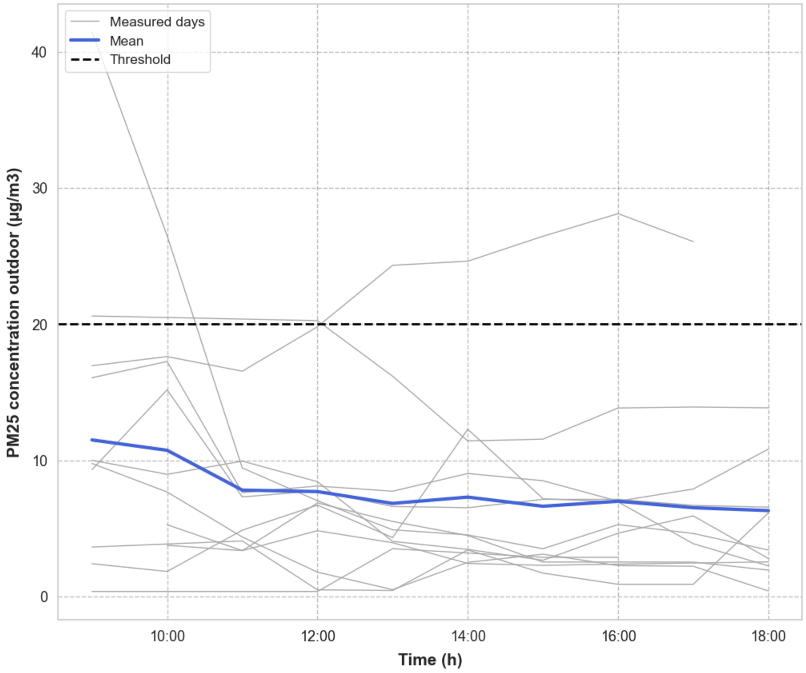


Figure 54: Measured and mean outdoor $PM_{2.5}$ concentration, existing situation

The upper limit of the outdoor $PM_{2.5}$ concentration has been exceeded on three different days, totalling 602 min. During one of these days, the indoor $PM_{2.5}$ concentration was also exceeded for a total of 124 min, which averages 10 minutes per workday. Hence, a slight correlation can be found between the exceedance of the indoor and outdoor $PM_{2.5}$ concentrations. However, it is important to note that the outdoor $PM_{2.5}$ data was retrieved from the internet and does not represent the same context as the indoor $PM_{2.5}$ data. A stronger correlation would be expected when both would be measured in the same context. It should also be noted that no correlation was found between the wind direction and the exceedance of the indoor or outdoor $PM_{2.5}$ concentration.

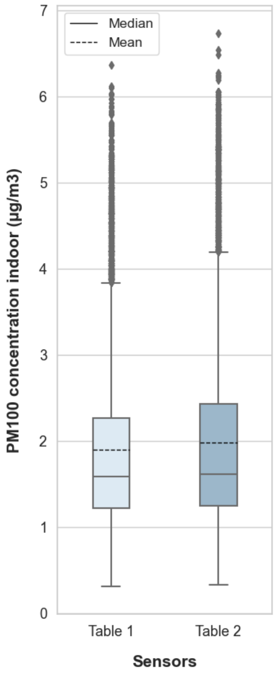


Figure 55: Indoor PM_{10} concentration boxplot, existing situation

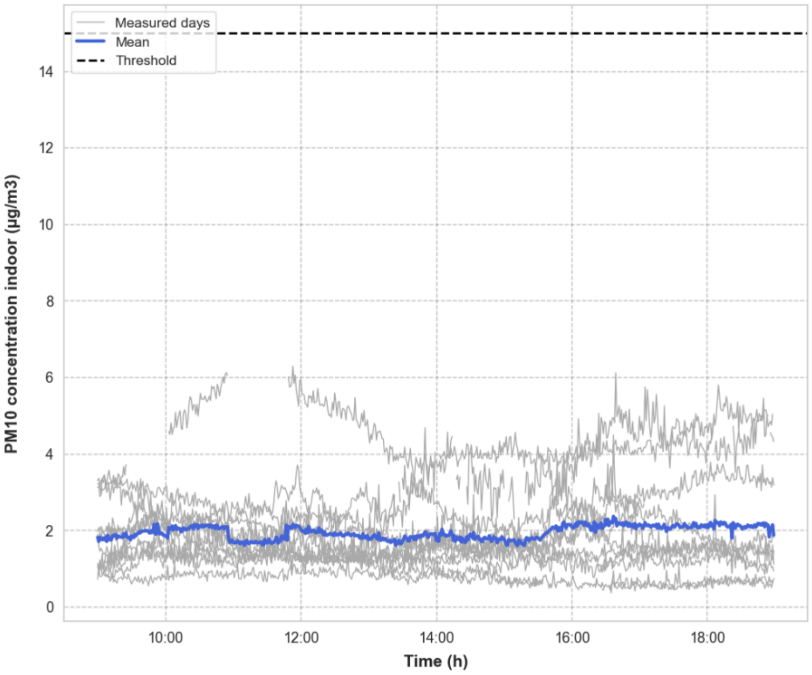


Figure 56: Measured and mean indoor PM_{10} concentration, existing situation

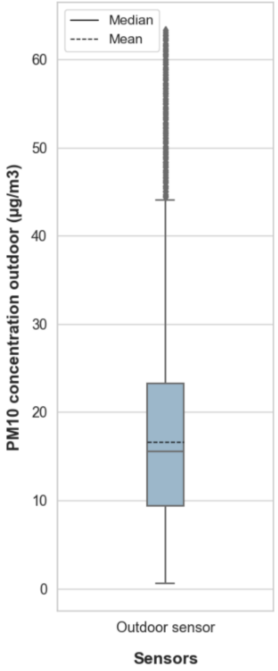


Figure 57: Outdoor PM_{10} concentration boxplot, existing situation

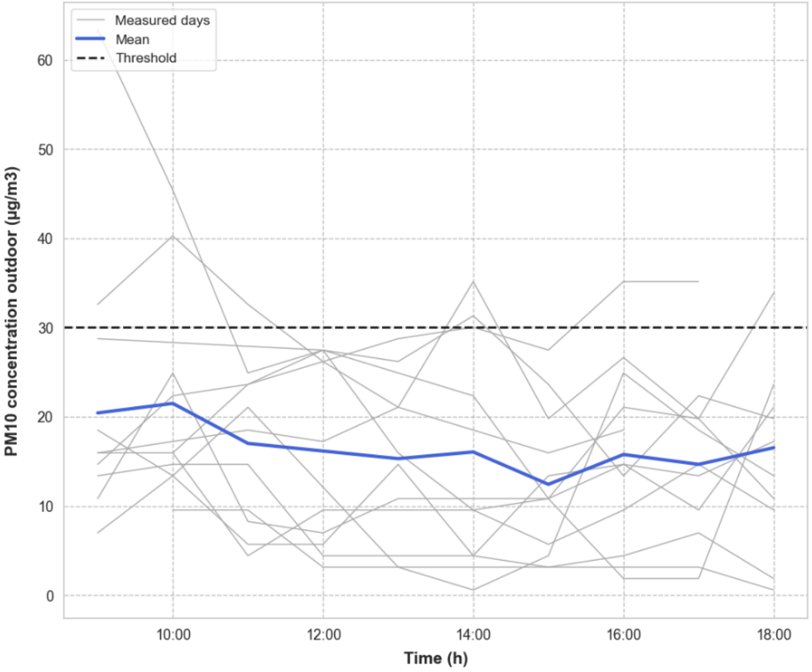


Figure 58: Measured and mean outdoor PM_{10} concentration, existing situation

The upper limit of the outdoor PM_{10} concentration has been exceeded on four different days and includes the same days in which the outdoor $PM_{2.5}$ was exceeded, hence showing a correlation. The outdoor PM_{10} concentration has been exceeded for a total of 593 minutes, which averages 49 minutes per workday. No correlation was found between the wind direction and the exceedance of the outdoor PM_{10} concentration. It should be noted that the outdoor PM_{10} data was retrieved from the internet and does not represent the same context as the indoor PM_{10} data. The indoor PM_{10} concentration was not exceeded.

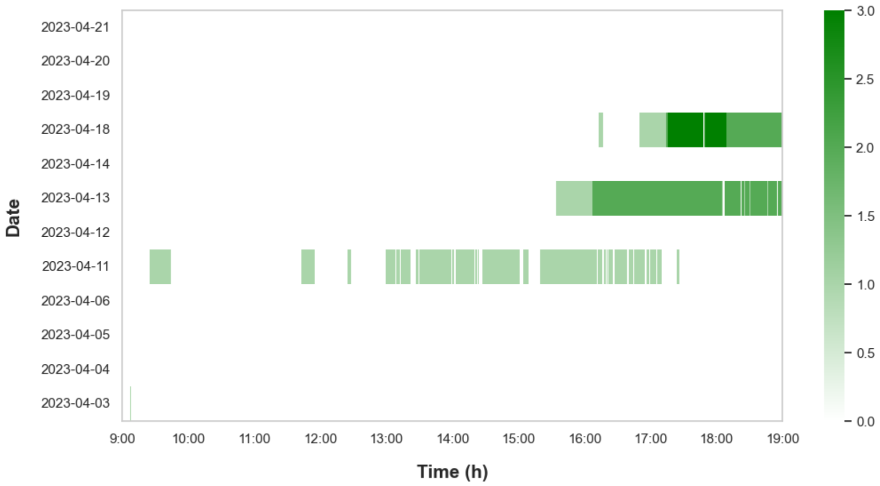


Figure 59: Number of windows that were open during the existing situation. Darker green indicates that more windows were opened simultaneously.

The windows have been opened for a total of 583 min, which averages 49 minutes per workday. The windows were primarily open in the afternoon. However, it should be taken into account that not all windows were monitored inside the BT-studio.

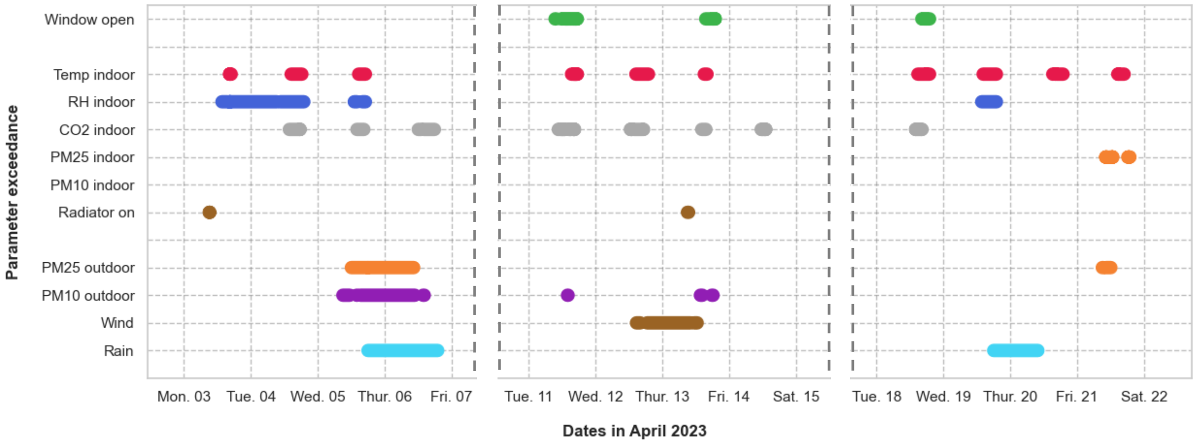


Figure 60: Overview of the different parameters when they exceed the specified thresholds for the existing situation. In addition, the figure indicates when the window was open and when the radiator was turned on.

Figure 60, provides an overview of the different parameters when they exceed the specified thresholds. As previously explained, a correlation can be seen between:

- indoor CO_2 concentration, indoor temperature and indoor relative humidity;
- Indoor $PM_{2.5}$ and outdoor $PM_{2.5}$;
- Outdoor $PM_{2.5}$ and outdoor PM_{10}.

Furthermore, the figure shows that the windows were open a few times when the thresholds of the indoor temperature and indoor CO_2 concentration got exceeded. Simultaneously, it shows that the window could have been opened more to improve the indoor environment, although it should be considered that not all windows were monitored in the BT-studio. The figure shows also that the windows were closed when the radiators were turned on, indicating that no energy loss occurred directly. However, it should be considered that similar to the windows, not all radiators were monitored.

13.1.2 Subjective measurements

A general survey was conducted at the start of the experiment to validate the results of the objective measurements and to create a better understanding of window operation. This survey received 37 respondents. The results and corresponding conclusions are shown in this section.

Composition respondents

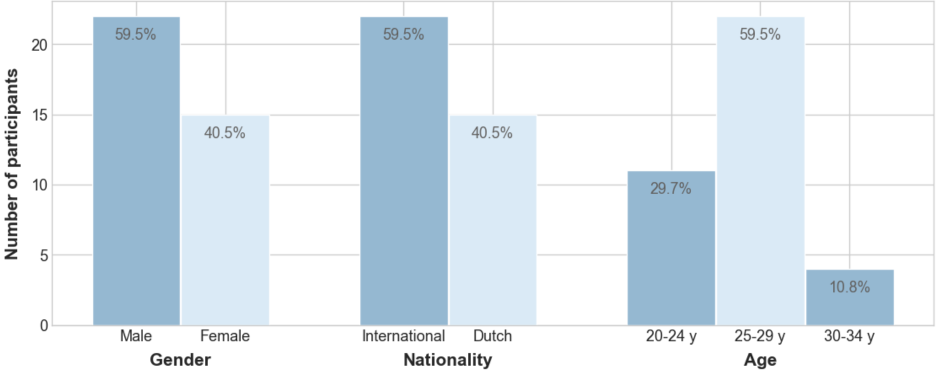


Figure 61: Gender, nationality and age distribution of the survey respondents

Figure 61 shows the composition of the respondents, representing primarily young adults with a balanced distribution in gender and backgrounds. As a result, the perspective of other age ranges (e.g., adults) is not included in the survey and presents a limitation to consider. The mean age of the respondents is 26 years.

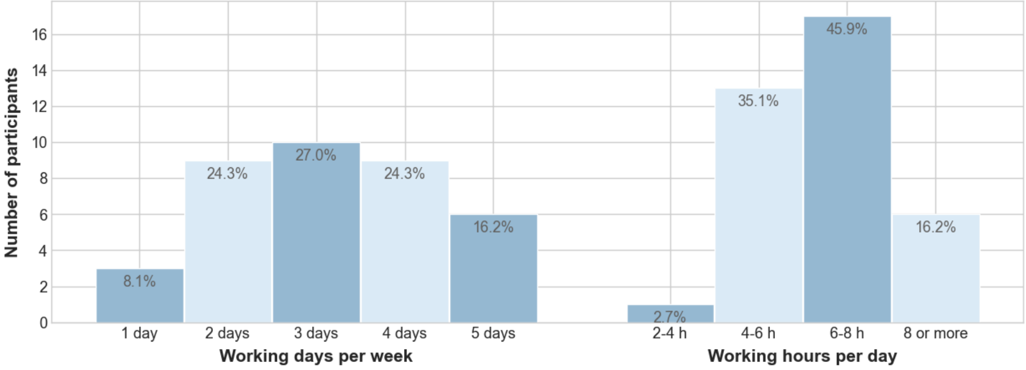


Figure 62: Average working days per week and working hours per day of the occupants

Figure 62 shows the average working schedule of the respondents with a mean of 3 days per week and 6 to 8 hours per day. This seems sufficient enough to create a general judgement of the indoor environment. No respondents have been excluded from the analyses based on their working schedule to keep a broad composition with different perspectives.

Indoor environment

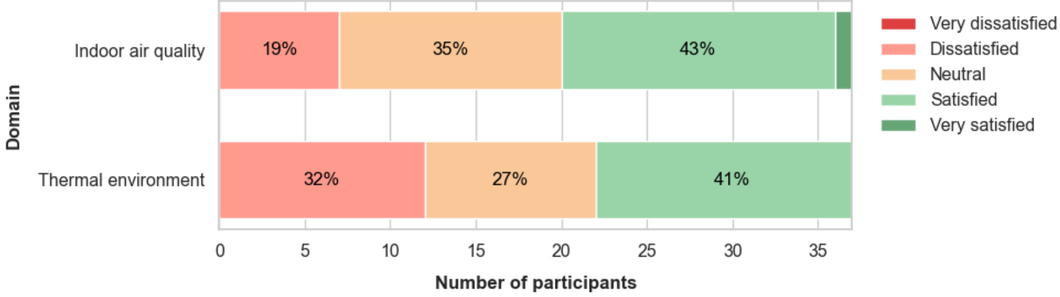


Figure 63: Satisfaction with the indoor air quality and thermal environment inside the BT-studio

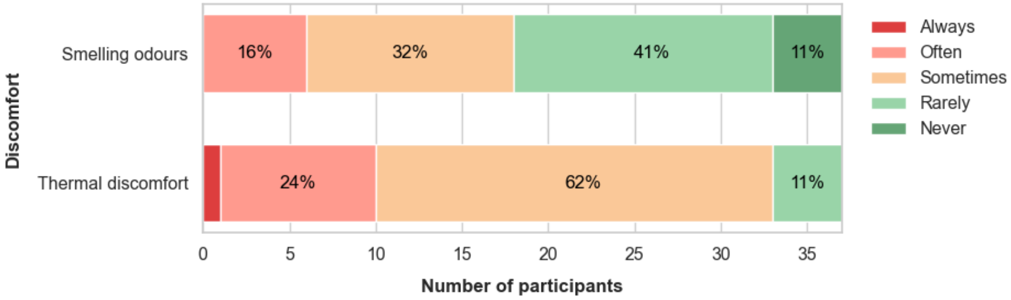


Figure 64: Frequency of discomfort related to the indoor air quality and thermal environment inside the BT-studio

According to Figure 63, only ±40% of the respondents are satisfied with the indoor air quality and thermal environment inside the BT-studio. Figure 64 shows that 89% of the respondents experience thermal discomfort from sometimes to often, and 48% smell odours from sometimes to often. These results coincide with the objective measurements which showed that the thresholds of the indoor CO_2 concentration and temperature were exceeded multiple times.

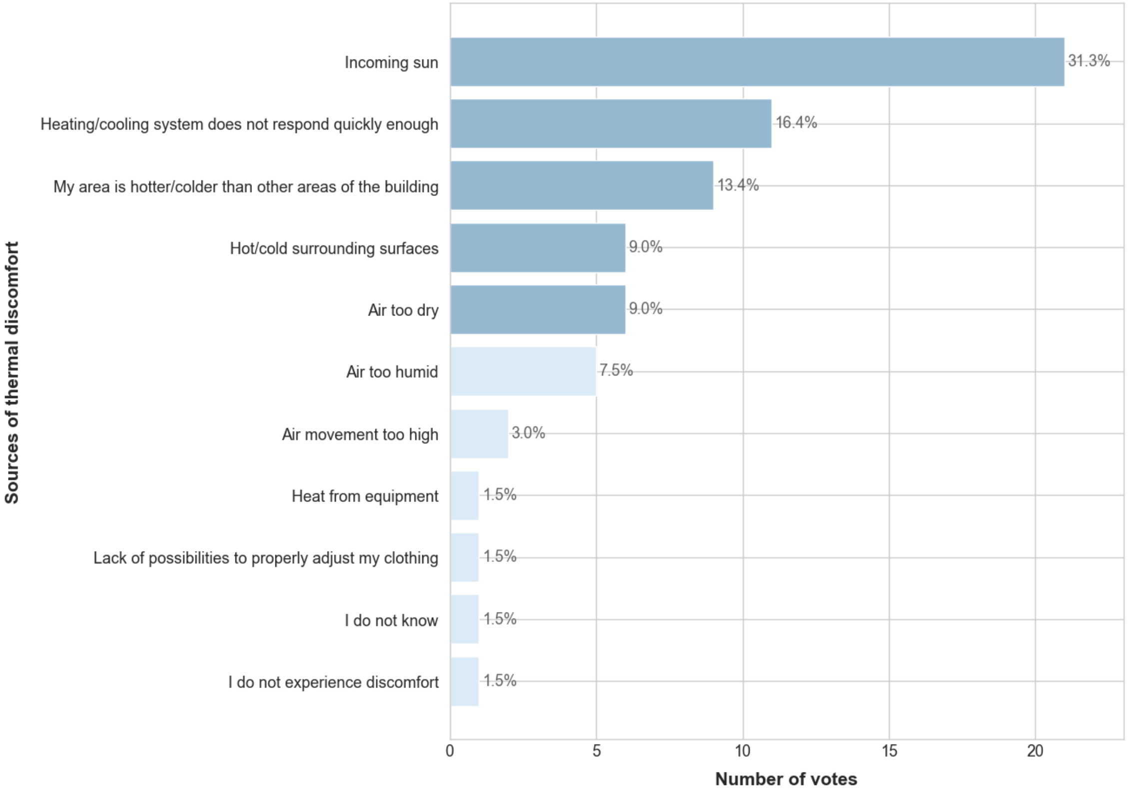


Figure 65: Sources of discomfort related to the thermal environment inside the BT-studio

Figure 65 shows different sources that cause thermal discomfort inside the BT-studio. It appears that the incoming sun is one of the main reasons, which most likely also contributes to the exceedance of the indoor temperature. This significant impact of the sun forms a limitation for the new situation since the designed algorithm does not take the sun radiation into account, as explained in chapter 10. Other significant contributors to thermal discomfort are related to the installations, thermal mass and indoor relative humidity. Concerning the latter, the objective measurements show that the indoor relative humidity falls several times below the under limit which corresponds to the subjective perception 'Air too dry'. However, the objective measurements do not correspond with the perception 'Air too humid' and could have been experienced outside the measurement period.

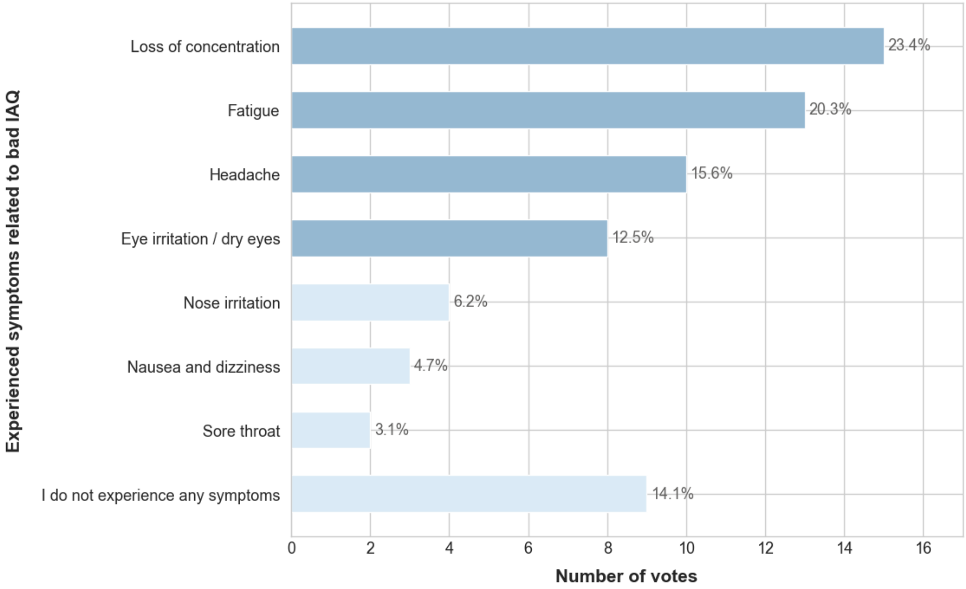


Figure 66: Regularly experienced symptoms that can be related to bad indoor air quality inside the BT-studio

Figure 66 shows different symptoms that can be related to bad indoor air quality inside the BT-studio. The symptoms of loss of concentration, fatigue, headache, nausea and dizziness could be related to high CO_2 concentrations. However, these symptoms are more likely to be the cause of high noise levels inside the BT-studio since the CO_2 levels have been kept below 1000 ppm. The symptoms of eye irritation/dry eyes, nose irritation, and sore throat can be related to low indoor relative humidity levels and correspond to the objective measurements in which the humidity falls several times below the threshold of 30%.

Window opening

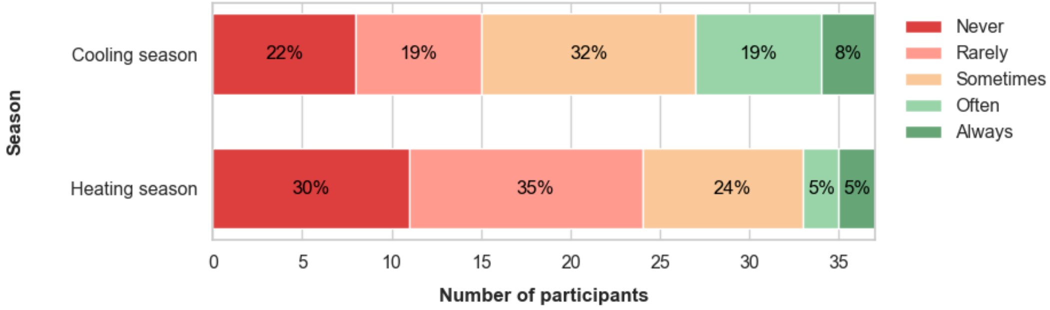


Figure 67: Frequency of window operation during the heating and cooling season

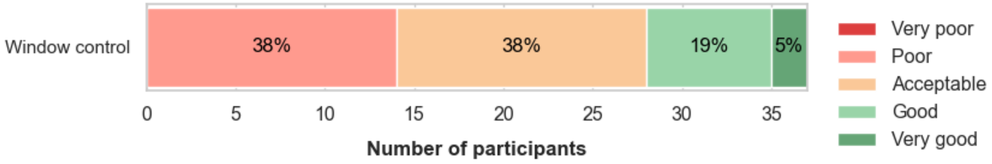


Figure 68: Perceived window control inside the BT-studio

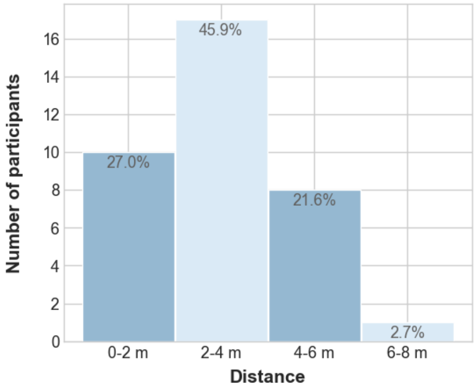


Figure 69: Distance from an openable window to the workplace where respondents usually sit inside the BT-studio

Figure 67 indicates how often respondents operate the window inside the BT-studio during the heating and cooling season. In this figure, it stands out that 41% never or rarely operates the windows during the cooling season. A higher frequency of window operations would be expected when you consider the weather and complaints about the thermal environment and indoor air quality. One explanation for the low usage of openable windows is the poor perceived window control as indicated in Figure 68. However, the poor perception of the window control contradicts the presence of many openable windows and the short distance to open them, as illustrated by Figure 69. According to four respondents, the poor perception is attributed to the inclination of the windows. They expressed that the inclined position is not effective enough to improve the indoor environment.

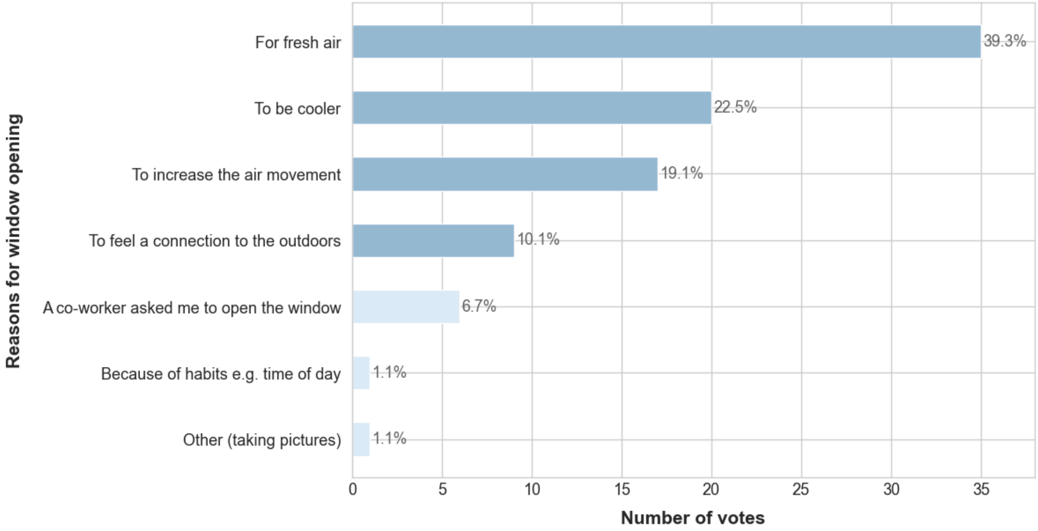


Figure 70: Most important reasons for window opening

Figure 70 illustrates the most important reasons for window opening and has a similar outcome as the study of Ackerly and Brager (2013).

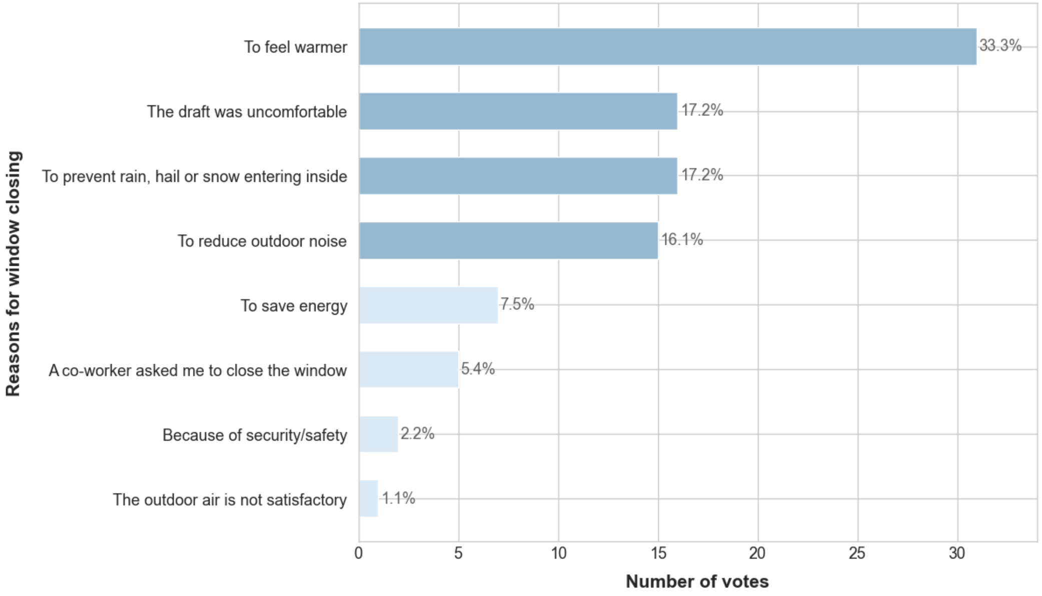


Figure 71: Most important reasons for window closing

Figure 71 shows the most important reasons for window closing. The results of this figure coincide with the conclusions of the literature study which indicated that heat loss, wind and rain are important drivers for window closing. Outdoor noise appears also to be an important driver.

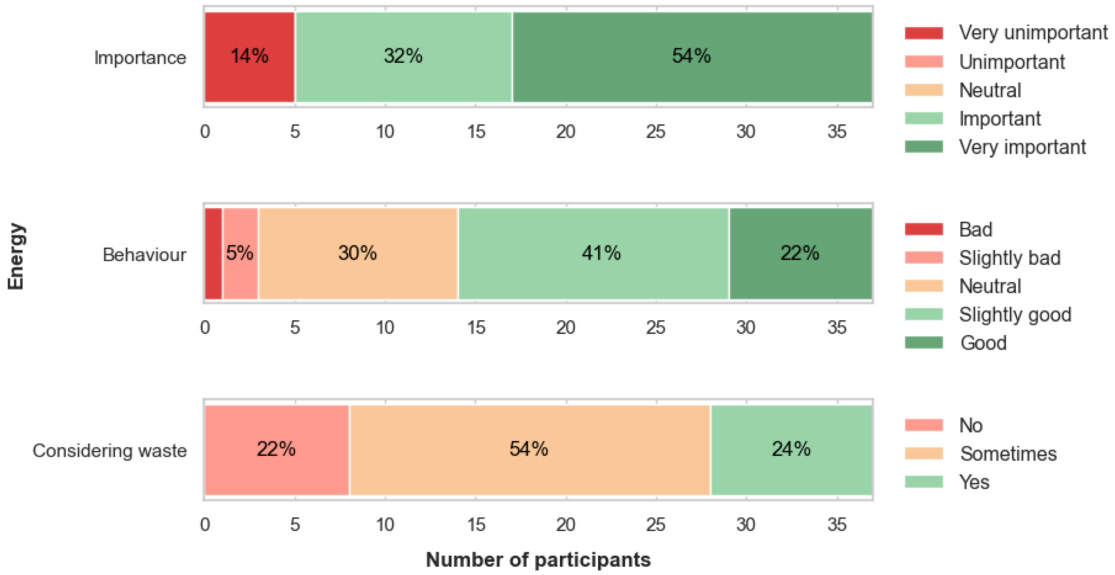


Figure 72: Top: Perceived importance of energy-efficient buildings; Middle: Perceived energy efficiency of own behaviour inside buildings; Bottom: Whether respondents consider (thermal) energy waste when opening a window

Figure 72 indicates that respondents primarily value energy-efficient buildings and do consider (thermal) energy waste when opening a window. However, this conclusion cannot be validated by objective measurements which forms a limitation. It is conceivable that respondents may tend to perceive their energy-efficient behaviour more favourable than it really is. It should also be noted that all respondents are educated in building sustainability which could have improved their energy-efficient behaviour.

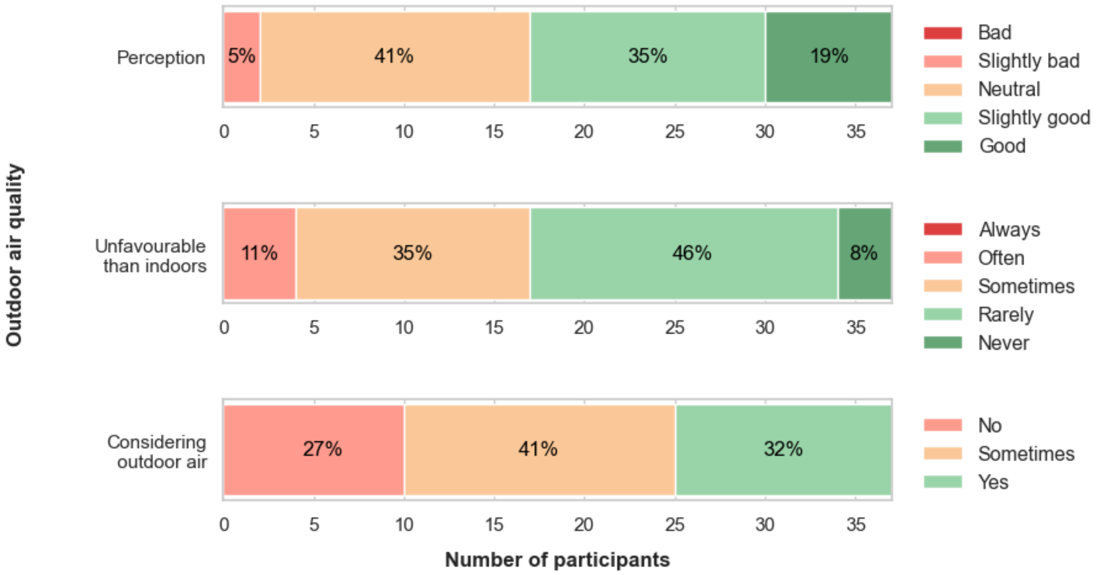


Figure 73: Top: Perceived quality of the outdoor air; Middle: Perceived frequency of the outdoor air quality being worse than the indoor air quality; Bottom: Whether occupants consider the outdoor air quality when opening a window

Figure 73 indicates that respondents primarily judge the outdoor air quality as (slightly) good and perceive it to be better than the indoor air quality. It also shows that respondents in general do consider the outdoor air quality when opening a window.

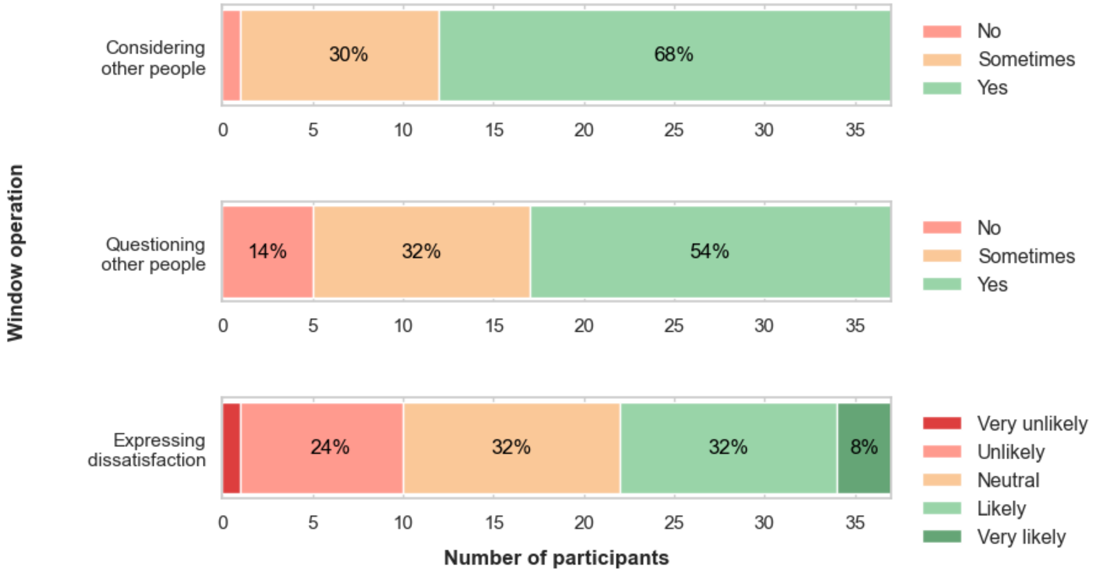


Figure 74: Top: Whether the comfort of other people is considered when operating a window; Middle: Whether the comfort of other people is questioned when operating a window; Bottom: Probability of expressing dissatisfaction when someone operates the window

Figure 74 indicates that most respondents do consider other people when operating a window in which 54 to 86% are (very) likely to question others for approval. Interestingly, only 40% of the respondents are (very) likely to express their dissatisfaction when someone else operates the window.

13.2 New situation

13.2.1 Objective measurements

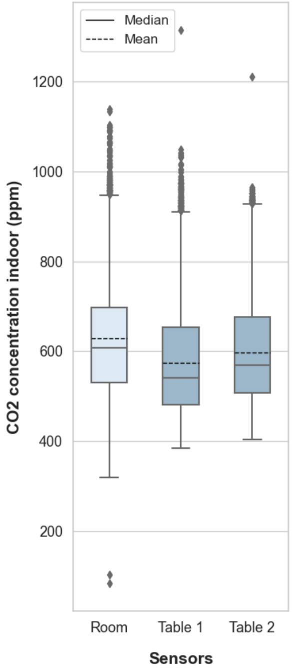


Figure 75: Indoor CO₂ concentration boxplot, new situation

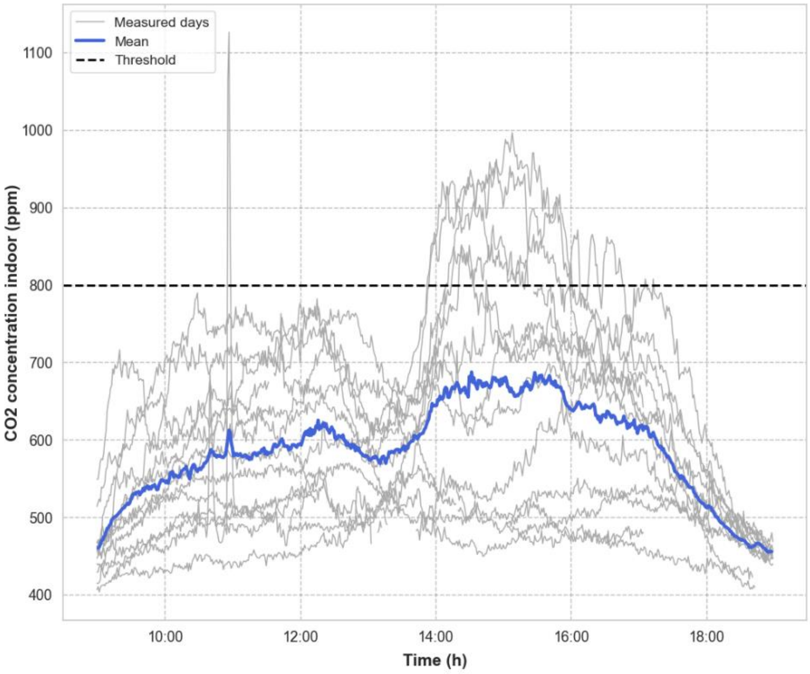


Figure 76: Measured and mean indoor CO₂ concentration, new situation

The indoor CO_2 concentration in the new situation exhibits similar patterns as previously discussed for the existing situation and is shown in Figure 75 to Figure 76. The upper limit of the indoor temperature has been exceeded for a total of 492 min, which averages 38 minutes per workday.

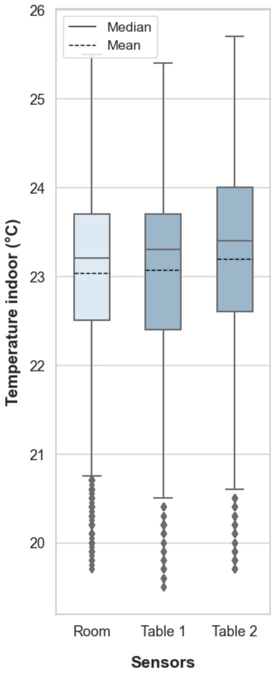


Figure 77: Indoor temperature boxplot per sensor, new situation

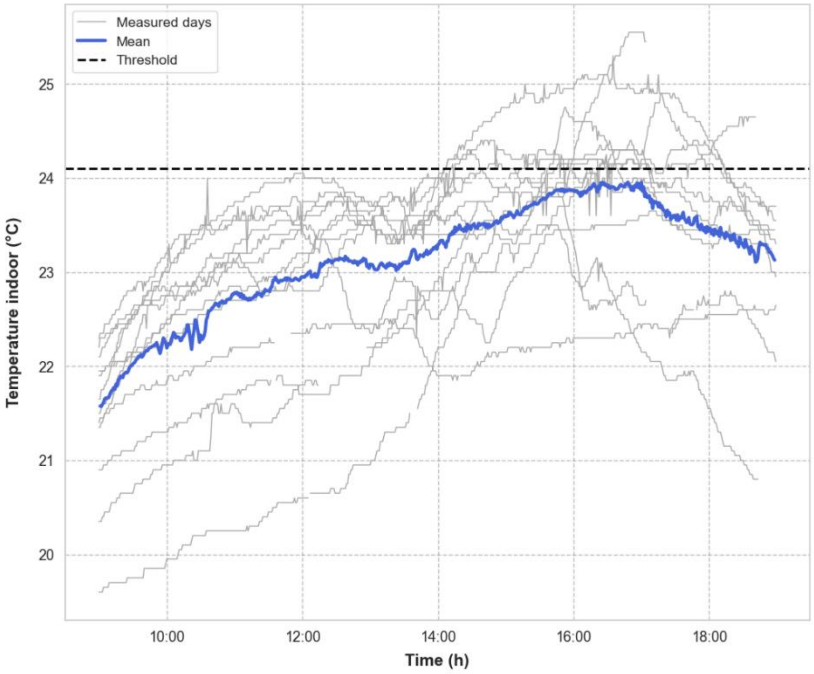


Figure 78: Measured and mean indoor temperature, new situation

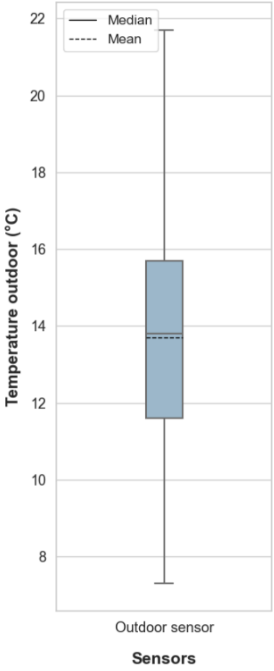


Figure 79: Outdoor temperature boxplot, new situation

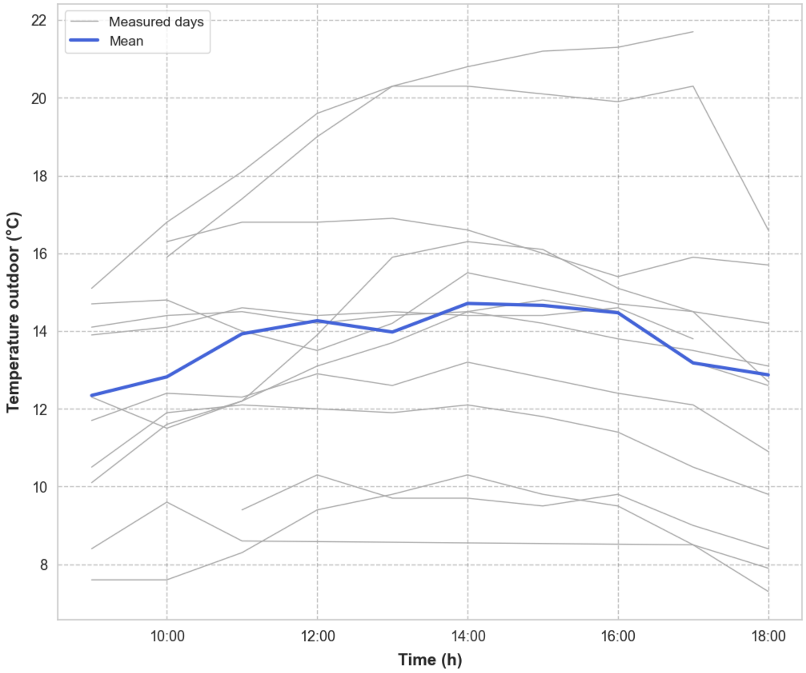


Figure 80: Measured and mean outdoor temperature, new situation

The indoor and outdoor temperatures in the new situation exhibit similar patterns as previously discussed for the existing situation and are shown in Figure 77 to Figure 80. The upper limit of the indoor temperature has been exceeded for a total of 674 min, which averages 52 minutes per workday.

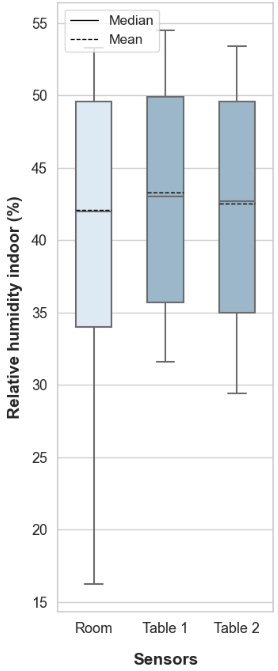


Figure 81: Indoor relative humidity boxplot, new situation

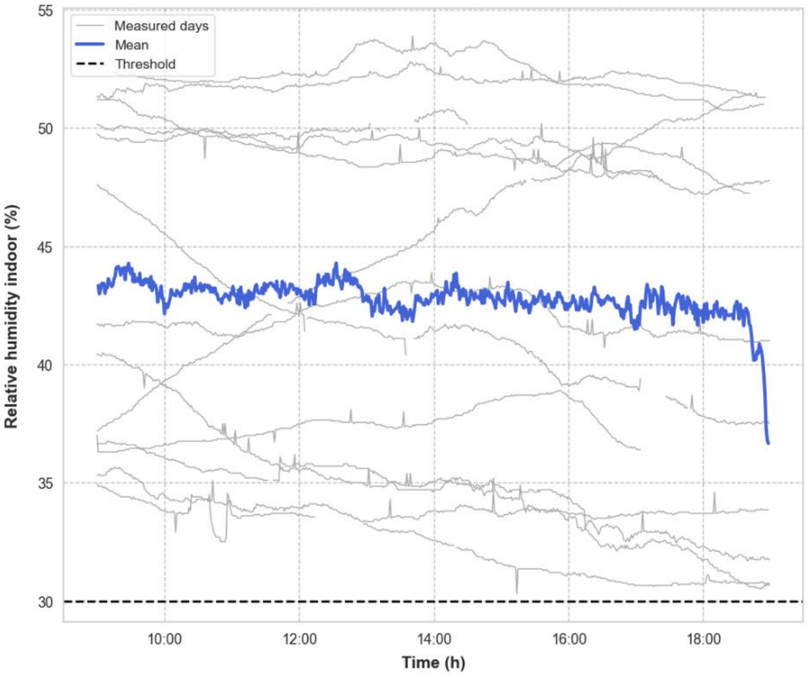


Figure 82: Measured and mean indoor relative humidity, new situation

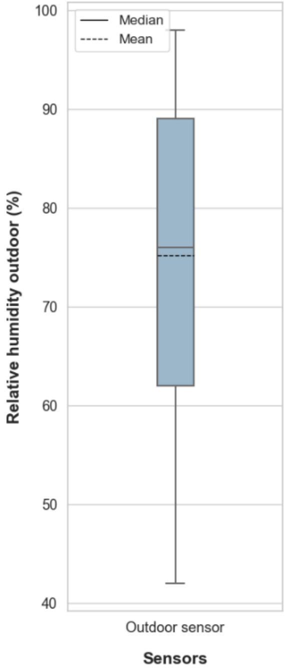


Figure 83: Outdoor relative humidity boxplot, new situation

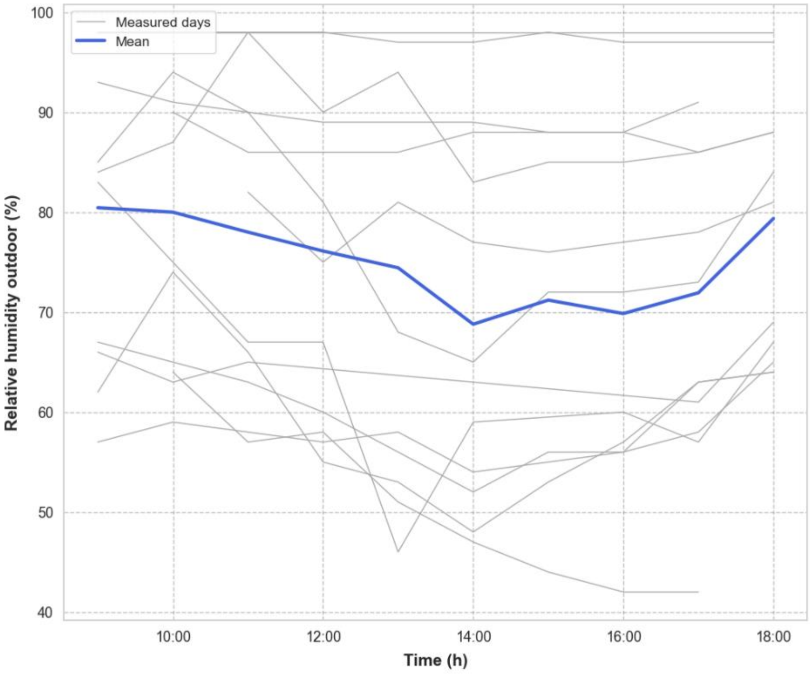


Figure 84: Measured and mean outdoor relative humidity, new situation

The indoor and outdoor relative humidity in the new situation exhibit similar patterns as previously discussed for the existing situation and are shown in Figure 81 to Figure 84. The indoor relative humidity has not fallen below the threshold.

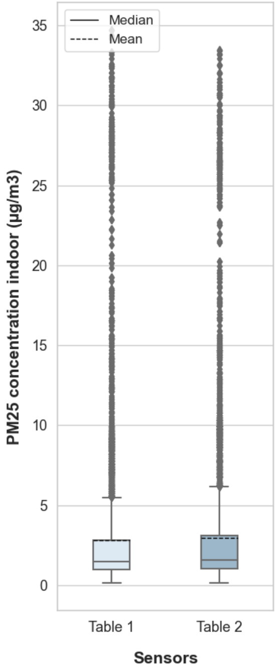


Figure 85: Indoor $PM_{2.5}$ concentration boxplot, new situation

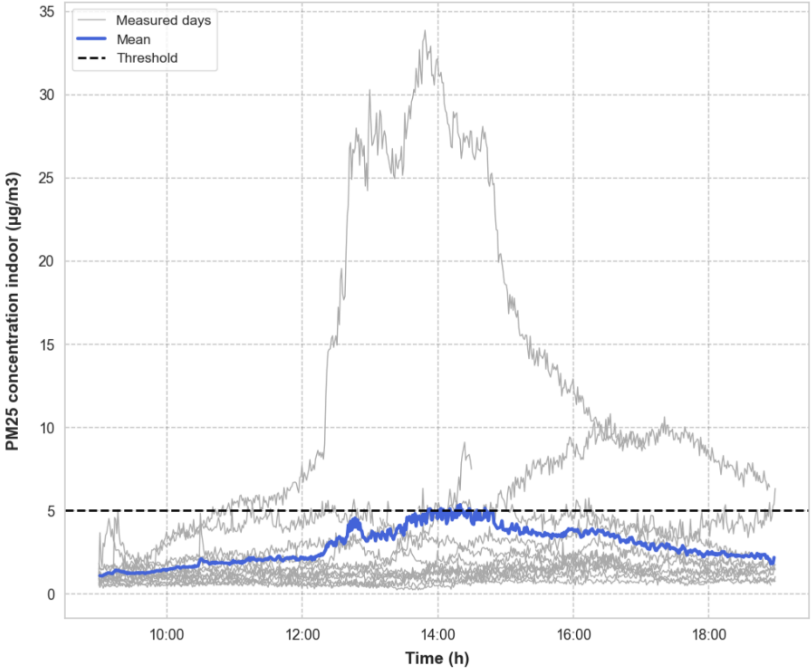


Figure 86: Measured and mean indoor $PM_{2.5}$ concentration, new situation

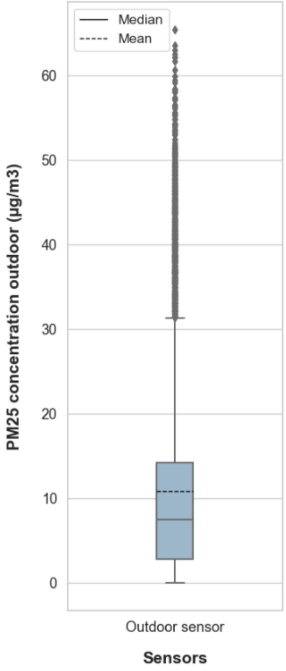


Figure 87: Outdoor $PM_{2.5}$ concentration boxplot, new situation

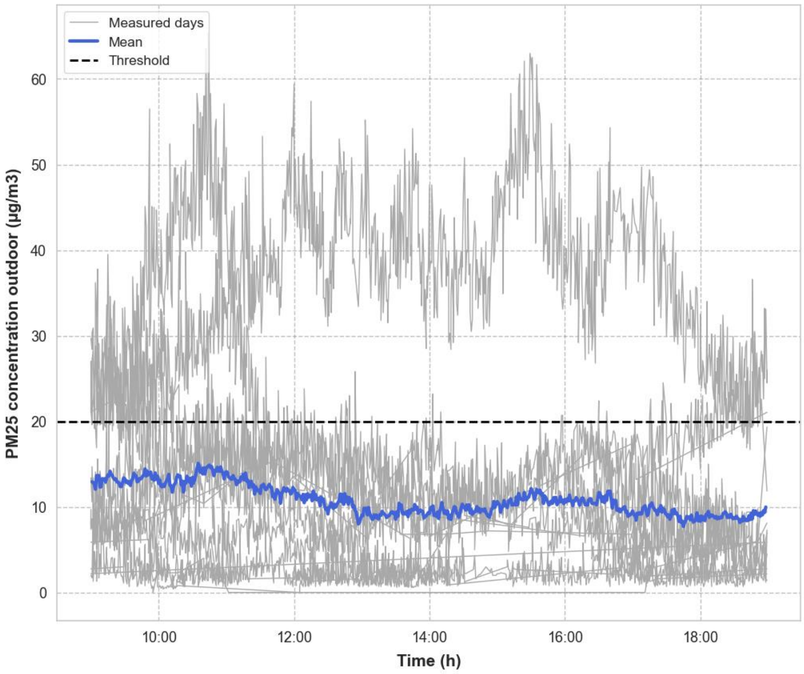


Figure 88: Measured and mean outdoor $PM_{2.5}$ concentration, new situation

The indoor and outdoor $PM_{2.5}$ concentrations in the new situation exhibit similar patterns as previously discussed for the existing situation. As an exception, a stronger correlation can be found between the indoor and outdoor $PM_{2.5}$ concentrations since both were measured in the same context. The upper limit of the outdoor $PM_{2.5}$ concentration has been exceeded on six different days, totalling 1397 min. During four of these days, the indoor $PM_{2.5}$ concentration was also exceeded for a total of 1030 min, which averages 1 hour and 19 minutes per workday.

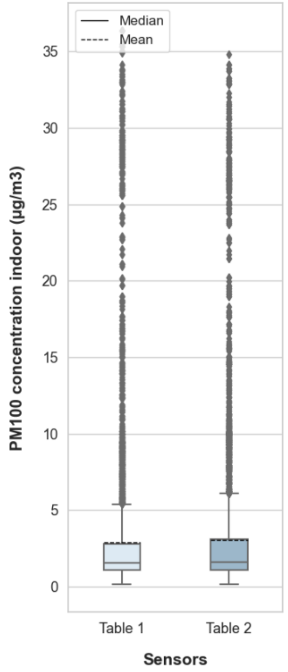


Figure 89: Indoor PM$_{10}$ concentration boxplot, new situation

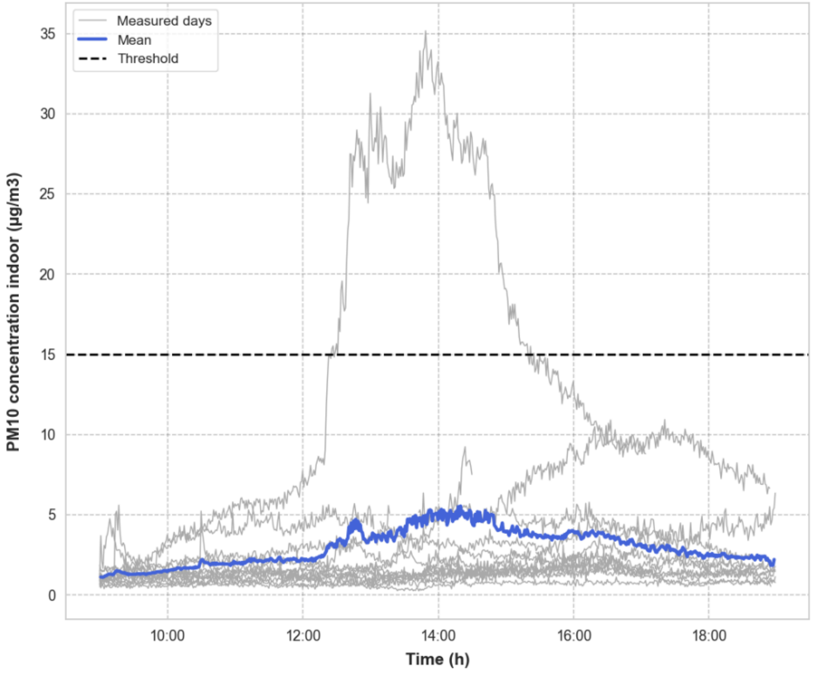


Figure 90: Measured and mean indoor PM$_{10}$ concentration, new situation

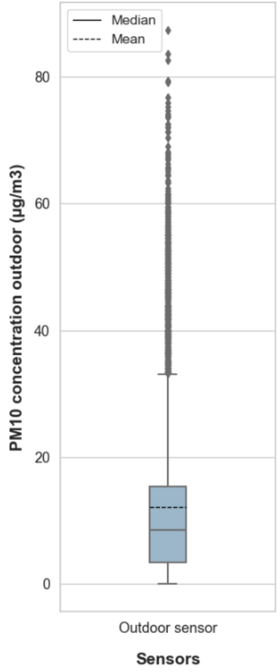


Figure 91: Outdoor PM$_{10}$ concentration boxplot, new situation

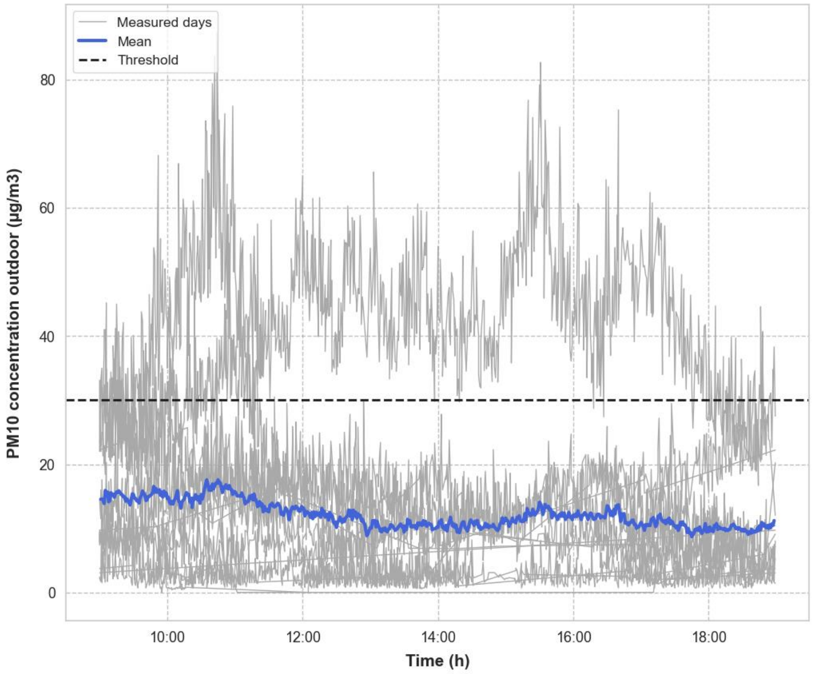


Figure 92: Measured and mean outdoor PM$_{10}$ concentration, new situation

The indoor and outdoor PM$_{10}$ concentrations in the new situation exhibit similar patterns as previously discussed for the existing situation. As an exception, a stronger correlation can be found between the indoor and outdoor PM$_{10}$ concentrations since both were measured in the same context. The upper limit of the outdoor PM$_{10}$ concentration has been exceeded on five different days, totalling 931 min. During one of these days, the indoor PM$_{10}$ concentration was also exceeded for a total of 252 min, which averages 19 minutes per workday.

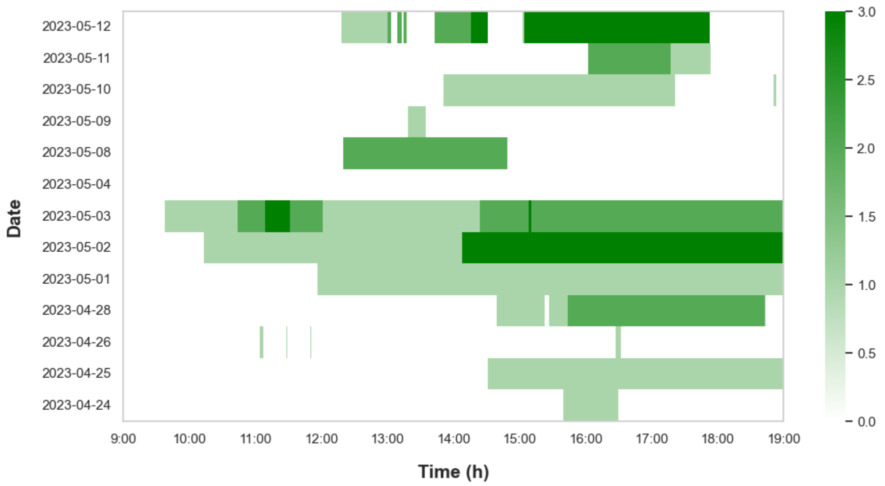


Figure 93: Number of windows that were open during the new situation. Darker green indicates that more windows were opened simultaneously.

The windows have been opened for a total of 3627 min, which averages to 4 hours and 39 minutes per workday. The windows were primarily open in the afternoon. However, it should be taken into account that not all windows were monitored inside the BT-studio.

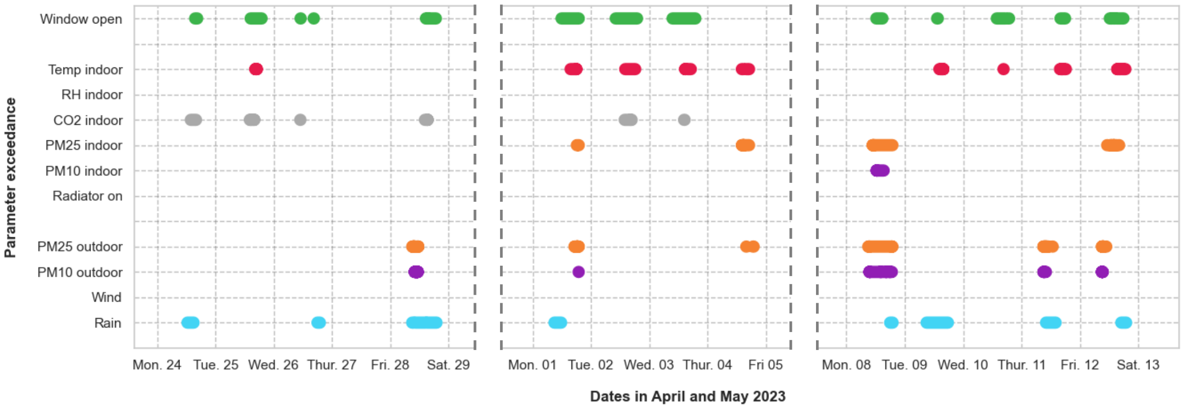


Figure 94: Overview of the different parameters when they exceed the specified thresholds for the new situation. In addition, the figure indicates when the window was open and when the radiator was turned on.

Figure 94, provides an overview of the different parameters when they exceed the specified thresholds for the new situation. The figure exhibits similar patterns as previously discussed for the existing situation. Moreover, it reveals that the windows were open when the rain threshold was exceeded, suggesting that the non-validated rain threshold could be higher. The figure shows also that the monitored radiators were not used in the new situation.

13.3 Comparison of the existing and new situation

13.3.1 Objective measurements

Figure 95 to Figure 104 make a comparison between the existing and new situation by plotting the mean for all measured parameters in both situations. Figure 95 to Figure 98 show that the new situation has an increased window opening time together with a decreased CO_2 concentration and indoor temperature. This indicates that these parameters improved by a higher window opening time. At the same time, Figure 101 to Figure 104 suggest that the indoor particulate matter was increased in the new situation by a higher window opening time. This relation is in particular indicated by the increased indoor PM_{10} concentration and decreased outdoor PM_{10} concentration.

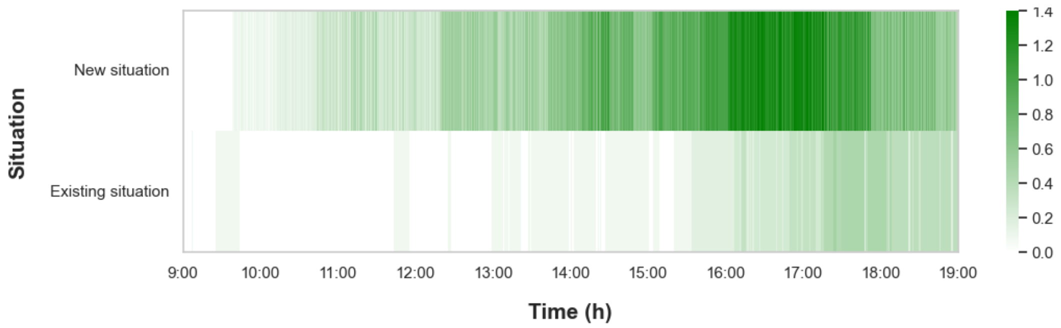


Figure 95: Mean number of windows that were open during the existing and new situation

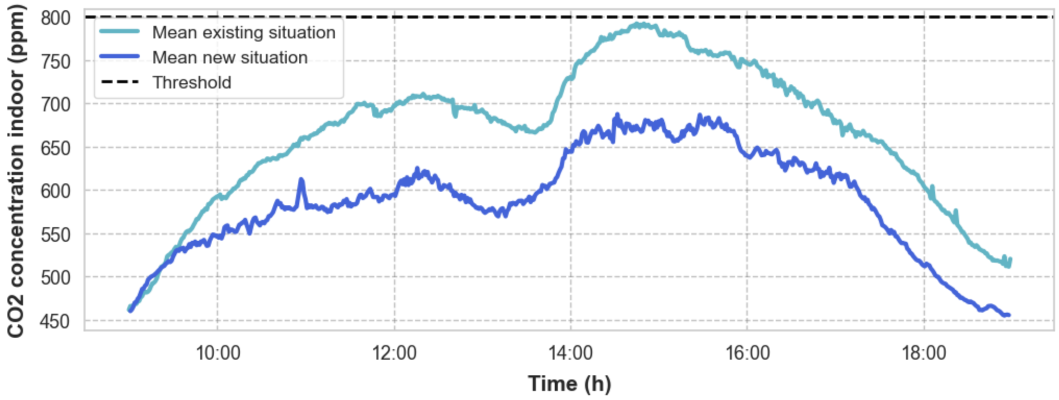


Figure 96: Mean CO_2 concentration for the existing and new situation

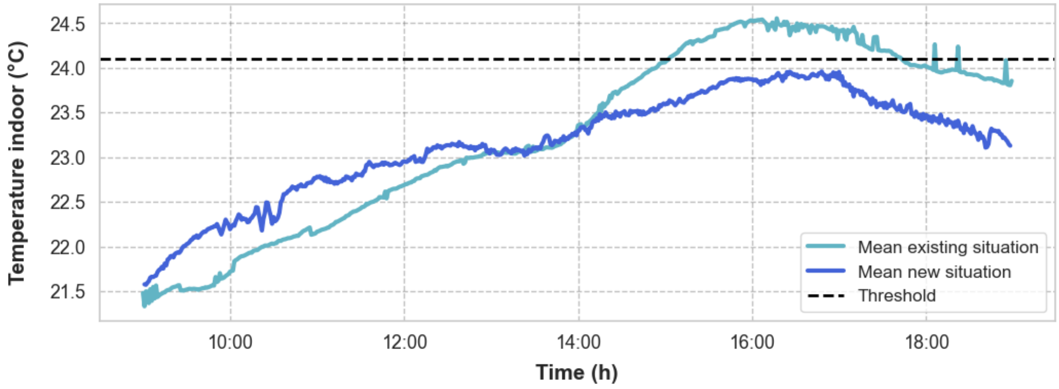


Figure 97: Mean indoor temperature for the existing and new situation

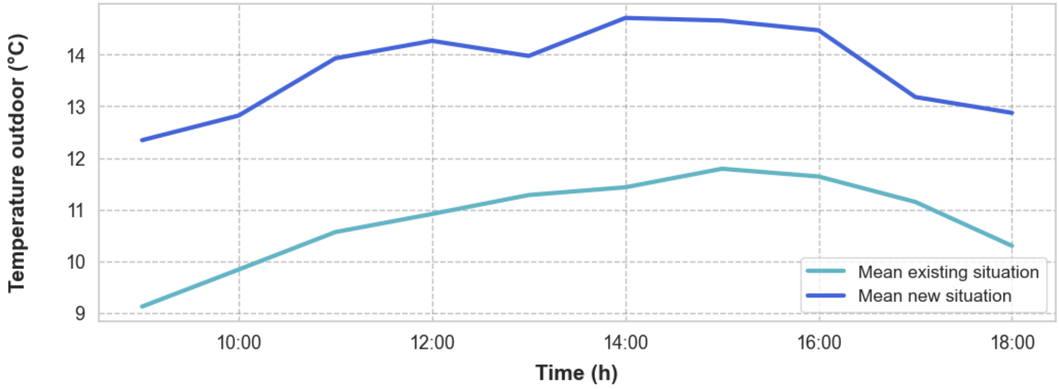


Figure 98: Mean outdoor temperature for the existing and new situation

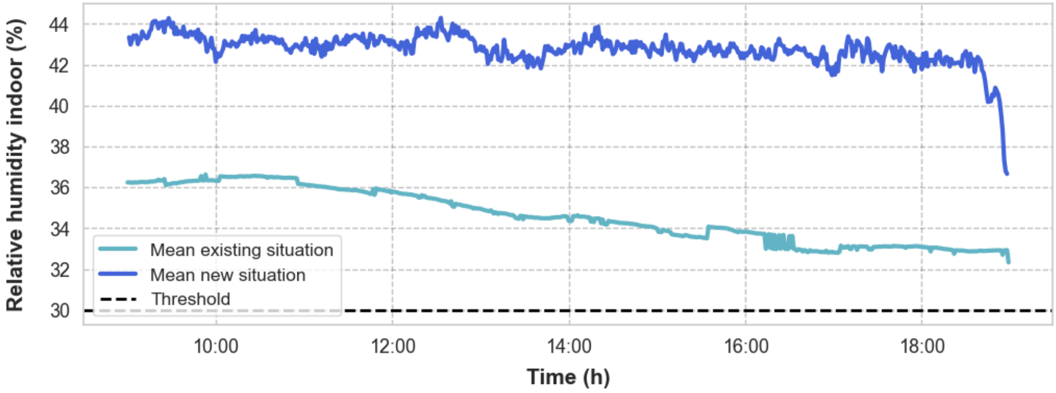


Figure 99: Mean indoor relative humidity for the existing and new situation

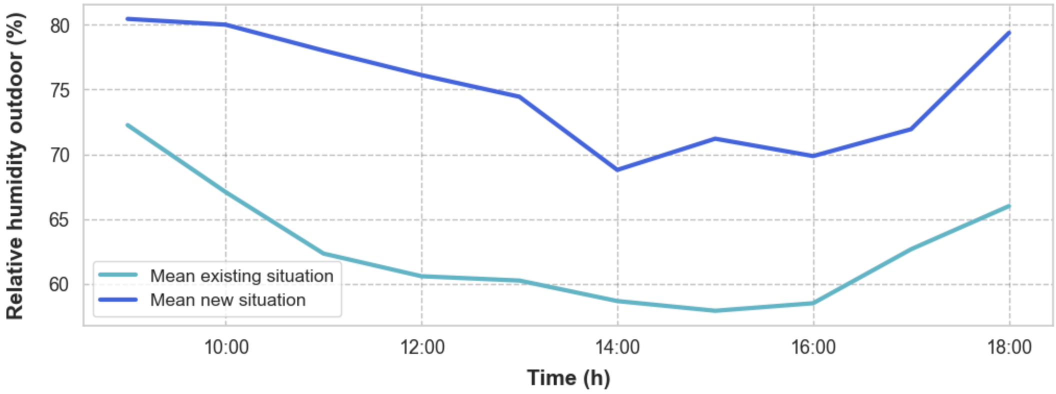


Figure 100: Mean outdoor relative humidity for the existing and new situation

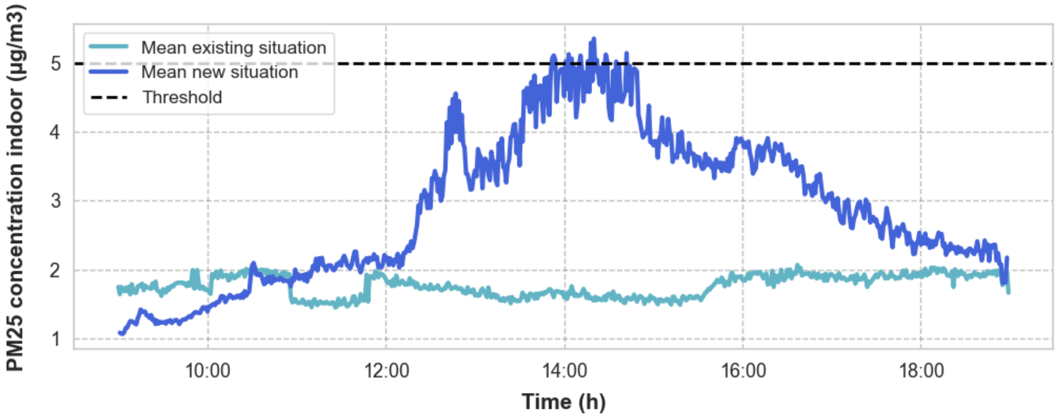


Figure 101: Mean indoor $PM_{2.5}$ concentration for the existing and new situation

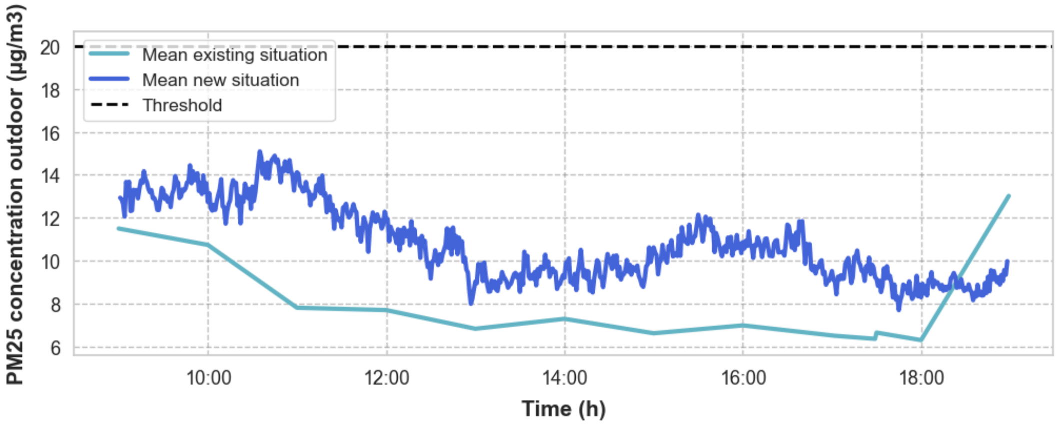


Figure 102: Mean outdoor $PM_{2.5}$ concentration for the existing and new situation

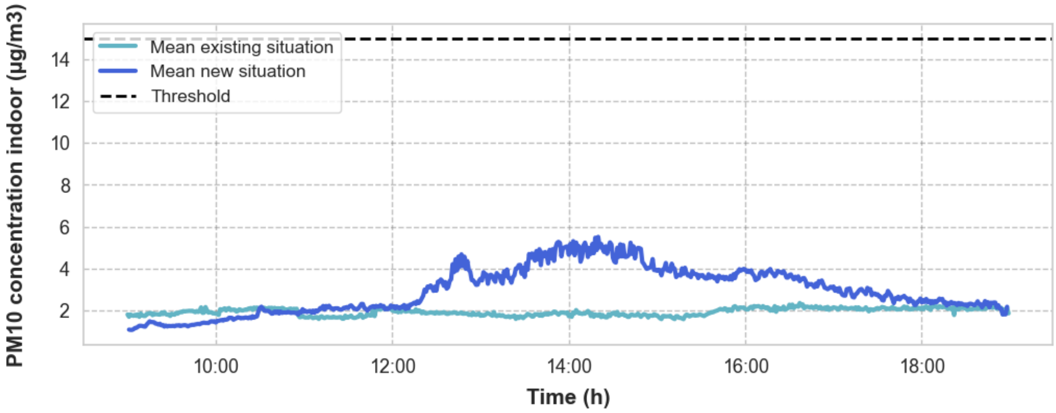


Figure 103: Mean indoor PM_{10} concentration for the existing and new situation

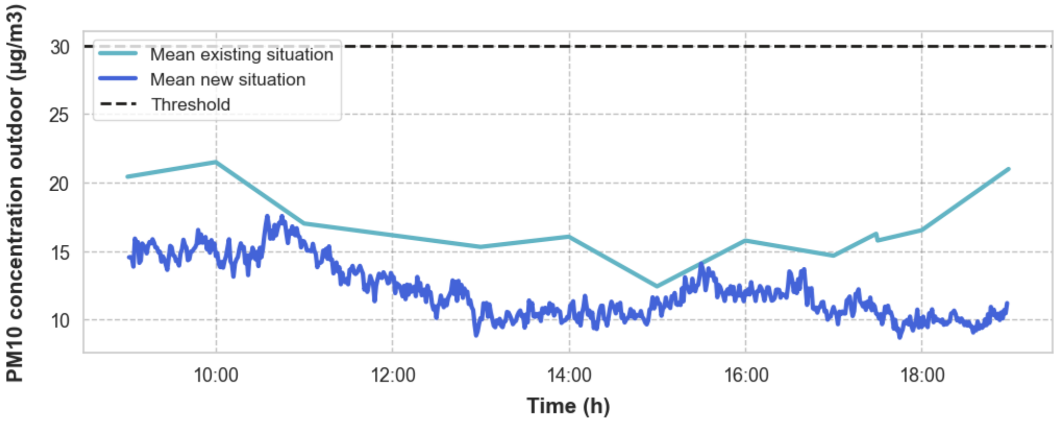


Figure 104: Mean outdoor PM_{10} concentration for the existing and new situation

In addition to the figures, Table 12 provides a comparison between the existing and new situation by showing the average time of exceedance per workday for each parameter. The table shows also the ineffective window opening time for both situations, which is defined as the time in which the window state is not according to the designed algorithm.

Table 12: Average time of exceedance per workday for each parameter in the existing and new situation.

Parameter	**Exceedance existing situation** [mean per workday]	**Exceedance new situation** [mean per workday]	**Ratio**	**Improvement**
Indoor CO_2	1 hour 53 minutes	38 minutes	- 66 %	Yes
Indoor temperature	2 hours 19 minutes	52 minutes	- 63 %	Yes
Indoor relative humidity	1 hour 43 minutes	-	-	Yes
Indoor $PM_{2.5}$	10 minutes	1 hour 19 minutes	+ 690 %	No
Outdoor $PM_{2.5}$	50 minutes	1 hour 47 minutes	+ 114 %	No
Indoor PM_{10}	-	19 minutes	-	No
Outdoor PM_{10}	49 minutes	1 hour 12 minutes	+ 47 %	No
Window opening time	48 minutes	4 hours 39 minutes	+ 481 %	-
Ineffective window opening time	2 hours 51 minutes	1 hour 17 minutes	- 55 %	Yes

Table 12 shows a 55% decrease of the ineffective window opening time in the new situation, despite the increased indoor particulate matter. This suggests an improvement of the window opening behaviour. However, the question remains to what extent this improvement can be attributed to the window feedback system. It is important to consider that the new situation had a higher outdoor temperature, as shown in Figure 98, which can be another reason for the improved window opening behaviour. The subjective measurements in the next section will provide a better understanding of the influence that the window feedback system had.

13.3.2 Subjective measurements

After conducting the experiment, a survey was carried out to validate the results of the objective measurements. This survey focused on identifying the impact of the window feedback system and how the design can be improved. The survey received 15 respondents. The results and corresponding conclusions are shown in this section.

Composition respondents

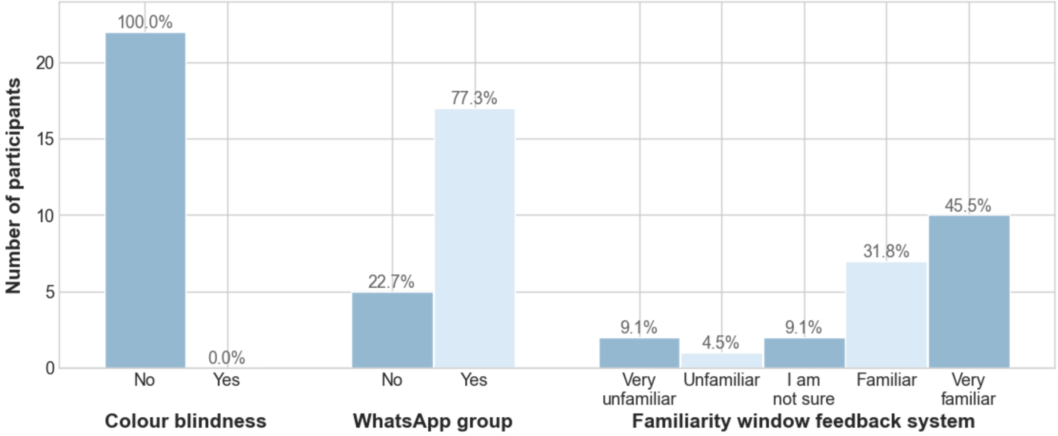


Figure 105: Distribution of colour blindness, membership in the 'Building Technology' WhatsApp group, and the level of familiarity with the window feedback system.

Figure 105 shows that none of the respondents is colour-blind and could have made a clear distinction between the different feedback colours. It also shows that two-thirds of the respondents were members of the 'Building Technology' WhatsApp group, indicating they had the possibility to read additional information about the window feedback system. One-third of the respondents did not receive this message and are also not (very) familiar with the system.

Satisfaction indoor environment

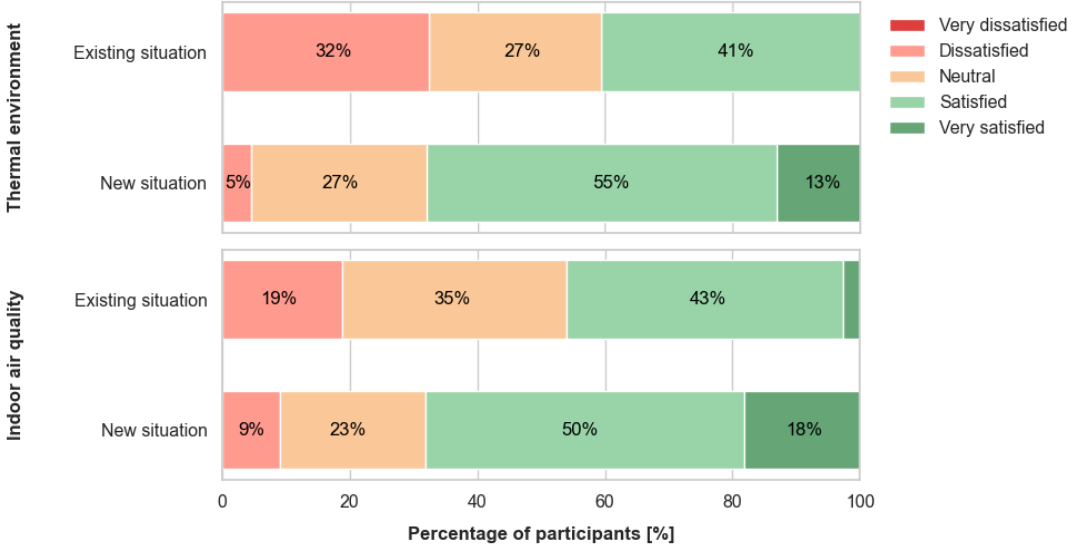


Figure 106: Satisfaction levels of the indoor air quality and thermal environment during the existing and new situation.

Figure 106 presents the satisfaction levels of the indoor air quality and thermal environment during the existing and new situation. Both situations had a different number of respondents which is why the distribution is shown in percentages of participants. The existing situation had 37 respondents while the new situation had 15 respondents. According to the figure, the satisfaction levels during the new situation improved for both the indoor air quality and the thermal environment. However, it should be taken into account that the new situation is less representative due to the significantly lower number of respondents.

Understanding the system

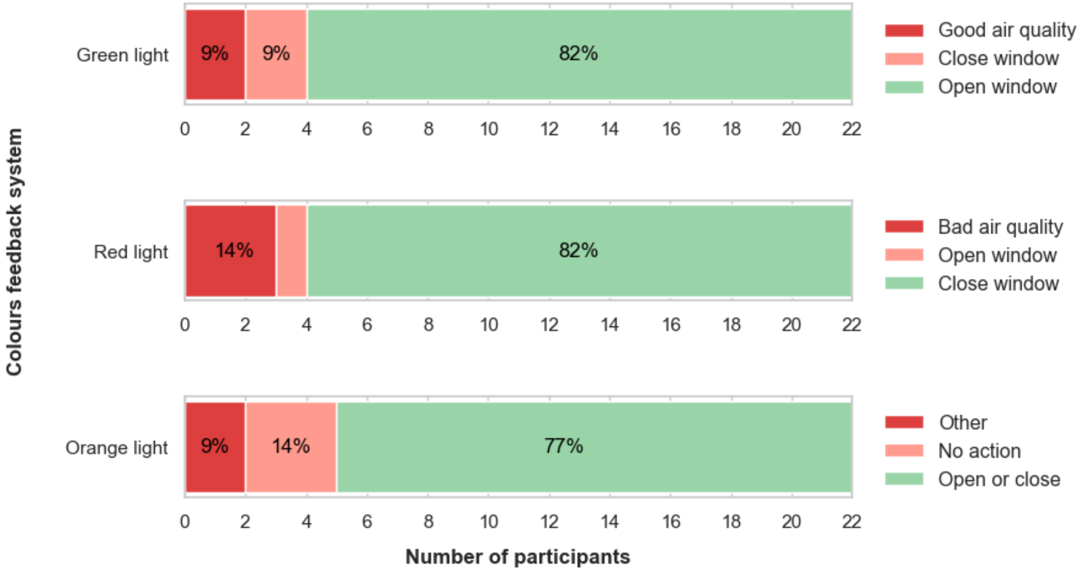


Figure 107: Perception of the meaning behind the window feedback colours. The green bar indicates the correct interpretation.

Figure 107 indicates that most respondents understood the meaning behind the colours. Four respondents did not understand the colours in which two did not receive additional information through WhatsApp and indicated to be very unfamiliar with the system. The other two respondents were members of the 'Building Technology' WhatsApp group and indicated being familiar with the system.

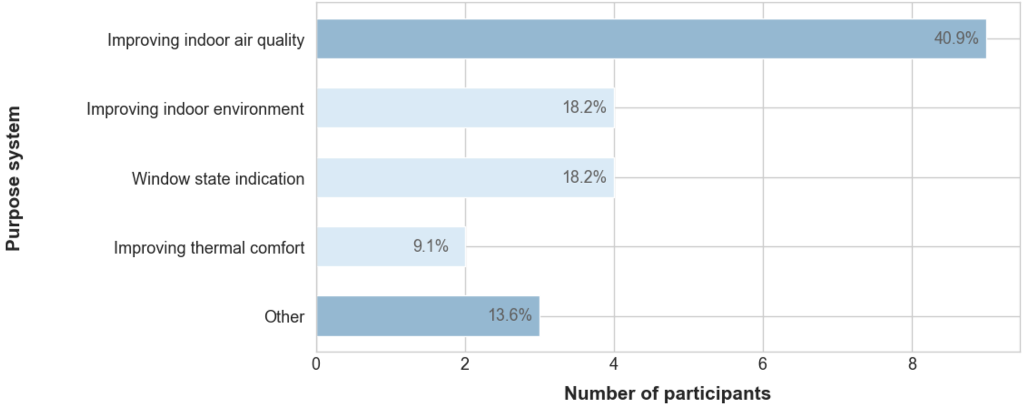


Figure 108: Perception of the purpose behind the window feedback system

Figure 108 indicates that all respondents understood a part of the purpose behind the window feedback system. None of the participants explicitly mentioned enhancing energy efficiency or social interaction as a purpose. It is important to note that the outcome may have been influenced by the respondents' prior knowledge of the built environment, as they were educated about it.

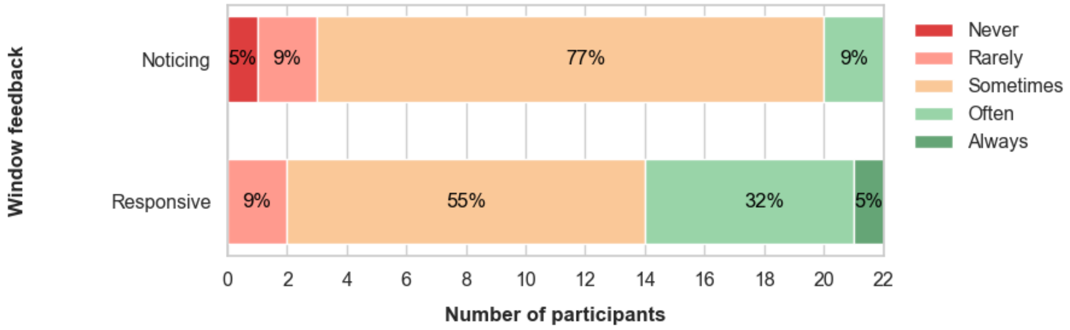


Figure 109: Frequency of noticing the feedback of the window feedback system and being prepared to operate the window based on the feedback.

Figure 109 indicates that a majority of the respondents notice the feedback sometimes or more often. It also shows that a majority of the respondents are prepared to operate the window sometimes or more frequently according to the provided feedback. The respondents indicated that their work is preventing them from operating the window more often.

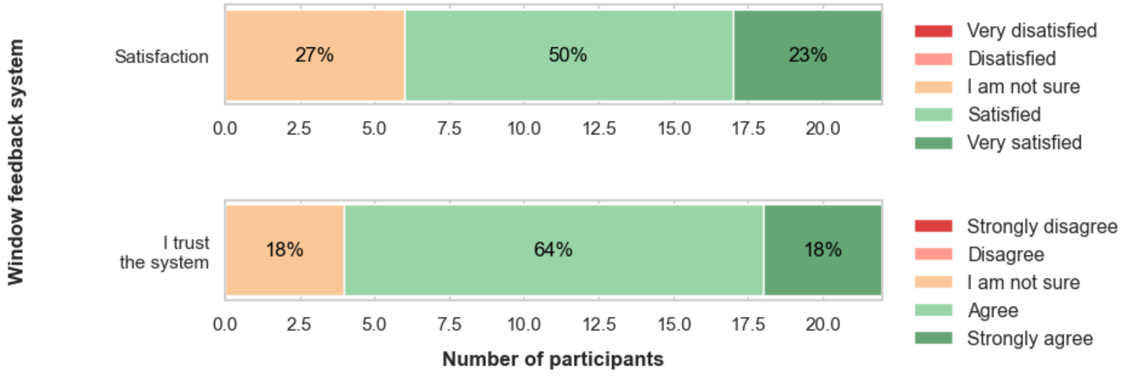


Figure 110: Satisfaction levels with the window feedback system and whether respondents trust the provided feedback

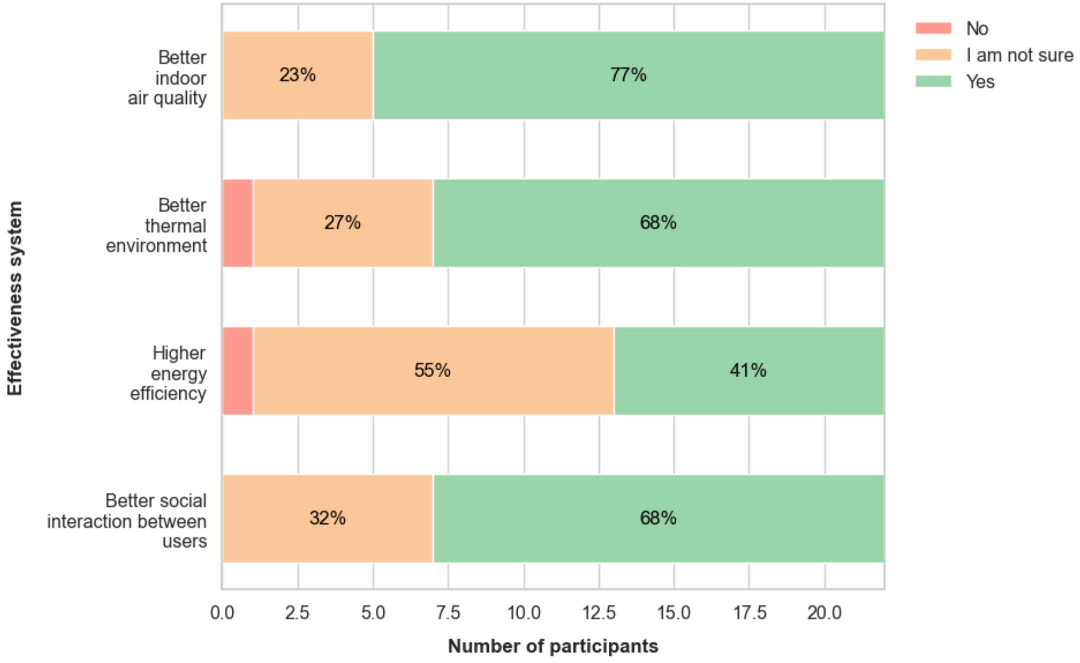


Figure 111: Perception of whether the window feedback system contributes to enhancing the indoor air quality, thermal environment, energy efficiency and social interaction between users.

Figure 110 shows that a majority of the respondents are satisfied with the window feedback system and trust the provided feedback. More than half of the respondents believe that the window feedback system contributes to enhancing the indoor air quality, thermal environment and social interaction between users, as suggested by Figure 111. Fewer respondents believe that the system contributes to improving the energy efficiency.

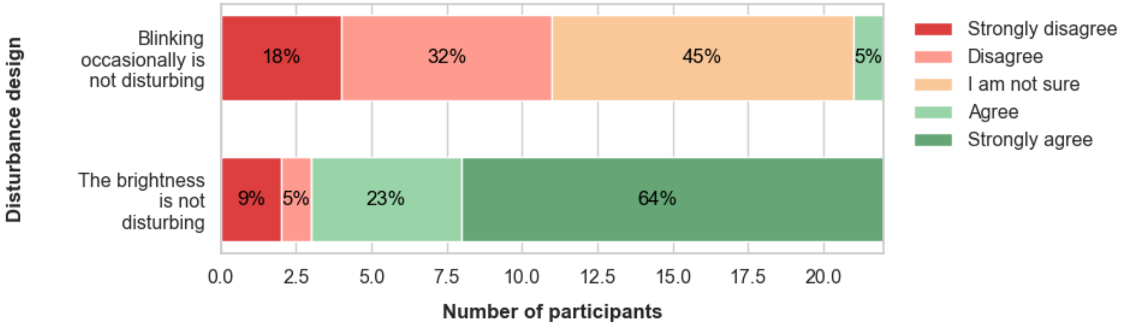


Figure 112: Whether the lights of the window feedback system are not disturbing with the current brightness or when blinking.

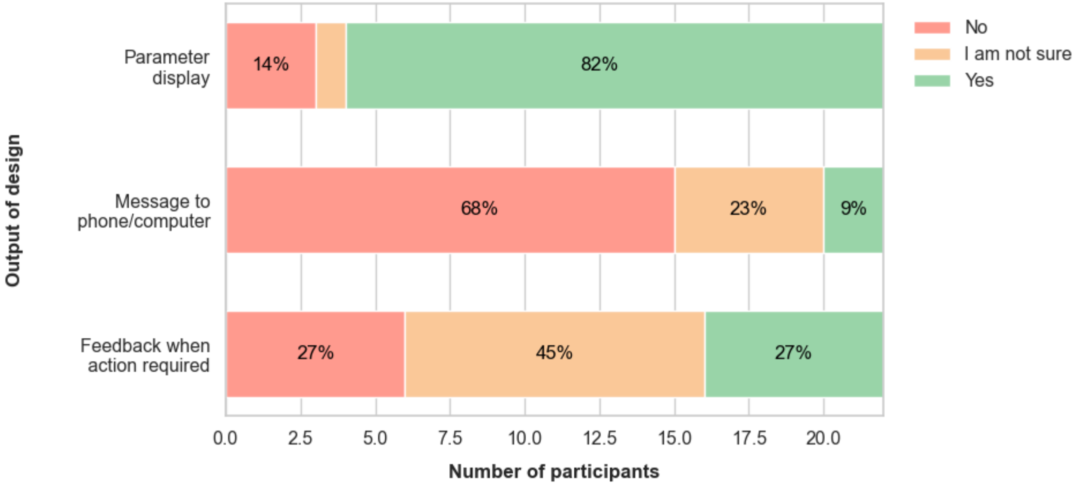


Figure 113: Whether the current feedback could have improved regarding a parameter display, a message to the phone/computer and the feedback frequency.

Figure 112 indicates that a majority of the respondents are not disturbed by the current brightness of the window feedback system and could be disturbed if the lights were blinking. Figure 113 shows that almost all respondents would have preferred a parameter display in addition to the window feedback system. However, it should be considered that the respondents have a prior knowledge of the built environment which could have affected their preference. Figure 113**Fout! Verwijzingsbron niet gevonden.** indicates that a majority of the respondents wouldn't prefer a message to their phone or computer. In addition, it shows that about one-third of the respondents prefer to receive feedback only when an action is required.

CONCLUSION

14 Conclusion

By conducting an experiment, this research investigated the influence that ambient light window feedback systems can have on the indoor climate and occupants' satisfaction in open-plan workplaces. The research focused on determining the effectiveness of these systems and on establishing design guidelines for further developments.

The experiment took place inside the building technology studio of TU Delft's faculty of architecture and lasted for 6 weeks. During this period, the first three weeks consisted of measuring the existing situation. In the remaining three weeks, a window feedback system was implemented to identify its influence compared to the existing situation. Both objective and subjective measurements were conducted during the existing and new situation, as presented in chapter 13.

For the existing situation, the objective measurements suggest that the indoor environment can be improved on several aspects and includes the temperature, relative humidity, CO_2 concentration and particulate matter concentration. This is in agreement with the subjective measurements of the first survey in which a majority of the respondents experienced discomfort related to the indoor air quality and thermal environment.

For the new situation, the objective and subjective measurements suggest that the indoor environment improved compared to the existing situation. The window opening time increased by 481% while the ineffective window opening time was reduced by 55%. Specifically, the temperature, relative humidity and CO_2 concentration improved. As an exception, the particulate matter concentration deteriorated. All changes can be related to the increased window opening time.

According to the subjective measurements of the last survey, the window feedback system had a significant influence on the increased and effective window opening time. A majority of the respondents indicated that they understood the system, did act according to the provided feedback and were satisfied with the implementation. In addition, a majority indicated to have trust in the system and its ability to improve the indoor air quality, thermal environment, energy efficiency and social interaction between users. However, it should be considered that the new situation had higher outdoor temperatures, which could have been another significant reason for the increased window opening time. Nevertheless, this study shows that ambient light window feedback systems can be promising inside open-plan workplaces. In addition, the following design recommendations are made for the further development of the algorithm and window feedback system:

- Include the indoor mean radiant temperature, outdoor noise and solar radiation as parameters in the algorithm for a more accurate outcome;
- Reconsider the importance of the outdoor air quality in the algorithm. Currently, the outdoor air quality has a higher importance than the indoor air quality which may not be correct in certain scenarios. For example, when both the indoor and outdoor air quality are exceeded and the indoor air quality is more of a concern.
- Include a parameter display. This is preferred according to the subjective measurements.
- Do not include blinking lights or feedback messages to phones/computers. This is not preferred according to the subjective measurements.
- Reconsider the meaning of the lights. It seems for occupants to be more intuitive when the colour red stands for 'open' and the colour green for 'close'. However, this is not supported by subjective measurements. Nevertheless, a majority of the respondents in the last survey understood the meaning of the lights. Most likely due to the additional information that was provided through a WhatsApp message and a legend.

15 Recommendations

This chapter presents recommendations for further research based on the findings and limitations that were identified during this research. Please refer for the limitations of the light interface design to section 9.4, for the algorithm design to section 10.2.4 and for the methodology to section 0.

Duration of the experiment

The experimental research was conducted for 6 weeks and served as a pilot study to provide an indication of the influence that ambient light window feedback systems can have. Due to the limited period of experimentation, the conclusion does not take seasonal variations into account. As a result, it is not clear to what extent the window feedback system played a role in the increased window opening time and to what extent it was caused by the higher outdoor temperature. To create a more reliable and inclusive conclusion, it is recommended to extent the experiment duration to 2 years. This will allow a full year of data collection for both the existing and new situation.

It is noteworthy to mention that efforts were made to reinforce the conclusion by using different methods. These methods involved analysing the response time based on the feedback, calculating correlations and comparing measurements of the existing and new situation under similar outdoor temperatures. All of these methods proved to be unsuccessful due to the limited data.

Satisfactory light interface design

The light interface design in this research is primarily based on general information and experimental studies with a small test group. While these sources provided more insight, it is important to acknowledge the limitations regarding the scope and sample size. As a result, the substantiation of the design is limited and more research is required regarding what a satisfactory light interface design is. For example, by determining the optimum characteristics such as the brightness, size and positioning of the window feedback system.

Satisfactory algorithm design

The algorithm design in this research is based on the literature research by recognizing parameters, and own formulated design principles. Although the algorithm design proved to be working, this research did not determine what a satisfactory algorithm design is. For example, by comparing the impact of different algorithms on the indoor climate and occupant’s satisfaction. It is recommended to do more research regarding this area.

Artificial intelligence

Artificial intelligence is becoming increasingly important and playing a bigger role in the built environment. It would be interesting to identify how artificial intelligence can be used to improve the window feedback system. For example, by recognizing internal drivers or by providing feedforward instead of feedback.

Weather conditions

The thresholds of the weather conditions in the algorithm design are based on a limited number of studies and own perceptions. More knowledge is required regarding the window operation in relation to the weather.

REFERENCES

16 References

Abdul-Wahab, S. A., Chin Fah En, S., Elkamel, A., Ahmadi, L., & Yetilmezsoy, K. (2015). A review of standards and guidelines set by international bodies for the parameters of indoor air quality. *Atmospheric Pollution Research*, *6*(5), 751–767. https://doi.org/10.5094/apr.2015.084

Abrahamse, W., Steg, L., Vlek, C., & Rothengatter, T. (2005). A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology*, *25*(3), 273–291. https://doi.org/10.1016/j.jenvp.2005.08.002

Ackerly, K., Baker, L., & Brager, G. (2011). Window Use in Mixed-Mode Buildings: A Literature Review. *UC Berkeley Envelope Systems*.

Ackerly, K., & Brager, G. (2011). Occupant Response to Window Control Signaling Systems; Appendix C: Mixed-mode Signal Case Study Summary. *UC Berkeley Envelope Systems*.

Ackerly, K., & Brager, G. (2013). Window signalling systems: control strategies and occupant behaviour. *Building Research &Amp; Information*, *41*(3), 342–360. https://doi.org/10.1080/09613218.2013.772044

Amasyali, K., & El-Gohary, N. M. (2016). Energy-related values and satisfaction levels of residential and office building occupants. *Building and Environment*, *95*, 251–263. https://doi.org/10.1016/j.buildenv.2015.08.005

ASHRAE 55. (2017). *Thermal Environmental Conditions for Human Occupancy*.

Avella, F., Gupta, A., Peretti, C., Fulici, G., Verdi, L., Belleri, A., & Babich, F. (2021). Low-Invasive CO2-Based Visual Alerting Systems to Manage Natural Ventilation and Improve IAQ in Historic School Buildings. *Heritage*, *4*(4), 3442–3468. https://doi.org/10.3390/heritage4040191

Barthelmes, V., Fabi, V., Corgnati, S., & Serra, V. (2018). Human Factor and Energy Efficiency in Buildings: Motivating End-Users Behavioural Change. *Advances in Intelligent Systems and Computing*, 514–525. https://doi.org/10.1007/978-3-319-96068-5_58

Boerstra, A. C. (2016). Personal Control over Indoor Climate in Offices. In *Impact on Comfort, Health and Productivity*.

Bordass, B., Leaman, A., & Bunn, R. (2007). *Controls for End Users: A guide for good design and implementation*.

Buechner, V. L., & Maier, M. A. (2016). Not always a matter of context: direct effects of red on arousal but context-dependent moderations on valence. *PeerJ*, *4*, e2515. https://doi.org/10.7717/peerj.2515

Buso, T., Fabi, V., Andersen, R. K., & Corgnati, S. P. (2015). Occupant behaviour and robustness of building design. *Building and Environment*, *94*, 694–703. https://doi.org/10.1016/j.buildenv.2015.11.003

CEU. (2019, December 27). *Color Theory Helps Explain Our Relationship to Nature and Wellbeing*. I+S. Retrieved February 21, 2023, from https://www.iands.design/ceu/article/10168389/color-theory-helps-explain-our-relationship-to-nature-and-wellbeing

CIBSE. (1999). *Environmental design CIBSE Guide A*.

CIBSE. (2022). *Monitoring indoor environmental quality*. The Chartered Institution of Building Services Engineers London.

Claude-Alain, R., & Foradini, F. (2002). Simple and Cheap Air Change Rate Measurement Using CO2Concentration Decays. *International Journal of Ventilation*, *1*(1), 39–44. https://doi.org/10.1080/14733315.2002.11683620

Day, J. K., McIlvennie, C., Brackley, C., Tarantini, M., Piselli, C., Hahn, J., O'Brien, W., Rajus, V. S., De Simone, M., Kjærgaard, M. B., Pritoni, M., Schlüter, A., Peng, Y., Schweiker, M., Fajilla, G., Becchio, C., Fabi, V., Spigliantini, G., 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. https://doi.org/10.1016/j.buildenv.2020.106920

De Dear, R., & Brager, G. (1998). Developing an adaptive model of thermal comfort and preference. *Center for the Built Environment*, *104*, 145–167. https://escholarship.org/content/qt4qq2p9c6/qt4qq2p9c6.pdf?t=lpz1vq

D'Oca, S., Chen, C. F., Hong, T., & Belafi, Z. (2017). Synthesizing building physics with social psychology: An interdisciplinary framework for context and occupant behavior in office buildings. *Energy Research &Amp; Social Science*, *34*, 240–251. https://doi.org/10.1016/j.erss.2017.08.002

Elliot, A. J. (2015). Color and psychological functioning: a review of theoretical and empirical work. *Frontiers in Psychology*, *6*. https://doi.org/10.3389/fpsyg.2015.00368

Fabi, V. (2013). Influence of Occupant's Behaviour on Indoor Environmental Quality and Energy Consumptions. In *A Roadmap to predict the unpredictable energy-related occupant behaviour*.

Fabi, V., Andersen, R. V., Corgnati, S., & Olesen, B. W. (2012). Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment*, *58*, 188–198. https://doi.org/10.1016/j.buildenv.2012.07.009

Fabi, V., Corgnati, S. P., & Barthelmes, V. M. (2016). Impact of an engagement campaign on user behaviour change in office environment. *Conference Paper*.

Halawa, E., & Van Hoof, J. (2012). The adaptive approach to thermal comfort: A critical overview. *Energy and Buildings*, *51*, 101–110. https://doi.org/10.1016/j.enbuild.2012.04.011

Hoof, J. V. (2010). Thermal comfort: research and practice. *Frontiers in Bioscience*, *15*(1), 765. https://doi.org/10.2741/3645

Huizenga, C., Zhang, H., Mattelaer, P., Yu, T., Arens, E., & Lyons, P. (2006). Window performance for human thermal comfort. *Center for the Built Environment*. https://escholarship.org/content/qt6rp85170/qt6rp85170.pdf?t=lptabj

IEA. (2022). *Buildings*. Retrieved November 20, 2022, from https://www.iea.org/topics/buildings

Jack, R., Loveday, D., Allinson, D., & Lomas, K. (2016). Quantifying the Effect of Window Opening on the Measured Heat Loss of a Test House. *Sustainable Ecological Engineering Design*, 183–196. https://doi.org/10.1007/978-3-319-32646-7_13

Khovalyg, D., Kazanci, O. B., Halvorsen, H., Gundlach, I., Bahnfleth, W. P., Toftum, J., & Olesen, B. W. (2020). Critical review of standards for indoor thermal environment and air quality. *Energy and Buildings*, *213*, 109819. https://doi.org/10.1016/j.enbuild.2020.109819

Liu, Y., Chong, W. T., Yau, Y. H., Chang, L., Cui, T., Yu, H., Cui, Y., & Pan, S. (2022). Rethinking the limitations of research on occupants' window-opening behavior: A review. *Energy and Buildings*, *277*, 112552. https://doi.org/10.1016/j.enbuild.2022.112552

Lowther, S., Dimitroulopoulou, S., Foxall, K., Shrubsole, C., Cheek, E., Gadeberg, B. L., & Sepai, O. (2021). Low Level Carbon Dioxide Indoors—A Pollution Indicator or a Pollutant? A Health-Based Perspective. *Environments*, *8*(11), 125. https://doi.org/10.3390/environments8110125

Lu, S. (2017). Using Ambient Lighting in Persuasive Communication. *TU/E*.

Lu, S. S., Ham, J., & Midden, C. C. (2016). The influence of color association strength and consistency on ease of processing of ambient lighting feedback. *Journal of Environmental Psychology*, *47*, 204–212. https://doi.org/10.1016/j.jenvp.2016.06.005

Mahdavi, A., Berger, C., Amin, H., Ampatzi, E., Andersen, R. K., Azar, E., Barthelmes, V. M., Favero, M., Hahn, J., Khovalyg, D., Knudsen, H. N., Navarro, A. L., Roetzel, A., Sangogboye, F. C., Schweiker, M., Taheri, M., Teli, D., Touchie, M. F., & Verbruggen, S. (2021). The Role of Occupants in Buildings' Energy Performance Gap: Myth or Reality? *Sustainability*, *13*(6), 3146. https://doi.org/10.3390/su13063146

Matviienko, A., Rauschenberger, M., Cobus, V., Timmermann, J., Müller, H., Fortmann, J., Löcken, A., Trappe, C., Heuten, W., & Boll, S. (2015). Deriving design guidelines for ambient light systems. *Mobile and Ubiquitous Multimedia*. https://doi.org/10.1145/2836041.2836069

MOBISTYLE. (2019). MOBISTYLE makes energy efficiency understandable by providing users attractive personalized information on energy use, indoor environment, health and lifestyle. *REHVA Journal*.

MOBISTYLE. (2020a). *Motivating end-users behavioral change by combined ICT based modular Information on energy use, indoor environment, health and lifestyle: Data on energy use and impact on energy use of the awareness and information campaigns* (D 6.2).

MOBISTYLE. (2020b). *Motivating end-users behavioral change by combined ICT based modular Information on energy use, indoor environment, health and lifestyle: Evaluation on the effectiveness of the combined information and feedback campaigns* (D 6.3).

Nandan, A., Siddiqui, N. A., Singh, C., & Aeri, A. (2021). Occupational and environmental impacts of indoor air pollutant for different occupancy: a review. *Toxicology and Environmental Health Sciences*, *13*(4), 303–322. https://doi.org/10.1007/s13530-021-00102-9

Nicol, F., Humphreys, M., & Roaf, S. (2012). *Adaptive Thermal Comfort: Principles and Practice*. Routledge.

Quora. (2016). *What is the limit of human vision?* Retrieved February 22, 2023, from https://www.quora.com/What-is-the-limit-of-human-vision-in-miles

RIVM. (2018). *Regelgeving voor fijnstof*. https://www.rivm.nl/fijn-stof/regelgeving#:~:text=Regelgeving%20voor%20de%20fijnere%20fractie,3%20die%20geldt%20vanaf%202020.

Rupp, R. F., Vásquez, N. G., & Lamberts, R. (2015). A review of human thermal comfort in the built environment. *Energy and Buildings*, *105*, 178–205. https://doi.org/10.1016/j.enbuild.2015.07.047

Schweiker, M., Hawighorst, M., & Wagner, A. (2016). The influence of personality traits on occupant behavioural patterns. *Energy and Buildings*, *131*, 63–75. https://doi.org/10.1016/j.enbuild.2016.09.019

Taleghani, M., Tenpierik, M., Kurvers, S., & Van Den Dobbelsteen, A. (2013). A review into thermal comfort in buildings. *Renewable and Sustainable Energy Reviews*, *26*, 201–215. https://doi.org/10.1016/j.rser.2013.05.050

University of Waikato. (2012, March 14). *Colours of light*. Science Learning Hub. Retrieved February 21, 2023, from https://www.sciencelearn.org.nz/resources/47-colours-of-light

Van Der Linden, A. C., Zeegers, A., & Kuijpers-Van Gaalen. (2018). *Building Physics* (2nd ed.). ThiemeMeulenhoff.

Warren, P. R., & Parkins, L. M. (1984). *Window-Opening Behavior in Office Buildings* (Vol. 90). ASHRAE Transactions.

Wei, W., Wargocki, P., Zirngibl, J., Bendžalová, J., & Mandin, C. (2020). Review of parameters used to assess the quality of the indoor environment in Green Building certification schemes for offices and hotels. *Energy and Buildings*, *209*, 109683. https://doi.org/10.1016/j.enbuild.2019.109683

World Health Organization [WHO]. (2021). WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. *WHO*.

Wouters, P., De Gids, W. F., Warren, P. R., & Jackman, P. J. (1987). Ventilation rates and energy losses due to window opening behaviour. *Ventilation Technology*.

Yau, Y., & Chew, B. (2012). A review on predicted mean vote and adaptive thermal comfort models. *Building Services Engineering Research and Technology*, *35*(1), 23–35. https://doi.org/10.1177/0143624412465200

Yun, G. Y., & Steemers, K. (2008). Time-dependent occupant behaviour models of window control in summer. *Building and Environment*, *43*(9), 1471–1482. https://doi.org/10.1016/j.buildenv.2007.08.001

APPENDIX

I Reflection
II Survey questions
III Code for sensors
IV Algorithm code
V Code for data organising and cleaning

Appendix I: Reflection

Research

This graduation project combines two main fields of the building technology track which are façade design and climate design. The focus of this research lies on the experimentation of ambient light window feedback systems and their impact on the indoor air quality, thermal comfort, energy efficiency and social interaction between users. The window feedback system is part of the façade and is therefore in connection with the urban conditions (e.g., noise, outdoor temperature) and the architectural design (e.g., occupants' experience on the inside). This makes the project also in relation with the Master of Science in Architecture, Urbanism and Building Sciences.

The methodology of the research is divided into two parts and consists of literature research and research by experimentation. The literature research formed the initial part of the study and provided important considerations for the experiment. In addition, it formed guidelines for designing the window feedback system and its algorithm. The research by experimentation part provided objective and subjective data to determine the effectiveness of the implemented window feedback system. In addition, the data helped in determining design recommendations for the further development of the window feedback system and its algorithm. This makes the cycle between research and design complete.

The strength of this methodology lies on its approach of incorporating both objective and subjective measurements during the experiment. This approach helped in validating the conclusions by referring to both types of measurements. In addition, a comparison was made with the literature to further reinforce the conclusions. One limitation of this methodology is the design process of the window feedback system which relied on a limited number of studies that were found during the literature research. These studies were not sufficient enough to substantiate all the design choices. Reflecting back, this process could have been improved by conducting a small-scale experiment to generate design recommendations for the system. This approach would also have ensured the occupants' involvement in creating the window feedback system design, who play a crucial role in the system's functioning. Another limitation was the distribution of the second survey which was carried out through QR codes placed nearby openable windows. This method did not work as expected since most occupants did not respond to the survey. Reflecting back, conducting short interviews would have been a more effective method that ensures responses from the occupants.

Concerning the relevance, this graduation project contributes to a larger social, professional and scientific framework. From a social perspective, this research contributes towards more efficient behaviour that enhances the energy consumption and indoor climate in various kinds of buildings. It helps towards a society which behaves more environmentally friendly and which is more conscious of their well being. Improving the occupants' behaviour can be especially helpful in already well insulated and airtight buildings, since the occupants' actions have more significance in these buildings on the overall energy consumption and indoor climate. It can also be helpful in existing buildings in which the ventilation is entirely dependent on the window operation. From a scientific perspective, this research can be helpful in creating a better understanding of window feedback systems and their effect on the energy efficiency, occupants' comfort and indoor climate. It provides also a better understanding of the drivers and the occupants' reasoning for window operation. In addition, it contributes to the further development of window feedback systems by providing design guidelines.

Complications during the experiment

During the experiment, several complications occurred that hindered the progress of this research. The following section describes these complications and provides possible solutions to consider for future iterations. A distinction is made between complications that are related to the context, hardware, software and other.

Context

- The chosen case study for this experiment was initially not the first choice. It was selected as an alternative because the first-choice case study had several shortcomings that became clear during the pre-measurements. The case study was changed in a relatively short period which resulted in a lack of communication with the staff of TU Delft. Consequently, the security unplugged all the hardware after each workday and eventually terminated the experiment after 6 weeks. To prevent similar issues in the future, it is recommended to inform all relevant parties on time.

Hardware

- The temperature and relative humidity measurements of the outdoor sensor were not accurate and was most likely caused by the handmade case. While the case aimed to protect the sensor from weather conditions, it unintentionally restricted the internal heat from escaping. Consequently, the temperature measurements appeared to be higher and the relative humidity measurements to be lower. This inaccuracy could have been prevented by using a weather station shield instead of the handmade case.
- To enhance fire safety, the outdoor sensor was connected to a power bank instead of the mains power. However, this arrangement resulted occasionally in a low power supply that disrupted the measurements. To enhance the reliability, it is recommended to connect all hardware to the mains power.
- As part of the measurement setup, different cables were connected by soldering. These connections proved to be fragile to movements and became detached on multiple occasions, resulting in measurement errors. One way of minimizing this risk is by strengthening the connections with glue that can be easily removed afterwards.
- The Raspberry Pi required to be reset each day due to the hardware being unplugged by the security as explained before. An attempt was made to automatically reset the raspberry pi but was not successful. Additionally. it should be noted that the Raspberry Pi needs to be connected to the monitor before powering it on, otherwise it will not be displayed on the monitor.

Software

- During the experiment, the Raspberry Pi received data from 7 Wemos devices which included data from 26 parameters. At the start of the experiment, all the data was sent simultaneously to the Raspberry Pi which caused an information overload. To address this issue, the sensors were programmed to enter a short sleep mode, allowing other sensors to transmit their data without overwhelming the Raspberry Pi.
- The LED light received information from the Raspberry Pi through the Wemos device. After unplugging the hardware, the LED light would not behave according to the given output. The reason for this behaviour is not clear, but the problem was solved by changing the topic name of the Wemos device on a daily basis.

Other

- The used hardware for the experiment was kept in place by using tape. However, some of these tapes were getting loose after a few weeks or were hard to remove after finishing the experiment. Therefore, it is recommended to select the type of tape carefully.

Appendix II: Survey questions

First survey

Topic		Question	Response options	Response type	Variable	Variable type	Correlation
Personal information	1	Could you indicate what your age is?	Number	Numerical discrete	Age	Confounding	
	2	Could you indicate your gender?	Male Female non-binary/third gender prefer not to say	Categorical nominal	Gender	Independent	
	3	Which country are you from?	Text	Open answer	Nationality	Confounding	
	4	How would you rate the importance of energy efficient buildings?	5-point likert scale: very unimportant - very important	Categorical nominal	Perception	Independent	
	5	How would you rate the energy efficiency of your own behaviour inside buildings?	5-point likert scale: bad - good	Categorical nominal	Behaviour	Independent	
	6	Approximately how many days per week do you work inside the BT-studio?	1 day 2 days 3 days 4 days 5 days	Categorical nominal	Working hours	Independent	
	7	Approximately how many hours do you spend inside the BT-studio on a working day?	0 to 2 hours 2 to 4 hours 4 to 6 hours 6 to 8 hours 8 or more hours	Categorical nominal	Working hours	Independent	
Window operation	8	Generally, how far from an openable window do you usually sit inside the BT-studio?	0 to 2 meters 2 to 4 meters 4 to 6 meters 6 to 8 meters 8 or more meters I differs a lot	Categorical nominal	Distance	Independent	
	9	Generally, how often do you open the window inside the BT-studio? During heating and cooling season	5-point likert scale: never - always	Numerical discrete	Window openings	Dependent	**Questions: 6-11 + 20-30** Working time, distance window, thermal comfort, IAQ
	10	Could you indicate your most important reasons for window opening? multiple answers are possible	To be cooler For fresh air To increase the air movement To feel a connection to the outdoors Because of habits e.g. time of day A co-worker asked me to open the window Not applicable, I never open the windows Other (please specify)	Categorical nominal (multiple choice)	Reasoning	Dependent	**Questions: 6-11 + 20-30** Working time, distance window, thermal comfort, IAQ
	11	Could you indicate your most important reasons for window closing? multiple answers are possible	To feel warmer The outdoor air is not satisfactory The draft was uncomfortable To prevent rain, hail or snow entering inside To reduce outdoor noise To save energy Because of habits e.g. time of the day Because of security / safety A co-worker asked me to close the window Not applicable, I never close the windows Other (please specify)	Categorical nominal (multiple choice)	Reasoning	Dependent	**Questions: 4-11 + 20-30** Importance energy efficiency, Working time, distance window, thermal comfort, IAQ
	12	How would you rate your perceived control of the window operation inside the BT-studio?	5-point likert scale: very poor - very good	Categorical nominal	Perception	Dependent	**Questions: 2 + 8-11** Gender, distance window
	13	Do you consider (thermal) energy waste when opening a window?	No Sometimes Yes	Categorical nominal	Reasoning	Dependent	**Questions: 4+5** Importance energy efficiency
	14	Do you think about the comfort of other people when opening or closing the window?	No Sometimes Yes	Categorical nominal	Reasoning	Independent	
	15	Do you ask other people if it is okay when you want to open or close a window?	No Sometimes Yes	Categorical nominal	Reasoning	Independent	
	16	Imagine someone else opens or closes the window without your permission, and you are dissatisfied with the window state. How likely would you express your dissatisfaction?	5-point likert scale: very likely - very unlikely	Categorical nominal	Reasoning	Independent	
Thermal comfort	17	Generally, how satisfied are you with the thermal environment inside the BT-studio?	5-point likert scale: very dissatisfied - very satisfied	Categorical nominal	Perception	Independent	
	18	How often do you experience thermal discomfort inside the BT-studio?	5-point likert scale: never - always	Categorical nominal	Perception	Independent	
	19	If you experience discomfort with the thermal environment, how would you describe the source of this discomfort? multiple answers are possible	I don't experience discomfort Air movement too high Air too dry Air too humid Incoming sun Hot/cold surrounding surfaces (floor, ceiling, walls or windows) Heat from equipment My area is hotter/colder than other areas of the building Lack of possibilities to properly adjust the clothing Heating/cooling system does not respond quickly enough I do not know Other (please specify)	Categorical nominal (multiple choice)	Perception	Independent	
Indoor air quality	20	How would you rate your knowlegde about indoor air quality?	5-point likert scale: novice - expert	Categorical nominal	Knowledge	Independent	
	21	Generally, how do you judge the air quality outside?	5-point likert scale: bad - good	Categorical nominal	Perception	Independent	
	22	Generally, how often do you think that the air quality outside is worse than indoors?	5-point likert scale: never - always	Categorical nominal	Perception	Independent	
	23	Do you consider the air quality outside when opening a window?	No Sometimes Yes	Categorical nominal	Reasoning	Dependent	**Questions: 24+25** Perception outdoor air quality
	24	Generally, how satisfied are you with the indoor air quality inside the BT-studio?	5-point likert scale: very dissatisfied - very satisfied	Categorical nominal	Perception	Independent	
	25	How frequently do you smell odors inside the BT-studio?	5-point likert scale: never - always	Categorical nominal	Perception	Independent	
	26	Do you experience one of the following symptoms regularly inside the BT-studio? Multiple answers are possible	Fatigue Loss of concentration Nausea and dizziness Headache Eye irritation / dry eyes Nose irritation Sore throat I don't experience any symptoms	Categorical nominal (multiple choice)	Perception	Independent	
	27	Are there any comments you would like to provide about the window operation, thermal environment and indoor air quality inside the BT-studio?	Text	Open answer			

Second survey

Topic		Question	Response options	Response type	Variable	Variable type	Correlation
Window operation	1	Could you indicate if you opened or closed the window?	I opened the window I closed the window	Categorical nominal	Window operation	Independent	
	2	Could you indicate the distance from your seat to the opened window?	0 to 2 meters 2 to 4 meters 4 to 6 meters 6 to 8 meters 8 or more meters I don't have a seat	Categorical nominal	Distance	Independent	
	3A	Could you indicate your reason for opening the window? Multiple answers are possible	I noticed the window feedback signal For fresh air To increase the air movement To feel a connection to the outdoors Because of habits (e.g. time of day) A co-worker asked me to open the window To be cooler Other (please specify)	Categorical nominal	Reasoning	Dependent	**First survey:** **Questions: 6-11 + 20-30** Working time, distance window, thermal comfort, IAQ
	3B	Could you indicate your reason for closing the window? Multiple answers are possible	I noticed the window feedback signal The outdoor air is not satisfactory The draft was uncomfortable To prevent rain, hail or snow entering inside To reduce outdoor noise To save energy Because of habits (e.g. time of day) A co-worker asked me to close the window To feel warmer Other (please specify)	Categorical nominal	Reasoning	Dependent	**First survey:** **Questions: 4-11 + 20-30** Importance energy efficiency, Working time, distance window, thermal comfort, IAQ
	4	Before operating the window, did you consider the comfort of other occupants inside the BT-studio?	Yes and I asked about their comfort Yes and I did not ask about their comfort No, I did not consider their comfort There are no other people	Categorical nominal	Reasoning	Independent	

Third survey

Topic		Question	Response options	Response type	Variable	Variable type	Correlation
Personal information and Satisfaction	1	Have you participated in this experiment before?	No Yes	Categorical nominal	Engagement	Independent	
	2	Could you indicate if you are colour blind?	No, I am not colour blind Yes, I am colour blind I prefer not to answer	Categorical nominal	Colour blindness	Independent	
	3	Could you indicate if you are a member of the 'Building Technology' group chat on WhatsApp?	No, I am not a member Yes, I am a member	Categorical nominal	Engagement	Independent	
	4	In the past 3 weeks, how satisfied were you with the thermal environment inside the BT-studio?	5-point likert scale: very dissatisfied - very satisfied	Categorical nominal	Satisfaction	Independent	
	5	In the past 3 weeks, how satisfied were you with the indoor air quality inside the BT-studio?	5-point likert scale: very dissatisfied - very satisfied	Categorical nominal	Satisfaction	Independent	
	6	The picture above shows the window feedback system that has been implemented inside the BT-studio. How familiar are you with this system inside the BT-studio?	5-point likert scale: very unfamiliar - very familiar	Categorical nominal	Engagement	Independent	
Understanding	7	The window feedback system can display three colours: red, green and orange. Could you indicate what the meaning of these colours are? Please be as specific as possible.	Text	Open answer	Colours	Dependent	**Questions: 6** Engagement
	8	Could you indicate what the purpose of the window feedback system is? Please be as specific as possible.	Text	Open answer	Purpose	Dependent	**Questions: 6** Engagement
Design Perception	9	How often would you be prepared to operate a window based on the feedback of the window feedback system?	5-point likert scale: never - always	Categorical nominal	Readiness	Independent	
	10	Could you also indicate the reason of the chosen frequency? Please be as specific as possible.	Text	Open answer	Readiness	Independent	
	11	How satisfied are you with the implementation of the window feedback system inside the BT-studio?	5-point likert scale: very dissatisfied - very satisfied	Categorical nominal	Perception	Independent	
	12	Could you indicate the reason for your satisfaction of the implementation of the window feedback system? Please be as specific as possible.	Text	Open answer	Perception	Independent	
	13	To what extent do you agree to this statement: The brightness of the window feedback system is not disturbing	5-point likert scale: strongly disagree - strongly agree	Categorical nominal	Brightness	Independent	
	14	To what extent do you agree to this statement: It would not be disturbing if the lights of the window feedback system were blinking occasionally.	5-point likert scale: strongly disagree - strongly agree	Categorical nominal	Blinking	Independent	
	15	Would you have preferred a display that shows the measured parameters (e.g. temperature, CO2) in addition to the window feedback system?	No I am not sure Yes	Categorical nominal	Output type	Independent	
	16	Would you have preferred a feedback message to your phone or computer instead of the current window feedback system?	No I am not sure Yes	Categorical nominal	Output type	Independent	
	17	Currently, the existing window feedback system provides continuous feedback on the optimal window state. Would you prefer a system that provides feedback only when an action of the user is required?	No I am not sure Yes	Categorical nominal	Output type	Independent	
	18	To what extent do you agree to this statement: I trust the recommended action of the window feedback system.	5-point likert scale: strongly disagree - strongly agree	Categorical nominal	Contribution	Independent	
	19	Could you indicate the reason of your trust?	Text	Open answer	Contribution	Independent	
	20	How often do you notice the feedback of the window feedback system?	5-point likert scale: never - always	Categorical nominal	Contribution	Dependent	**Questions: 9-13** Readiness, perception, satisfaction, brightness
	21	Do you think the window feedback system contributes to a better indoor air quality?	No I am not sure Yes	Categorical nominal	Contribution	Dependent	**Questions: 3-4 + 8-12 + 18-19** Satisfaction, purpose, readiness, trust
	22	Do you think the window feedback system contributes to a better thermal environment?	No I am not sure Yes	Categorical nominal	Contribution	Dependent	**Questions: 3-4 + 8-12 + 18-19** Satisfaction, purpose, readiness, trust
	23	Do you think the window feedback system contributes to a higher energy efficiency?	No I am not sure Yes	Categorical nominal	Contribution	Dependent	**Questions: 3-4 + 8-12 + 18-19** Satisfaction, purpose, readiness, trust
	24	Do you think the window feedback system can support a better social interaction between users in shared offices? For example by functioning as a third party between occupants that prefer a different window state.	No I am not sure Yes	Categorical nominal	Contribution	Dependent	**Questions: 3-4 + 8-12 + 18-19** Satisfaction, purpose, readiness, trust
	25	Are there any improvements you would suggest concerning the design and positioning of the window feedback system?	Text	Open answer			

Appendix III: Code for sensors

CO_2 sensor

```
#include <ESP8266WiFi.h>
#include <PubSubClient.h>
#include <WiFiManager.h>
#include <SoftwareSerial.h>
#include "Arduino.h"
#include "cozir.h"

// Update these with values suitable for your network.
const char* ssid = "Rasp-access";
const char* password = "OccupantInteraction";
const char* mqtt_server = "192.168.4.1"; //IP Broker
#define ROUTE "sensors" // Message route
#define ID "l1,a1"               // Device ID


WiFiClient espClient;
PubSubClient client(espClient);
long lastMsg = 0;
char msg[50];
int value = 0;

SoftwareSerial COZIRSerial(12, 14);
COZIR czr(&COZIRSerial);

//*************************************************************************************************************************

void setup() {
  int16_t ret;
  uint8_t auto_clean_days = 4;
  uint32_t auto_clean;

  COZIRSerial.begin(9600);
  czr.init();
  Serial.begin(115200);
  Serial.print("COZIR_LIB_VERSION: ");
  Serial.println(COZIR_LIB_VERSION);
  Serial.println();

  delay(100);
  czr.getVersionSerial();
  delay(5);
  while (COZIRSerial.available())
  {
    Serial.write(COZIRSerial.read());
```

```
  }
  delay(100);

  czr.getConfiguration();
  delay(5);
  while (COZIRSerial.available())
  {
    COZIRSerial.write(COZIRSerial.read());
  }
  delay(1000);

  // set to polling explicitly.
  czr.setOperatingMode(CZR_POLLING);
  delay(1000);

  delay(1000);

  setup_wifi();
  client.setServer(mqtt_server, 1883);
  client.setCallback(callback);
  WiFi.hostname(String(String(ID)+"C"));
  Serial.println("MAC:" + WiFi.macAddress());
  }

void loop() {
  //connecting to mqtt server
  if (!client.connected()) {
    delay(100);                          // **Yo**
    reconnect();
  }
  client.loop();

  //reading CO2 concentrations
  float t = czr.celsius();
  float f = czr.fahrenheit();
  float h = czr.humidity();
  uint32_t c = czr.CO2();



  //Sending to mqtt broker
  String DataSent = String(String(ID)+","+String(t)+","+String(h)+","+String(c));
  DataSent.toCharArray(msg,50);
  client.publish(ROUTE, msg);
  Serial.println(DataSent);
  Serial.println(msg);
  delay(30000);
  }
```

```
//*****************************************************************************************************
********************

void setup_wifi() {
  delay(10);
  // We start by connecting to a WiFi network
  Serial.println();
  Serial.print("Connecting to ");
  Serial.println(ssid);

  WiFi.begin(ssid, password);

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }

  randomSeed(micros());

  Serial.println("");
  Serial.println("WiFi connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());
}

void callback(char* topic, byte* payload, unsigned int length) {
  Serial.print("Message arrived [");
  Serial.print(topic);
  Serial.print("] ");
  for (int i = 0; i < length; i++) {
    Serial.print((char)payload[i]);
  }
  Serial.println();

}

void reconnect() {
  // Loop until we're reconnected
  while (!client.connected()) {
    Serial.print("Attempting MQTT connection...");
    // Create a random client ID
    String clientId = "ESP8266Client-";
    clientId += String(random(0xffff), HEX);
    // Attempt to connect
    if (client.connect(clientId.c_str())) {
      Serial.println("connected");
      // Once connected, publish an announcement...
     // client.publish(ROUTE, MESSAGE);
      // ... and resubscribe
```

```
      client.subscribe(ROUTE);
    } else {
      Serial.print("failed, rc=");
      Serial.print(client.state());
      Serial.println(" try again in 2 seconds");
      // Wait 2 seconds before retrying
      delay(2000);
    }
  }
}
```

CO$_2$ + Particulate matter sensor

```
#include <ESP8266WiFi.h>
#include <PubSubClient.h>
#include <WiFiManager.h>
#include <SoftwareSerial.h>
#include <sps30.h>
#include "Arduino.h"
#include "cozir.h"

// Update these with values suitable for your network.
const char* ssid = "Rasp-access";
const char* password = "OccupantInteraction";
const char* mqtt_server = "192.168.4.1"; //IP Broker
#define ROUTE "sensors" // Message route
#define ID "l1,b2"               // Device ID


WiFiClient espClient;
PubSubClient client(espClient);
long lastMsg = 0;
char msg[50];
int value = 0;

SoftwareSerial COZIRSerial(12, 14);
COZIR czr(&COZIRSerial);

//****************************************************************************************************************************

void setup() {
  int16_t ret;
  uint8_t auto_clean_days = 4;
  uint32_t auto_clean;
```

```
  COZIRSerial.begin(9600);
  czr.init();
  sensirion_i2c_init();

  Serial.begin(115200);
  Serial.print("COZIR_LIB_VERSION: ");
  Serial.println(COZIR_LIB_VERSION);
  Serial.println();

  delay(100);
  czr.getVersionSerial();
  delay(5);
  while (COZIRSerial.available())
  {
    Serial.write(COZIRSerial.read());
  }
  delay(100);

  czr.getConfiguration();
  delay(5);
  while (COZIRSerial.available())
  {
    COZIRSerial.write(COZIRSerial.read());
  }
  delay(1000);

  // set to polling explicitly.
  czr.setOperatingMode(CZR_POLLING);
  delay(1000);

  while (sps30_probe() != 0) {
    Serial.print("SPS sensor probing failed\n");
    delay(500);
  }

#ifndef PLOTTER_FORMAT
  Serial.print("SPS sensor probing successful\n");
#endif /* PLOTTER_FORMAT */

  ret = sps30_set_fan_auto_cleaning_interval_days(auto_clean_days);
  if (ret) {
    Serial.print("error setting the auto-clean interval: ");
    Serial.println(ret);
  }

  ret = sps30_start_measurement();
  if (ret < 0) {
    Serial.print("error starting measurement\n");
  }
```

```
#ifndef PLOTTER_FORMAT
  Serial.print("measurements started\n");
#endif /* PLOTTER_FORMAT */

#ifdef SPS30_LIMITED_I2C_BUFFER_SIZE
  Serial.print("Your Arduino hardware has a limitation that only\n");
  Serial.print("  allows reading the mass concentrations. For more\n");
  Serial.print("  information, please check\n");
  Serial.print("  https://github.com/Sensirion/arduino-sps#esp8266-partial-legacy-support\n");
  Serial.print("\n");
  delay(2000);
#endif

  delay(1000);



  setup_wifi();
  client.setServer(mqtt_server, 1883);
  client.setCallback(callback);
  WiFi.hostname(String(String(ID)+"C"));
  Serial.println("MAC:" + WiFi.macAddress());
  }

void loop() {
  //connecting to mqtt server
  if (!client.connected()) {
    delay(100);                          // **Yo**
    reconnect();
  }
  client.loop();

  //reading CO2 concentrations
  float t = czr.celsius();
  float f = czr.fahrenheit();
  float h = czr.humidity();
  uint32_t c = czr.CO2();

  struct sps30_measurement m;
  char serial[SPS30_MAX_SERIAL_LEN];
  uint16_t data_ready;
  int16_t ret;

  do {
    ret = sps30_read_data_ready(&data_ready);
    if (ret < 0) {
      Serial.print("error reading data-ready flag: ");
      Serial.println(ret);
    } else if (!data_ready)
```

```
      Serial.print("data not ready, no new measurement available\n");
    else
      break;
    delay(100); /* retry in 100ms */
  } while (1);

  ret = sps30_read_measurement(&m);
  if (ret < 0) {
    Serial.print("error reading measurement\n");
  } else {

#ifndef PLOTTER_FORMAT
    Serial.print("PM  1.0: ");
    Serial.println(m.mc_1p0);
    Serial.print("PM  2.5: ");
    Serial.println(m.mc_2p5);
    Serial.print("PM  4.0: ");
    Serial.println(m.mc_4p0);
    Serial.print("PM 10.0: ");
    Serial.println(m.mc_10p0);

//#ifndef SPS30_LIMITED_I2C_BUFFER_SIZE
//    Serial.print("NC  0.5: ");
//    Serial.println(m.nc_0p5);
//    Serial.print("NC  1.0: ");
//    Serial.println(m.nc_1p0);
//    Serial.print("NC  2.5: ");
//    Serial.println(m.nc_2p5);
//    Serial.print("NC  4.0: ");
    //Serial.println(m.nc_4p0);
    //Serial.print("NC 10.0: ");
    //Serial.println(m.nc_10p0);

    Serial.print("Typical partical size: ");
    Serial.println(m.typical_particle_size);
#endif

    Serial.println();

  }



  //Sending to mqtt broker
  String DataSent =
String(String(ID)+","+String(t)+","+String(h)+","+String(c)+","+String(m.mc_1p0)+","+String(m.mc_2p5)+"
,"+String(m.mc_10p0));
  DataSent.toCharArray(msg,50);
  client.publish(ROUTE, msg);
  Serial.println(DataSent);
```

```
  Serial.println(msg);
  delay(30000);
  }

//**************************************************************************************************************************

void setup_wifi() {
  delay(10);
  // We start by connecting to a WiFi network
  Serial.println();
  Serial.print("Connecting to ");
  Serial.println(ssid);

  WiFi.begin(ssid, password);

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }

  randomSeed(micros());

  Serial.println("");
  Serial.println("WiFi connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());
}

void callback(char* topic, byte* payload, unsigned int length) {
  Serial.print("Message arrived [");
  Serial.print(topic);
  Serial.print("] ");
  for (int i = 0; i < length; i++) {
    Serial.print((char)payload[i]);
  }
  Serial.println();

}

void reconnect() {
  // Loop until we're reconnected
  while (!client.connected()) {
    Serial.print("Attempting MQTT connection...");
    // Create a random client ID
    String clientId = "ESP8266Client-";
    clientId += String(random(0xffff), HEX);
    // Attempt to connect
    if (client.connect(clientId.c_str())) {
```

```
      Serial.println("connected");
      // Once connected, publish an announcement...
     // client.publish(ROUTE, MESSAGE);
      // ... and resubscribe
      client.subscribe(ROUTE);
    } else {
      Serial.print("failed, rc=");
      Serial.print(client.state());
      Serial.println(" try again in 2 seconds");
      // Wait 2 seconds before retrying
      delay(2000);
    }
  }
}
```

Contact + Temperature sensor

```
#include <ESP8266WiFi.h>
#include <PubSubClient.h>
#include <WiFiManager.h>
#include <SoftwareSerial.h>
#include "Arduino.h"
#include <ezButton.h>
#include <Wire.h>


// Update these with values suitable for your network.
const char* ssid = "Rasp-access";
const char* password = "OccupantInteraction";
const char* mqtt_server = "192.168.4.1"; //IP Broker
#define ROUTE "sensors" // Message route
#define ID "l1,d2"               // Device ID

WiFiClient espClient;
PubSubClient client(espClient);
long lastMsg = 0;
char msg[90];
int value = 0;

int switch_d;
int switch_d2;

ezButton toggleSwitch(2);
ezButton toggleSwitch2(13);
```

```
//************************************************************************************************************************



void setup() {
  pinMode(0,OUTPUT);
  digitalWrite(0,LOW);
  delay(50);
  Wire.begin();


  Serial.begin(115200);

  delay(1000);


  setup_wifi();
  client.setServer(mqtt_server, 1883);
  client.setCallback(callback);
  WiFi.hostname(String(String(ID)+"C"));
  Serial.println("MAC:" + WiFi.macAddress());
  }

void loop() {
  //connecting to mqtt server
  if (!client.connected()) {
    delay(100);                          // **Yo**
    reconnect();
  }
  client.loop();

  toggleSwitch.loop(); // MUST call the loop() function first
  int state = toggleSwitch.getState();
  //Serial.println(state);
  if (state == HIGH){  //if it is LOW then the switch is closed
  switch_d=0 ;

  }
  else{
    switch_d=1;
  }

  toggleSwitch2.loop(); // MUST call the loop() function first
  int state2 = toggleSwitch2.getState();
  //Serial.println(state);
  if (state2 == HIGH){  //if it is LOW then the switch is closed
  switch_d2=0 ;
```

```
  }
  else{
    switch_d2=1;
  }


  //Sending to mqtt broker
  String DataSent =
String(String(ID)+","+String(switch_d)+","+String(switch_d2)+","+String(tempC)+","+String(tempC1)+","+String(tempC2));
  DataSent.toCharArray(msg,90);
  client.publish(ROUTE, msg);
  Serial.println(DataSent);
  Serial.println(msg);
  delay(30000);
  }

//*****************************************************************************************************
********************

void setup_wifi() {
  delay(10);
  // We start by connecting to a WiFi network
  Serial.println();
  Serial.print("Connecting to ");
  Serial.println(ssid);

  WiFi.begin(ssid, password);

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }

  randomSeed(micros());

  Serial.println("");
  Serial.println("WiFi connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());
}

void callback(char* topic, byte* payload, unsigned int length) {
  Serial.print("Message arrived [");
  Serial.print(topic);
  Serial.print("] ");
  for (int i = 0; i < length; i++) {
    Serial.print((char)payload[i]);
  }
```

```
  Serial.println();

}

void reconnect() {
  // Loop until we're reconnected
  while (!client.connected()) {
    Serial.print("Attempting MQTT connection...");
    // Create a random client ID
    String clientId = "ESP8266Client-";
    clientId += String(random(0xffff), HEX);
    // Attempt to connect
    if (client.connect(clientId.c_str())) {
      Serial.println("connected");
      // Once connected, publish an announcement...
     // client.publish(ROUTE, MESSAGE);
      // ... and resubscribe
      client.subscribe(ROUTE);
    } else {
      Serial.print("failed, rc=");
      Serial.print(client.state());
      Serial.println(" try again in 2 seconds");
      // Wait 2 seconds before retrying
      delay(2000);
    }
  }
}
```

Contact sensor

```
#include <ESP8266WiFi.h>
#include <PubSubClient.h>
#include <WiFiManager.h>
#include <SoftwareSerial.h>
#include "Arduino.h"
#include <ezButton.h>
#include <Wire.h>


// Update these with values suitable for your network.
const char* ssid = "Rasp-access";
const char* password = "OccupantInteraction";
const char* mqtt_server = "192.168.4.1"; //IP Broker
#define ROUTE "sensors" // Message route
#define ID "l1,d1"               // Device ID

WiFiClient espClient;
```

```
PubSubClient client(espClient);
long lastMsg = 0;
char msg[90];
int value = 0;

int switch_d;
int switch_d2;

ezButton toggleSwitch(2);
ezButton toggleSwitch2(13);

//*************************************************************************************************************************




void setup() {
  pinMode(0,OUTPUT);
  digitalWrite(0,LOW);
  delay(50);
  Wire.begin();


  Serial.begin(115200);

  delay(1000);


  setup_wifi();
  client.setServer(mqtt_server, 1883);
  client.setCallback(callback);
  WiFi.hostname(String(String(ID)+"C"));
  Serial.println("MAC:" + WiFi.macAddress());
  }

void loop() {
  //connecting to mqtt server
  if (!client.connected()) {
    delay(100);                           // **Yo**
    reconnect();
  }
  client.loop();

  toggleSwitch.loop(); // MUST call the loop() function first
  int state = toggleSwitch.getState();
  //Serial.println(state);
  if (state == HIGH){  //if it is LOW then the switch is closed
  switch_d=0 ;
```

```
  }
  else{
    switch_d=1;
  }

  toggleSwitch2.loop(); // MUST call the loop() function first
  int state2 = toggleSwitch2.getState();
  //Serial.println(state);
  if (state2 == HIGH){  //if it is LOW then the switch is closed
  switch_d2=0 ;

  }
  else{
    switch_d2=1;
  }


  //Sending to mqtt broker
  String DataSent = String(String(ID)+","+String(switch_d));
  DataSent.toCharArray(msg,90);
  client.publish(ROUTE, msg);
  Serial.println(DataSent);
  Serial.println(msg);
  delay(30000);
  }

//******************************************************************************************************
********************

void setup_wifi() {
  delay(10);
  // We start by connecting to a WiFi network
  Serial.println();
  Serial.print("Connecting to ");
  Serial.println(ssid);

  WiFi.begin(ssid, password);

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }

  randomSeed(micros());

  Serial.println("");
  Serial.println("WiFi connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());
```

```
}

void callback(char* topic, byte* payload, unsigned int length) {
  Serial.print("Message arrived [");
  Serial.print(topic);
  Serial.print("] ");
  for (int i = 0; i < length; i++) {
    Serial.print((char)payload[i]);
  }
  Serial.println();

}

void reconnect() {
  // Loop until we're reconnected
  while (!client.connected()) {
    Serial.print("Attempting MQTT connection...");
    // Create a random client ID
    String clientId = "ESP8266Client-";
    clientId += String(random(0xffff), HEX);
    // Attempt to connect
    if (client.connect(clientId.c_str())) {
      Serial.println("connected");
      // Once connected, publish an announcement...
     // client.publish(ROUTE, MESSAGE);
      // ... and resubscribe
      client.subscribe(ROUTE);
    } else {
      Serial.print("failed, rc=");
      Serial.print(client.state());
      Serial.println(" try again in 2 seconds");
      // Wait 2 seconds before retrying
      delay(2000);
    }
  }
}
```

Outdoor Particulate matter sensor

```
#include <ESP8266WiFi.h>
#include <PubSubClient.h>
#include <WiFiManager.h>
#include <SoftwareSerial.h>
//#include "Arduino.h"
```

```
// Update these with values suitable for your network.
const char* ssid = "Rasp-access";
const char* password = "OccupantInteraction";
const char* mqtt_server = "192.168.4.1"; //IP Broker
#define ROUTE "sensors" // Message route
#define ID "l1,e1"               // Device ID

WiFiClient espClient;
PubSubClient client(espClient);
long lastMsg = 0;
char msg[90];
int value = 0;



//*****************************************************************************************************************************

#include <Arduino.h>
#include <SensirionI2CSen5x.h>
#include <Wire.h>

// The used commands use up to 48 bytes. On some Arduino's the default buffer
// space is not large enough
#define MAXBUF_REQUIREMENT 48

#if (defined(I2C_BUFFER_LENGTH) &&                 \
     (I2C_BUFFER_LENGTH >= MAXBUF_REQUIREMENT)) || \
    (defined(BUFFER_LENGTH) && BUFFER_LENGTH >= MAXBUF_REQUIREMENT)
#define USE_PRODUCT_INFO
#endif

SensirionI2CSen5x sen5x;

void printModuleVersions() {
    uint16_t error;
    char errorMessage[256];

    unsigned char productName[32];
    uint8_t productNameSize = 32;

    error = sen5x.getProductName(productName, productNameSize);

    if (error) {
        Serial.print("Error trying to execute getProductName(): ");
        errorToString(error, errorMessage, 256);
```

```
        Serial.println(errorMessage);
    } else {
        Serial.print("ProductName:");
        Serial.println((char*)productName);
    }

    uint8_t firmwareMajor;
    uint8_t firmwareMinor;
    bool firmwareDebug;
    uint8_t hardwareMajor;
    uint8_t hardwareMinor;
    uint8_t protocolMajor;
    uint8_t protocolMinor;

    error = sen5x.getVersion(firmwareMajor, firmwareMinor, firmwareDebug,
                             hardwareMajor, hardwareMinor, protocolMajor,
                             protocolMinor);
    if (error) {
        Serial.print("Error trying to execute getVersion(): ");
        errorToString(error, errorMessage, 256);
        Serial.println(errorMessage);
    } else {
        Serial.print("Firmware: ");
        Serial.print(firmwareMajor);
        Serial.print(".");
        Serial.print(firmwareMinor);
        Serial.print(", ");

        Serial.print("Hardware: ");
        Serial.print(hardwareMajor);
        Serial.print(".");
        Serial.println(hardwareMinor);
    }
}

void printSerialNumber() {
    uint16_t error;
    char errorMessage[256];
    unsigned char serialNumber[32];
    uint8_t serialNumberSize = 32;

    error = sen5x.getSerialNumber(serialNumber, serialNumberSize);
    if (error) {
        Serial.print("Error trying to execute getSerialNumber(): ");
        errorToString(error, errorMessage, 256);
        Serial.println(errorMessage);
    } else {
        Serial.print("SerialNumber:");
        Serial.println((char*)serialNumber);
```

```
    }
}

void setup() {

  Serial.begin(115200);

  while (!Serial) {
        delay(100);
    }

    Wire.begin();

    sen5x.begin(Wire);

    uint16_t error;
    char errorMessage[256];
    error = sen5x.deviceReset();
    if (error) {
        Serial.print("Error trying to execute deviceReset(): ");
        errorToString(error, errorMessage, 256);
        Serial.println(errorMessage);
    }

// Print SEN55 module information if i2c buffers are large enough
#ifdef USE_PRODUCT_INFO
    printSerialNumber();
    printModuleVersions();
#endif

    float tempOffset = 0.0;
    error = sen5x.setTemperatureOffsetSimple(tempOffset);
    if (error) {
        Serial.print("Error trying to execute setTemperatureOffsetSimple(): ");
        errorToString(error, errorMessage, 256);
        Serial.println(errorMessage);
    } else {
        Serial.print("Temperature Offset set to ");
        Serial.print(tempOffset);
        Serial.println(" deg. Celsius (SEN54/SEN55 only");
    }

    // Start Measurement
    error = sen5x.startMeasurement();
    if (error) {
        Serial.print("Error trying to execute startMeasurement(): ");
        errorToString(error, errorMessage, 256);
        Serial.println(errorMessage);
    }
```

```
  delay(1000);


  setup_wifi();
  client.setServer(mqtt_server, 1883);
  client.setCallback(callback);
  WiFi.hostname(String(String(ID)+"C"));
  Serial.println("MAC:" + WiFi.macAddress());
  }

void loop() {
  //connecting to mqtt server
  if (!client.connected()) {
    delay(100);                          // **Yo**
    reconnect();
  }
  client.loop();


    uint16_t error;
    char errorMessage[256];

    delay(1000);

    // Read Measurement
    float massConcentrationPm1p0;
    float massConcentrationPm2p5;
    float massConcentrationPm4p0;
    float massConcentrationPm10p0;
    float ambientHumidity;
    float ambientTemperature;
    float vocIndex;
    float noxIndex;

    error = sen5x.readMeasuredValues(
        massConcentrationPm1p0, massConcentrationPm2p5, massConcentrationPm4p0,
        massConcentrationPm10p0, ambientHumidity, ambientTemperature, vocIndex,
        noxIndex);

    if (error) {
        Serial.print("Error trying to execute readMeasuredValues(): ");
        errorToString(error, errorMessage, 256);
        Serial.println(errorMessage);
    } else {
        Serial.print("MassConcentrationPm1p0:");
        Serial.print(massConcentrationPm1p0);
        Serial.print("\t");
        Serial.print("MassConcentrationPm2p5:");
```

```
        Serial.print(massConcentrationPm2p5);
        Serial.print("\t");
        Serial.print("MassConcentrationPm4p0:");
        Serial.print(massConcentrationPm4p0);
        Serial.print("\t");
        Serial.print("MassConcentrationPm10p0:");
        Serial.print(massConcentrationPm10p0);
        Serial.print("\t");
        Serial.print("AmbientHumidity:");
        if (isnan(ambientHumidity)) {
            Serial.print("n/a");
        } else {
            Serial.print(ambientHumidity);
        }
        Serial.print("\t");
        Serial.print("AmbientTemperature:");
        if (isnan(ambientTemperature)) {
            Serial.print("n/a");
        } else {
            Serial.print(ambientTemperature);
        }
        Serial.print("\t");
        Serial.print("VocIndex:");
        if (isnan(vocIndex)) {
            Serial.print("n/a");
        } else {
            Serial.print(vocIndex);
        }
        Serial.print("\t");
        Serial.print("NoxIndex:");
        if (isnan(noxIndex)) {
            Serial.println("n/a");
        } else {
            Serial.println(noxIndex);
        }
    }

  //Sending to mqtt broker
  String DataSent = 
String(String(ID)+","+String(massConcentrationPm2p5)+","+String(massConcentrationPm10p0)+","+String(ambientTemperature)+","+String(ambientHumidity));
  DataSent.toCharArray(msg,90);
  client.publish(ROUTE, msg);
  Serial.println(DataSent);
  Serial.println(msg);
  //delay(30000);
  delay(100);
  ESP.deepSleep(30e6);
```

```
  }

//*****************************************************************************************************************************

void setup_wifi() {
  delay(10);
  // We start by connecting to a WiFi network
  Serial.println();
  Serial.print("Connecting to ");
  Serial.println(ssid);

  WiFi.begin(ssid, password);

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }

  randomSeed(micros());

  Serial.println("");
  Serial.println("WiFi connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());
}

void callback(char* topic, byte* payload, unsigned int length) {
  Serial.print("Message arrived [");
  Serial.print(topic);
  Serial.print("] ");
  for (int i = 0; i < length; i++) {
    Serial.print((char)payload[i]);
  }
  Serial.println();

}

void reconnect() {
  // Loop until we're reconnected
  while (!client.connected()) {
    Serial.print("Attempting MQTT connection...");
    // Create a random client ID
    String clientId = "ESP8266Client-";
    clientId += String(random(0xffff), HEX);
    // Attempt to connect
    if (client.connect(clientId.c_str())) {
      Serial.println("connected");
      // Once connected, publish an announcement...
```

```
     // client.publish(ROUTE, MESSAGE);
      // ... and resubscribe
      client.subscribe(ROUTE);
    } else {
      Serial.print("failed, rc=");
      Serial.print(client.state());
      Serial.println(" try again in 2 seconds");
      // Wait 2 seconds before retrying
      delay(2000);
    }
  }
}
```

LED control

```
#include <ESP8266WiFi.h>
#include <PubSubClient.h>
#include <Wire.h>
#include <WiFiManager.h>
#include <Ticker.h>
#include <FastLED.h>

#define RGB_PIN           2              // LED DATA PIN
#define RGB_LED_NUM    61           // 10 LEDs [0...9]
#define BRIGHTNESS       200           // brightness range [0..255]
#define CHIP_SET       WS2812B      // types of RGB LEDs
#define COLOR_CODE    GRB          //sequence of colors in data stream

// Define the array of LEDs
CRGB LEDs[RGB_LED_NUM];

// define 3 byte for the random color
byte  a, b, c;
#define UPDATES_PER_SECOND 100

char iByte = -1;

char in_message[100];
String strn;
String n ;
int x = 0 ;

// Update these with values suitable for your network.
const char* ssid = "Rasp-access";
const char* password = "OccupantInteraction";
const char* mqtt_server = "192.168.4.1"; //IP Broker
```

```
#define ROUTE "led18/sen2" // Message route
#define ID "l1,f1"               // Device ID

WiFiClient espClient;
PubSubClient client(espClient);
long lastMsg = 0;
char msg[20];

void setup_wifi() {
  delay(10);
  // We start by connecting to a WiFi network
  Serial.println(ssid);
  WiFi.begin(ssid, password);

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  randomSeed(micros());
  Serial.println("");
  Serial.println("WiFi connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());
}

void callback(char* topic, byte* payload, unsigned int length) {
  int i=0;
  for (i;i<length;i++) {
    in_message[i]=char(payload[i]);
  }
  in_message[i]='\0';
  Serial.println(in_message);
  Serial.println("data arrived");
  for (int i=0 ; i <= sizeof(in_message) ; i++ ){
  strn += in_message[i];
  }




  if (strn != "-1") {
    // read the incoming byte:

    if (strn== "0"){
      Serial.println("GREEN = WIN OPEN");
      for (int i = 0; i < RGB_LED_NUM; i++){
      LEDs[i] = CRGB(0,128,0 );
      FastLED.show();
      }
      delay(1000);
```

```
    }
    if (strn== "1"){
      Serial.println("RED = WIN CLOSED");
      for (int i = 0; i < RGB_LED_NUM; i++){
      LEDs[i] = CRGB(255, 0, 0 );
      FastLED.show();
      }
      delay(1000);
    }
    if (strn== "2"){
      Serial.println("ORANGE = no decision");
      for (int i = 0; i < RGB_LED_NUM; i++){
      LEDs[i] = CRGB(255,131,0);
      FastLED.show();
      }
      delay(1000);
    }
    strn="";
  }

}
//**********************************************************************************************************************************

void setup() {
  Serial.begin(9600);
  Serial.setTimeout(1);

  Serial.println("WS2812B LEDs strip Initialize");
  Serial.println("Please enter the 1 to 6 value.....Otherwise no any effect show");
  FastLED.addLeds<CHIP_SET, RGB_PIN, COLOR_CODE>(LEDs, RGB_LED_NUM);
  randomSeed(analogRead(0));
  FastLED.setBrightness(BRIGHTNESS);
  FastLED.setMaxPowerInVoltsAndMilliamps(5, 500);
  FastLED.clear();
  FastLED.show();


  delay(50);
  Wire.begin();
  delay(100);
  setup_wifi();
  client.setServer(mqtt_server, 1883);
  client.setCallback(callback);
  WiFi.hostname(String(String(ID)+"X"));
  Serial.println("MAC:" + WiFi.macAddress());

  Serial.println("Server started.");
  Serial.print("IP: "); Serial.println(WiFi.softAPIP());
```

```
  Serial.print("MAC:"); Serial.println(WiFi.softAPmacAddress());
}

void loop() {

  if (!client.connected()) {
    delay(1000);                          // **Yo**
    reconnect();
  }
  client.loop();
  //Serial.println(">>>>>>>>>>>>>>>>>>>>>>>>>>>>>>");

  //delay(10);
}

//******************************************************************************************************
********************

void reconnect() {
  // Loop until we're reconnected
  while (!client.connected()) {
    Serial.print("Attempting MQTT connection...");
    // Create a random client ID
    String clientId = "ESP8266Client-";
    clientId += String(random(0xffff), HEX);
    // Attempt to connect
    if (client.connect(clientId.c_str())) {
      Serial.println("connected");
      // Once connected, publish an announcement...
     // client.publish(ROUTE, MESSAGE);
      // ... and resubscribe
      client.subscribe(ROUTE);
    }
    else {
      //Serial.print("failed, rc=");
      //Serial.print(client.state());
      //Serial.println(" try again in 2 seconds");
      // Wait 2 seconds before retrying
      delay(50);
    }
  }
}
```

Appendix IV: Algorithm code

```
import time
import paho.mqtt.client as mqtt
import paho.mqtt.publish as publish
import sys
from time import sleep
from urllib.request import urlopen

import datetime as dt
import matplotlib.pyplot as plt
import matplotlib.animation as animation

from requests_html import HTMLSession
from bs4 import BeautifulSoup
import requests
import re

import numpy as np

Broker = "192.168.4.1"



#CO2
co2_1=""
co2_2=""

#PM 2.5
pm25_1=""
pm25_2=""

#PM 10
pm100_1=""
pm100_2=""

#Indoor temperature
temp_1=""
temp_2=""

temp_1a =""
temp_2a =""
temp_1b =""
temp_2b =""

#variables to count
count_1=0
count_2=0
count_3=0
```

```
#Surface temperature - radiators
st_1=""
st_2=""
st_3=""
st_4=""

#CS
cs_1=""
cs_2=""
cs_3=""
cs_4=""
cs_5=""

#outdoor variables
wind=""
rain=""
out_temp=""
out_pm25=""
out_pm100=""

#No decision
Command_1=""
Command_2=""
Command_3=""
Command_4=""
Command_5=""
Command_6=""

sub_topic = "sensors"    # receive messages on this topic

# mqtt section
# when connecting to mqtt do this;
def on_connect(client, userdata, flags, rc):
    print("Conectado, codigo : "+str(rc))
    print()
    client.subscribe(sub_topic)

# when receiving a mqtt message do this;
def on_message(client, userdata, msg):
    message = str(msg.payload)
    largo=len(message)-1
    mensaje=message[2:largo]

    #print('Dato: '+mensaje)
    lab=int(mensaje[1:2])
    deviceType=mensaje[3:4]
    deviceNumber=mensaje[4:5]

    datos=mensaje[6:largo]
```

```
    largodatos=len(datos)
    coma1=datos[0:largodatos].find(",")
    dato1=datos[0:coma1]

    global values

    line = datos
    global values
    values = line.split(",")

    #CO2
    global co2_1
    global co2_2

    #PM 2.5
    global pm25_1
    global pm25_2

    #PM 10
    global pm100_1
    global pm100_2

    #Indoor temperature
    global temp_1
    global temp_2

    global temp_1a
    global temp_1b
    global temp_2a
    global temp_2b

    #variables to count
    global count_1
    global count_2
    global count_3

    #Surface temperature - radiators
    global st_1
    global st_2
    global st_3
    global st_4

    #CS
    global cs_1
    global cs_2
    global cs_3
    global cs_4
    global cs_5
```

```
    #outdoor variables
    global wind
    global rain
    global out_temp
    global out_pm25
    global out_pm100

    #no decision
    global Command_1
    global Command_2
    global Command_3
    global Command_4
    global Command_5
    global Command_6

    #Rain + wind (Webscraping)
    html_text =
requests.get('https://weather.com/weather/hourbyhour/l/350e4cdda6259d9612c48c88b5374915a199af0df4fc1382
d4cf54a0b1d21881').text
    soup = BeautifulSoup(html_text, 'lxml')

    Current_hour = soup.find('div', class_= 'DaypartDetails--Content--2Yg3_ DaypartDetails--
contentGrid--2_szQ')
    Wind_scrape = Current_hour.find(attrs={"data-testid": "Wind"}).text
    Rain_scrape = Current_hour.find(attrs={"data-testid": "AccumulationValue"}).text

    Wind_str = re.findall(r'\d+', Wind_scrape)
    Wind_flt = float(Wind_str[0]) if Wind_str else 0.0
    wind = Wind_flt * 1.609 #km/h

    Rain_str = re.findall(r'\d\.\d+', Rain_scrape)
    Rain_flt = float(Rain_str[0]) if Rain_str else 0.0
    rain = Rain_flt * 25.4 #mm

    #Particulate matter + co2
    if deviceType=="b":
        if deviceNumber=='1':
            temp_1 = str(values[0])
            co2_1 = str(values[2])
            pm25_1 = str(values[4])
            pm100_1 = str(values [5])
            count_1+=1
            if count_1==1:
                temp_1a=temp_1 #current
            if count_1>10: #interval
                count_1=1
                temp_1b=temp_1a #past value

        if deviceNumber=='2':
```

```
        temp_2 = str(values[0])
        co2_2 = str(values[2])
        pm25_2 = str(values[4])
        pm100_2 = str(values [5])
        count_2+=1
        if count_2==1:
            temp_2a=temp_2 #current
        if count_2>10: #interval
            count_2=1
            temp_2b=temp_2a #past value

#Superficial temperature
if deviceType=="c":
    if deviceNumber=='1':
        cs_1 = str(values[0])
        cs_2 = str(values[1])
        st_1 = str(values[2])
        st_2 = str(values [4])

    if deviceNumber=='2':
        cs_3 = str(values[0])
        cs_4 = str(values[1])
        st_3 = str(values[2])
        st_4 = str(values [3])

#Window opening
if deviceType=="d":
    if deviceNumber=='1':
        cs_5 = str(values[0])
        count_3+=1
        if count_3>6: #interval
            count_3=1

#Outdoor variables
if deviceType=="e":
    if deviceNumber=='1':
        out_temp = str(values[2])
        out_pm25 = str(values[0])
        out_pm100 = str(values[1])



#______________A L G O R I T H M______________

#THRESHOLDS
#energy
Heat_thr = 30.0 #Energy, when is heating on

#air quality
```

```
CO2_thr = 800
PM25in_thr = 5
PM100in_thr = 15
PM25out_thr = 20
PM100out_thr = 30

#weather
Wind_thr = 28.8
Rain_thr = 4.0



#PARAMETERS FROM STRING TO FLOAT
#indoor air quality
CO2_1S = float(co2_1[0:9]) if co2_1 else CO2_thr
CO2_2S = float(co2_2[0:9]) if co2_2 else CO2_thr

PM25_1S = float(pm25_1[0:9]) if pm25_1 else PM25in_thr
PM25_2S = float(pm25_2[0:9]) if pm25_2 else PM25in_thr

PM100_1S = float(pm100_1[0:9]) if pm100_1 else PM100in_thr
PM100_2S = float(pm100_2[0:9]) if pm100_2 else PM100in_thr

#indoor temperature
TEMP_1S = float(temp_1[0:9]) if temp_1 else (float(temp_2[0:9]) if temp_2 else 20)
#TEMP_1AS = float(temp_1a[0:9]) if temp_1a else (float(temp_2a[0:9]) if temp_2a else 20)
#TEMP_1BS = float(temp_1b[0:9]) if temp_1b else (float(temp_2b[0:9]) if temp_2b else 20)

TEMP_2S = float(temp_2[0:9]) if temp_2 else (float(temp_1[0:9]) if temp_1 else 20)
TEMP_2AS = float(temp_2a[0:9]) if temp_2a else (float(temp_1a[0:9]) if temp_1a else 30)
TEMP_2BS = float(temp_2b[0:9]) if temp_2b else (float(temp_1b[0:9]) if temp_1b else 30)

Temp_avg = ((TEMP_2S + TEMP_1S) / 2) # 1st value

#surface temperature - radiators
ST_1S = float(st_1[0:9]) if st_1 else 0.0
ST_2S = float(st_2[0:9]) if st_2 else 0.0
ST_3S = float(st_3[0:9]) if st_3 else 0.0
ST_4S = float(st_4[0:9]) if st_4 else 0.0

#CS
CS_1S = float(cs_1[0:9]) if cs_1 else 0.0
CS_2S = float(cs_2[0:9]) if cs_2 else 0.0
CS_3S = float(cs_3[0:9]) if cs_3 else 0.0
CS_4S = float(cs_4[0:9]) if cs_4 else 0.0
CS_5S = float(cs_5[0:9]) if cs_5 else 0.0

#outdoor variables
Tout_DA = [12.4, 10.5, 9.1, 6.1, 5.2, 5.1, 6.4, 7.8, 8.3, 9.4, 10.6, 11.0, 9.9]
#https://weerstatistieken.nl/rotterdam/2023/april
```

```
    Length_TRM7 = len(Tout_DA)
    TRM7 = (Tout_DA[Length_TRM7-1] + 0.8*Tout_DA[Length_TRM7-2] + 0.6*Tout_DA[Length_TRM7-3] +
0.5*Tout_DA[Length_TRM7-4] + 0.4*Tout_DA[Length_TRM7-5] + 0.3*Tout_DA[Length_TRM7-6] +
0.2*Tout_DA[Length_TRM7-7])/3.8

    OUT_TEMP_S = (float(out_temp[0:9])-2) if out_temp else (Tout_DA[Length_TRM7-1])
    OUT_PM25_S = float(out_pm25[0:9]) if out_pm25 else 0.0
    OUT_PM100_S = float(out_pm100[0:9]) if out_pm100 else 0.0


    #___________ALGORITHM WORKFLOW___________
    #energy section
    Energy = []

    Temp_diff = []

    if Temp_avg > OUT_TEMP_S:
        Temp_diff.append('Outside is colder')
    else:
        Temp_diff.append('Outside is warmer')
        Energy.append('Energy gain')

    Heating = []
    for row in Temp_diff:
        if row == 'Outside is colder' and (ST_1S > Heat_thr or ST_2S > Heat_thr or ST_3S > Heat_thr or
ST_4S > Heat_thr):
            Heating.append('Heating is on')
            Energy.append('Energy loss')
        elif row == 'Outside is colder' and (ST_1S <= Heat_thr or ST_2S <= Heat_thr or ST_3S <=
Heat_thr or ST_4S <= Heat_thr):
            Heating.append('Heating is off')

    Int_heat = []
    for row in Heating:
        if row == 'Heating is off' and (TEMP_2AS > TEMP_2BS):
            Int_heat.append('Tin is rising')
            Energy.append('Energy gain')
        elif row == 'Heating is off' and (TEMP_2AS < TEMP_2BS):
            Int_heat.append('Tin is falling')
            Energy.append('Energy loss')
        elif row == 'Heating is off' and (TEMP_2AS == TEMP_2BS):
            Int_heat.append('Tin is constant')
            Energy.append('Energy loss')


    #outdoor conditions section
    Outdoor_con = []
    for row in Energy:
        if row == 'Energy gain' and (wind > Wind_thr or rain > Rain_thr):
```

```
            Outdoor_con.append('Unpref outcon')
        elif row == 'Energy gain' and (wind <= Wind_thr and rain <= Rain_thr):
            Outdoor_con.append('Pref outcon')

    #Indoor air quality section
    IAQ = []

    CO2_avg = ((CO2_1S + CO2_2S)/2)
    PM25_avg = ((PM25_1S + PM25_2S)/2)
    PM100_avg = ((PM100_1S + PM100_2S)/2)

    for row in Energy:
        if row == 'Energy loss' and (CO2_avg > CO2_thr or PM25_avg > PM25in_thr or PM100_avg >
PM100in_thr):
            IAQ.append('Unacceptable IAQ')
        elif row == 'Energy loss' and (CO2_avg <= CO2_thr and PM25_avg <= PM25in_thr and PM100_avg <=
PM100in_thr):
            IAQ.append('Acceptable IAQ')

    for row in Outdoor_con:
        if row == 'Unpref outcon' and (CO2_avg > CO2_thr or PM25_avg > PM25in_thr or PM100_avg >
PM100in_thr):
            IAQ.append('Unacceptable IAQ')
        elif row == 'Unpref outcon' and (CO2_avg <= CO2_thr and PM25_avg <= PM25in_thr and PM100_avg <=
PM100in_thr):
            IAQ.append('Acceptable IAQ')

    #thermal comfort section
    Therm_comf = []
    for row in IAQ:
        if row == 'Acceptable IAQ' and 10<TRM7<30 and Temp_avg>=(0.33*TRM7+18.8+2):
            Therm_comf.append('Thermal comfort exceeded')
        elif row == 'Acceptable IAQ' and 10<TRM7<30 and Temp_avg<(0.33*TRM7+18.8+2):
            Therm_comf.append('Thermal comfort good')

        elif row == 'Acceptable IAQ' and TRM7<=10 and Temp_avg>=24.1:
            Therm_comf.append('Thermal comfort exceeded')
        elif row == 'Acceptable IAQ' and TRM7<=10 and Temp_avg<24.1:
            Therm_comf.append('Thermal comfort good')

        elif row == 'Acceptable IAQ' and TRM7>=30 and Temp_avg>=30.7:
            Therm_comf.append('Thermal comfort exceeded')
        elif row == 'Acceptable IAQ' and TRM7>=30 and Temp_avg<30.7:
            Therm_comf.append('Thermal comfort good')


    #outdoor pollution section
    Out_AQ = []
```

```
    for row in Outdoor_con:
        if row == 'Pref outcon' and (OUT_PM25_S > PM25out_thr or OUT_PM100_S > PM100out_thr):
            Out_AQ.append('Unacceptable outdoor AQ')
        elif row == 'Pref outcon' and (OUT_PM25_S <= PM25out_thr and OUT_PM100_S <= PM100out_thr):
            Out_AQ.append('Acceptable outdoor AQ')

    for row in IAQ:
        if row == 'Unacceptable IAQ' and (OUT_PM25_S > PM25out_thr or OUT_PM100_S > PM100out_thr):
            Out_AQ.append('Unacceptable outdoor AQ')
        elif row == 'Unacceptable IAQ' and (OUT_PM25_S <= PM25out_thr and OUT_PM100_S <= PM100out_thr):
            Out_AQ.append('Acceptable outdoor AQ')

    for row in Therm_comf:
        if row == 'Thermal comfort exceeded' and (OUT_PM25_S > PM25out_thr or OUT_PM100_S > PM100out_thr):
            Out_AQ.append('Unacceptable outdoor AQ')
        elif row == 'Thermal comfort exceeded' and (OUT_PM25_S <= PM25out_thr and OUT_PM100_S <= PM100out_thr):
            Out_AQ.append('Acceptable outdoor AQ')

    #window opening/closing section
    Window_opp = []

    A = 'Open window'
    B = 'Close window'
    C = 'No decision'
    D = 'Go'

    for row in Out_AQ:
        if row == 'Acceptable outdoor AQ':
            Window_opp.append(A)
        elif row == 'Unacceptable outdoor AQ':
            Window_opp.append(B)

    for row in Therm_comf:
        if row == 'Thermal comfort good':
            Window_opp.append(B)

    Command_1 = Window_opp if count_3==1 else Command_1
    Command_2 = Window_opp if count_3==2 else Command_2
    Command_3 = Window_opp if count_3==3 else Command_3
    Command_4 = Window_opp if count_3==4 else Command_4
    Command_5 = Window_opp if count_3==5 else Command_5
    Command_6 = Window_opp if count_3==6 else Command_6

    Window_not_overruled = []
    Rule_open = (Command_1==[A] and Command_2==[A] and Command_3==[A] and Command_4==[A] and Command_5==[A] and Command_6==[A])
```

```
    Rule_closed = (Command_1==[B] and Command_2==[B] and Command_3==[B] and Command_4==[B] and Command_5==[B] and Command_6==[B])
    if Rule_open == True or Rule_closed == True:
        Window_not_overruled.append(D)

    Final_decision = []
    Final_decision.append(0) if Window_opp == [A] and Window_not_overruled == [D] else Final_decision.append(1) if Window_opp == [B] and Window_not_overruled == [D] else Final_decision.append(2)

    #info_sensor
client = mqtt.Client()
client.on_connect = on_connect
client.on_message = on_message
#to send info back to wemos
client.connect(Broker, 1883, 60)
client.loop_forever()
```

Appendix V: Code for data organizing and cleaning

Existing situation

```
import numpy as np
import pandas as pd
from csv import reader
import datetime as dt
import matplotlib.pyplot as plt
import seaborn as sns

#____________________________________________________________________________________________________________________________________________________

#ORGANISING DATA

#CS
First_row = ['Date', 'Time', 'Room', 'Sensor group', 'Sensor number', 'Window 5']
read_file = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CS.txt')
read_file.to_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CS.csv', index=None)
CS = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CS.csv', names=First_row)

CS.insert(0, 'DateTime', pd.to_datetime(CS['Date'].astype(str) + ' ' + CS['Time'].astype(str)))
#include datetime
CS_new = CS.drop(['Date', 'Time', 'Room', 'Sensor group', 'Sensor number'], axis = 1) #remove columns
CS_new['DateTime'] = CS_new['DateTime'].dt.floor('min') #Round down seconds to nearest minute
CS_new = CS_new.groupby('DateTime', as_index=False)['Window 5'].mean() #Get rid of identical values
CS_new = CS_new.set_index('DateTime') #Set DateTime as index

#print('')
#print('Contact sensor')
#print(CS_new.head())

#CO2
First_row = ['Date', 'Time', 'Room', 'Sensor group', 'Sensor number','Temp_room', 'RH_room', 'CO2_room']
read_file = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CO2.txt')
read_file.to_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CO2.csv', index=None)
CO2 = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CO2.csv', names=First_row)

CO2.insert(0, 'DateTime', pd.to_datetime(CO2['Date'].astype(str) + ' ' + CO2['Time'].astype(str)))
#include datetime
CO2_new = CO2.drop(['Date', 'Time', 'Room', 'Sensor group', 'Sensor number'], axis = 1) #remove columns

CO2_new['DateTime'] = CO2_new['DateTime'].dt.floor('min') #Round down seconds to nearest minute
CO2_new = CO2_new.groupby('DateTime', as_index=False)[['Temp_room', 'RH_room', 'CO2_room']].mean() #Get rid of identical values
CO2_new = CO2_new.set_index('DateTime') #Set DateTime as index

#print('')
```

```
#print('CO2')
#print(CO2_new.head())

#CO2_PM
First_row = ['Date', 'Time', 'Room', 'Sensor group', 'Sensor number','Temp_table', 'RH_table',
'CO2_table', 'PM10', 'PM25', 'PM100']
read_file = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CO2_PM.txt')
read_file.to_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CO2_PM.csv', index=None)
CO2_PM = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CO2_PM.csv', names=First_row)

CO2_PM.insert(0, 'DateTime', pd.to_datetime(CO2_PM['Date'].astype(str) + ' ' +
CO2_PM['Time'].astype(str))) #include datetime
CO2_PM_new = CO2_PM.drop(['Date', 'Time', 'Room', 'Sensor group'], axis = 1) #remove columns

CO2_PM_sensor1 = CO2_PM_new.loc[CO2_PM_new['Sensor number'] == 1, ['DateTime', 'Temp_table',
'RH_table', 'CO2_table', 'PM10', 'PM25', 'PM100']]#data from sensor 1 only
CO2_PM_sensor1['DateTime'] = CO2_PM_sensor1['DateTime'].dt.floor('min') #Round down seconds to nearest
minute
CO2_PM_sensor1 = CO2_PM_sensor1.groupby('DateTime', as_index=False)[['Temp_table', 'RH_table',
'CO2_table', 'PM10', 'PM25', 'PM100']].mean() #Get rid of identical values
CO2_PM_sensor1 = CO2_PM_sensor1.set_index('DateTime') #Set DateTime as index
CO2_PM_sensor1.columns = ['Temp_1', 'RH_1', 'CO2_1', 'PM10_1', 'PM25_1', 'PM100_1']

CO2_PM_sensor2 = CO2_PM_new.loc[CO2_PM_new['Sensor number'] == 2, ['DateTime', 'Temp_table',
'RH_table', 'CO2_table', 'PM10', 'PM25', 'PM100']]#data from sensor 2 only
CO2_PM_sensor2['DateTime'] = CO2_PM_sensor2['DateTime'].dt.floor('min') #Round down seconds to nearest
minute
CO2_PM_sensor2 = CO2_PM_sensor2.groupby('DateTime', as_index=False)[['Temp_table', 'RH_table',
'CO2_table', 'PM10', 'PM25', 'PM100']].mean() #Get rid of identical values
CO2_PM_sensor2 = CO2_PM_sensor2.set_index('DateTime') #Set DateTime as index
CO2_PM_sensor2.columns = ['Temp_2', 'RH_2', 'CO2_2', 'PM10_2', 'PM25_2', 'PM100_2']

#print('')
#print('CO2_PM_Sensor1')
#print(CO2_PM_sensor1.head())
#print('')
#print('CO2_PM_Sensor2')
#print(CO2_PM_sensor2.head())

#CS_TEMP
First_row = ['Date', 'Time', 'Room', 'Sensor group', 'Sensor number','Window_A', 'Window_B', 'Temp_C',
'Temp_D', 'Temp_E']
read_file = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CS_TEMP.txt')
read_file.to_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CS_TEMP.csv', index=None)
CS_TEMP = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CS_TEMP.csv', names=First_row)

CS_TEMP.insert(0, 'DateTime', pd.to_datetime(CS_TEMP['Date'].astype(str) + ' ' +
CS_TEMP['Time'].astype(str))) #include datetime
CS_TEMP_new = CS_TEMP.drop(['Date', 'Time', 'Room', 'Sensor group'], axis = 1) #remove columns
```

```
CS_TEMP_sensor1 = CS_TEMP_new.loc[CS_TEMP_new['Sensor number'] == 1, ['DateTime','Window_A', 'Window_B', 'Temp_C', 'Temp_D', 'Temp_E']]#data from sensor 1 only
CS_TEMP_sensor1['DateTime'] = CS_TEMP_sensor1['DateTime'].dt.floor('min') #Round down seconds to nearest minute
CS_TEMP_sensor1 = CS_TEMP_sensor1.groupby('DateTime', as_index=False)[['Window_A', 'Window_B', 'Temp_C', 'Temp_D', 'Temp_E']].mean() #Get rid of identical values
CS_TEMP_sensor1 = CS_TEMP_sensor1.set_index('DateTime') #Set DateTime as index
CS_TEMP_sensor1.columns = ['Window 3', 'Window 4', 'Rad 3', 'Rad Z', 'Rad 4']
CS_TEMP_sensor1 = CS_TEMP_sensor1.drop(['Rad Z'], axis = 1) #remove columns

CS_TEMP_sensor2 = CS_TEMP_new.loc[CS_TEMP_new['Sensor number'] == 2, ['DateTime','Window_A', 'Window_B', 'Temp_C', 'Temp_D', 'Temp_E']]#data from sensor 2 only
CS_TEMP_sensor2['DateTime'] = CS_TEMP_sensor2['DateTime'].dt.floor('min') #Round down seconds to nearest minute
CS_TEMP_sensor2 = CS_TEMP_sensor2.groupby('DateTime', as_index=False)[['Window_A', 'Window_B', 'Temp_C', 'Temp_D', 'Temp_E']].mean() #Get rid of identical values
CS_TEMP_sensor2 = CS_TEMP_sensor2.set_index('DateTime') #Set DateTime as index
CS_TEMP_sensor2.columns = ['Window 1', 'Window 2', 'Rad 1', 'Rad 2', 'Rad Z']
CS_TEMP_sensor2 = CS_TEMP_sensor2.drop(['Rad Z'], axis = 1) #remove columns

#print('')
#print('CS_TEMP_sensor1')
#print(CS_TEMP_sensor1.head())
#print('')
#print('CS_TEMP_sensor2')
#print(CS_TEMP_sensor2.head())

#WEATHER_DATA
First_row = ['Place', 'Date', 'Time', 'Wind_Speed01', 'Out_temp', 'Rain', 'Out_RH']
read_file = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\Weather Data KNMI.txt')
read_file.to_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\Weather Data KNMI.csv', index=None)
Weather = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\Weather Data KNMI.csv', names=First_row)
Weather['Time'] = Weather['Time'].astype(str) + ':00:00'
Weather['Time'] =Weather['Time'].replace('24:00:00', '00:00:00')

Weather
Weather.insert(0, 'DateTime', pd.to_datetime(Weather['Date'].astype(str) + ' ' + Weather['Time'].astype(str))) #include datetime
Weather_new = Weather.drop(['Place', 'Date', 'Time'], axis = 1) #remove columns
Weather_new = Weather_new.set_index('DateTime') #Set DateTime as index
Weather_new['Wind_Speed01'] = Weather_new['Wind_Speed01'] * 0.1 * 3.6 #convert from 10 m/s to km/h
Weather_new['Out_temp'] = Weather_new['Out_temp'] * 0.1 #convert from 10 celcius to celcius
Weather_new['Rain'] = Weather_new['Rain'] * 0.1 #convert from 10 mm to mm

#PM_OUT BY WEB SOURCE
First_row = ['Date', 'Time', 'Out_PM25', 'Out_PM100']
read_file = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\PM25_100.txt')
```

```
read_file.to_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\PM25_100.csv', index=None)
Out_PM25_100 = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\PM25_100.csv', names=First_row)

Out_PM25_100.insert(0, 'DateTime', pd.to_datetime(Out_PM25_100['Date'].astype(str) + ' ' +
Out_PM25_100['Time'].astype(str))) #include datetime
Out_PM25_100_new = Out_PM25_100.drop(['Date', 'Time'], axis = 1) #remove columns
Out_PM25_100_new = Out_PM25_100_new.set_index('DateTime') #Set DateTime as index

#PREPARE DATETIME
start_date = pd.Timestamp('2023-04-03 09:00:00') #Start day experiment
end_date = pd.Timestamp('2023-04-21 19:00:00') #Final day experiment
date_range = pd.date_range(start=start_date, end=end_date, freq='T') #T stands for per minute
business_hours = date_range[(date_range.weekday < 5) & (date_range.hour >= 9) & (date_range.hour <=
18)] #date_range.hour should be 19 to get 19:00, however 18 results in 19:00
df = pd.DataFrame(0, index=business_hours, columns=['value']) #Create Dataframe
df = df[~df.index.strftime('%Y-%m-%d').isin(['2023-04-07', '2023-04-10', '2023-04-17'])] #Drop holidays
df['Time'] = df.index.time

#Show = df.loc['2023-04-06 18:58:00':'2023-04-11 10:00:00', :]
#print(Show)

#MERGE DATA
Merged_df = df.merge(CS_new, how='left', left_index=True, right_index=True)
Merged_df = Merged_df.merge(CO2_new, how='left', left_index=True, right_index=True)
Merged_df = Merged_df.merge(CO2_PM_sensor1, how='left', left_index=True, right_index=True)
Merged_df = Merged_df.merge(CO2_PM_sensor2, how='left', left_index=True, right_index=True)
Merged_df = Merged_df.merge(CS_TEMP_sensor2, how='left', left_index=True, right_index=True)
Merged_df = Merged_df.merge(CS_TEMP_sensor1, how='left', left_index=True, right_index=True)
Merged_df = Merged_df.merge(Weather_new, how='left', left_index=True, right_index=True)
Merged_df = Merged_df.merge(Out_PM25_100_new, how='left', left_index=True, right_index=True)
Merged_df = Merged_df.drop(columns=['value', 'PM10_1', 'PM10_2'])

#REMOVE WRONG VALUES
Merged_df.loc[Merged_df['Temp_room'] == -100, 'Temp_room'] = np.nan
Merged_df.loc[Merged_df['Temp_1'] == -100, 'Temp_1'] = np.nan
Merged_df.loc[Merged_df['Temp_2'] == -100, 'Temp_2'] = np.nan

Merged_df.loc[Merged_df['Temp_room'] < 0, 'Temp_room'] = np.nan
Merged_df.loc[Merged_df['Temp_1'] < 0, 'Temp_1'] = np.nan
Merged_df.loc[Merged_df['Temp_2'] < 0, 'Temp_2'] = np.nan

Merged_df.loc[Merged_df['RH_room'] == 0, 'RH_room'] = np.nan
Merged_df.loc[Merged_df['RH_1'] == 0, 'RH_1'] = np.nan
Merged_df.loc[Merged_df['RH_2'] == 0, 'RH_2'] = np.nan

Merged_df.loc[Merged_df['CO2_room'] == 0, 'CO2_room'] = np.nan
Merged_df.loc[Merged_df['CO2_1'] == 0, 'CO2_1'] = np.nan
Merged_df.loc[Merged_df['CO2_2'] == 0, 'CO2_2'] = np.nan
```

```
Merged_df.loc[Merged_df['Rain'] == -1, 'Rain'] = 0.05

Merged_df.loc[~Merged_df['Window 1'].isin([0, 1]), 'Window 1'] = np.nan
Merged_df.loc[~Merged_df['Window 2'].isin([0, 1]), 'Window 2'] = np.nan
Merged_df.loc[~Merged_df['Window 3'].isin([0, 1]), 'Window 3'] = np.nan
Merged_df.loc[~Merged_df['Window 4'].isin([0, 1]), 'Window 4'] = np.nan
Merged_df.loc[~Merged_df['Window 5'].isin([0, 1]), 'Window 5'] = np.nan

#ADJUST / REMOVE WRONG VALUES
mask1 = Merged_df.index.date == pd.to_datetime('2023-04-03').date()
Merged_df.loc[mask1, 'CO2_room'] = Merged_df.loc[mask1, 'CO2_room'] - 400 #CO2_r was not correctly calibrated

mask = ~((Merged_df.index >= pd.to_datetime('2023-04-11 17:30:00')) & (Merged_df.index <= pd.to_datetime('2023-04-11 19:00:00')))
Merged_df = Merged_df[mask] #Time error raspberry pi and was not working well

#Additional columns mean
Merged_df['Temp_mean'] = Merged_df[['Temp_1', 'Temp_2']].mean(axis=1)
Merged_df['RH_mean'] = Merged_df[['RH_1', 'RH_2']].mean(axis=1)
Merged_df['CO2_mean'] = Merged_df[['CO2_1', 'CO2_2']].mean(axis=1)
Merged_df['PM25_mean'] = Merged_df[['PM25_1', 'PM25_2']].mean(axis=1)
Merged_df['PM100_mean'] = Merged_df[['PM100_1', 'PM100_2']].mean(axis=1)

#Additional columns threshold exceeded
Merged_df['Win_act'] = np.where((Merged_df[['Window 1', 'Window 2', 'Window 3', 'Window 4', 'Window 5']] == 0).any(axis=1), 13, np.nan)

Merged_df['Out_PM25'] = Merged_df['Out_PM25'].interpolate()
Merged_df['Out_PM100'] = Merged_df['Out_PM100'].interpolate()
Merged_df['Wind_Speed01'] = Merged_df['Wind_Speed01'].interpolate()
Merged_df['Rain'] = Merged_df['Rain'].interpolate()

Merged_df['Temp_thr'] = np.where(Merged_df['Temp_mean'] > 24.1, 11, np.nan)
Merged_df['RH_thr'] = np.where(Merged_df['RH_mean'] < 30, 10, np.nan)
Merged_df['CO2_thr'] = np.where(Merged_df['CO2_mean'] > 800, 9, np.nan)
Merged_df['PM25_thr'] = np.where(Merged_df['PM25_mean'] > 5, 8, np.nan)
Merged_df['PM100_thr'] = np.where(Merged_df['PM100_mean'] > 15, 7, np.nan)
Merged_df['Rad_act'] = np.where((Merged_df[['Rad 1', 'Rad 2', 'Rad 3', 'Rad 4']] > 30).any(axis=1), 6, np.nan)

Merged_df['Out_PM25_thr'] = np.where(Merged_df['Out_PM25'] > 20, 4, np.nan)
Merged_df['Out_PM100_thr'] = np.where(Merged_df['Out_PM100'] > 30, 3, np.nan)
Merged_df['Wind_thr'] = np.where(Merged_df['Wind_Speed01'] > 32.4, 2, np.nan)
Merged_df['Rain_thr'] = np.where(Merged_df['Rain'] > 0, 1, np.nan)

Merged_df.loc['2023-04-07 09:00:00':'2023-04-10 19:00:00', 'Wind_thr'] = np.nan

#NEW ORDER
```

```
new_order = ['Time', 'Out_temp', 'Temp_room', 'Temp_1', 'Temp_2', 'Temp_mean', 'Temp_thr', 'Out_RH',
'RH_room', 'RH_1', 'RH_2', 'RH_mean','RH_thr', 'CO2_room', 'CO2_1', 'CO2_2', 'CO2_mean','CO2_thr',
'Out_PM25', 'Out_PM25_thr', 'PM25_1', 'PM25_2', 'PM25_mean', 'PM25_thr', 'Out_PM100', 'Out_PM100_thr',
'PM100_1', 'PM100_2', 'PM100_mean', 'PM100_thr', 'Window 1', 'Window 2', 'Window 3', 'Window 4',
'Window 5', 'Win_act', 'Rad 1', 'Rad 2', 'Rad 3', 'Rad 4', 'Rad_act', 'Wind_Speed01',
'Wind_thr',  'Rain', 'Rain_thr']
Merged_df = Merged_df.reindex(columns=new_order)

#CHANGE NAMES
Merged_df = Merged_df.rename(columns={'Temp_room': 'Temp_r', 'Window 1': 'Win_1', 'Window 2': 'Win_2',
'Window 3': 'Win_3', 'Window 4': 'Win_4', 'Window 5': 'Win_5', 'Wind_Speed01': 'Wind', 'CO2_room':
'CO2_r', 'RH_room': 'RH_r'})

#***ADDITIONAL RELEVANT COLUMNS***

#temperature
mean_temp_table = Merged_df[['Temp_1', 'Temp_2']].mean(axis=1)
diff_temp_table = abs(Merged_df['Temp_1'] - Merged_df['Temp_2'])
diff_temp_romtab = abs(Merged_df['Temp_r'] - mean_temp_table)

#relative humidity
mean_RH_table = Merged_df[['RH_1', 'RH_2']].mean(axis=1)
diff_RH_table = abs(Merged_df['RH_1'] - Merged_df['RH_2'])
diff_RH_romtab = abs(Merged_df['RH_r'] - mean_RH_table)

#CO2
mean_CO2_table = Merged_df[['CO2_1', 'CO2_2']].mean(axis=1)
diff_CO2_table = abs(Merged_df['CO2_1'] - Merged_df['CO2_2'])
diff_CO2_romtab = abs(Merged_df['CO2_r'] - mean_CO2_table)

#PM25
mean_PM25_table = Merged_df[['PM25_1', 'PM25_2']].mean(axis=1)
diff_PM25_table = abs(Merged_df['PM25_1'] - Merged_df['PM25_2'])

#PM100
mean_PM100_table = Merged_df[['PM100_1', 'PM100_2']].mean(axis=1)
diff_PM100_table = abs(Merged_df['PM100_1'] - Merged_df['PM100_2'])

#Total number of open windows
Merged_df['Window_sum'] = (Merged_df['Win_1'] == 0).astype(int) + (Merged_df['Win_2'] == 0).astype(int)
+ (Merged_df['Win_3'] == 0).astype(int) + (Merged_df['Win_4'] == 0).astype(int) + (Merged_df['Win_5']
== 0).astype(int)
print(Merged_df.loc['2023-04-11 13:00:00':'2023-04-11 14:00:00', 'Window_sum'])





#Dataframes per day
```

```
Day3 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-03').date()]
Day4 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-04').date()]
Day5 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-05').date()]
Day6 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-06').date()]

Day11 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-11').date()]
Day12 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-12').date()]
Day13 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-13').date()]
Day14 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-14').date()]

Day18 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-18').date()]
Day19 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-19').date()]
Day20 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-20').date()]
Day21 = Merged_df.loc[Merged_df.index.date == pd.to_datetime('2023-04-21').date()]

Day3 = Day3.copy()
Day4 = Day4.copy()
Day5 = Day5.copy()
Day6 = Day6.copy()

Day11 = Day11.copy()
Day12 = Day12.copy()
Day13 = Day13.copy()
Day14 = Day14.copy()

Day18 = Day18.copy()
Day19 = Day19.copy()
Day20 = Day20.copy()
Day21 = Day21.copy()

def time_to_hours(t):
    return t.second / 3600 + t.minute / 60 + t.hour

Day3['Time'] = Day3['Time'].apply(time_to_hours)
Day4['Time'] = Day4['Time'].apply(time_to_hours)
Day5['Time'] = Day5['Time'].apply(time_to_hours)
Day6['Time'] = Day6['Time'].apply(time_to_hours)

Day11['Time'] = Day11['Time'].apply(time_to_hours)
Day12['Time'] = Day12['Time'].apply(time_to_hours)
Day13['Time'] = Day13['Time'].apply(time_to_hours)
Day14['Time'] = Day14['Time'].apply(time_to_hours)

Day18['Time'] = Day18['Time'].apply(time_to_hours)
Day19['Time'] = Day19['Time'].apply(time_to_hours)
Day20['Time'] = Day20['Time'].apply(time_to_hours)
Day21['Time'] = Day21['Time'].apply(time_to_hours)
```

```
#Mean of measured days
Day_mean = Merged_df

def time_to_hours(t):
    return t.second / 3600 + t.minute / 60 + t.hour
Day_mean['Time'] = Day_mean['Time'].apply(time_to_hours)

Day_mean = Day_mean.groupby('Time', as_index=False).mean()
Day_mean = Day_mean.sort_values('Time')



#Dataframe days without nan values
Day3nan = Day3.copy()
Day4nan = Day4.copy()
Day5nan = Day5.copy()
Day6nan = Day6.copy()

Day11nan = Day11.copy()
Day12nan = Day12.copy()
Day13nan = Day13.copy()
Day14nan = Day14.copy()

Day18nan = Day18.copy()
Day19nan = Day19.copy()
Day20nan = Day20.copy()
Day21nan = Day21.copy()

Day3nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day4nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day5nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day6nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)

Day11nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day12nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day13nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day14nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)

Day18nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
```

```
Day19nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day20nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day21nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)

Day3nan.dropna(inplace=True)
Day4nan.dropna(inplace=True)
Day5nan.dropna(inplace=True)
Day6nan.dropna(inplace=True)

Day11nan.dropna(inplace=True)
Day12nan.dropna(inplace=True)
Day13nan.dropna(inplace=True)
Day14nan.dropna(inplace=True)

Day18nan.dropna(inplace=True)
Day19nan.dropna(inplace=True)
Day20nan.dropna(inplace=True)
Day21nan.dropna(inplace=True)


#Mean of measured days without nan values
Day_mean_nan = Day_mean.copy()
Day_mean_nan.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day_mean_nan.dropna(inplace=True)
```

New situation

```
#CO2_PM
First_row = ['Date', 'Time', 'Room', 'Sensor group', 'Sensor number','Temp_table', 'RH_table', 'CO2_table', 'PM10', 'PM25', 'PM100']
read_file = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CO2_PM.txt')
read_file.to_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CO2_PM.csv', index=None)
CO2_PM = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew2\CO2_PM.csv', names=First_row)

CO2_PM.insert(0, 'DateTime', pd.to_datetime(CO2_PM['Date'].astype(str) + ' ' + CO2_PM['Time'].astype(str))) #include datetime
CO2_PM_new = CO2_PM.drop(['Date', 'Time', 'Room', 'Sensor group'], axis = 1) #remove columns

CO2_PM_sensor1 = CO2_PM_new.loc[CO2_PM_new['Sensor number'] == 1, ['DateTime', 'Temp_table', 'RH_table', 'CO2_table', 'PM10', 'PM25', 'PM100']]#data from sensor 1 only
CO2_PM_sensor1['DateTime'] = CO2_PM_sensor1['DateTime'].dt.floor('min') #Round down seconds to nearest minute
CO2_PM_sensor1 = CO2_PM_sensor1.set_index('DateTime') #Set DateTime as index
```

```
CO2_PM_sensor1 = CO2_PM_sensor1[~CO2_PM_sensor1.index.duplicated(keep='first')]
CO2_PM_sensor1.columns = ['Temp_1', 'RH_1', 'CO2_1', 'PM10_1', 'PM25_1', 'PM100_1']

CO2_PM_sensor2 = CO2_PM_new.loc[CO2_PM_new['Sensor number'] == 2, ['DateTime', 'Temp_table', 'RH_table', 'CO2_table', 'PM10', 'PM25', 'PM100']]#data from sensor 2 only
CO2_PM_sensor2['DateTime'] = CO2_PM_sensor2['DateTime'].dt.floor('min') #Round down seconds to nearest minute
CO2_PM_sensor2 = CO2_PM_sensor2.set_index('DateTime') #Set DateTime as index
CO2_PM_sensor2 = CO2_PM_sensor2[~CO2_PM_sensor2.index.duplicated(keep='first')]
CO2_PM_sensor2.columns = ['Temp_2', 'RH_2', 'CO2_2', 'PM10_2', 'PM25_2', 'PM100_2']


#PM_OUT BY SENSOR
First_row = ['Date', 'Time', 'Room', 'Sensor group', 'Sensor number', 'Out_PM25', 'Out_PM100', 'Out_temp_wr', 'Out_RH_wr']
read_file = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew\out_pm.txt')
read_file.to_csv(r'C:\Users\serha\Desktop\Python\0.Datanew\out_pm.csv', index=None)
Out_PM25_100 = pd.read_csv(r'C:\Users\serha\Desktop\Python\0.Datanew\out_pm.csv', names=First_row)
Out_PM25_100 = Out_PM25_100.iloc[1:]  # Remove the first row

Out_PM25_100.insert(0, 'DateTime', pd.to_datetime(Out_PM25_100['Date'].astype(str) + ' ' + Out_PM25_100['Time'].astype(str))) #include datetime
Out_PM25_100_new = Out_PM25_100.drop(['Date', 'Time', 'Room', 'Sensor group', 'Sensor number', 'Out_temp_wr', 'Out_RH_wr'], axis = 1) #remove columns

Out_PM25_100_new['DateTime'] = Out_PM25_100_new['DateTime'].dt.floor('min') #Round down seconds to nearest minute
Out_PM25_100_new = Out_PM25_100_new.drop_duplicates()

Out_PM25_100_new['Out_PM100'] = Out_PM25_100_new['Out_PM100'].astype(float)
Out_PM25_100_new = Out_PM25_100_new.set_index('DateTime') #Set DateTime as index


#PREPARE DATETIME
start_date = pd.Timestamp('2023-04-24 09:00:00') #Start day experiment
end_date = pd.Timestamp('2023-05-12 19:00:00') #Final day experiment
date_range = pd.date_range(start=start_date, end=end_date, freq='T') #T stands for per minute
business_hours = date_range[(date_range.weekday < 5) & (date_range.hour >= 9) & (date_range.hour <= 18)] #date_range.hour should be 19 to get 19:00, however 18 results in 19:00
df = pd.DataFrame(0, index=business_hours, columns=['value']) #Create Dataframe
df = df[~df.index.strftime('%Y-%m-%d').isin(['2023-04-27', '2023-05-05'])] #Drop holidays
df['Time'] = df.index.time

#Show = df.loc['2023-04-06 18:58:00':'2023-04-11 10:00:00', :]
#print(Show)

#MERGE DATA
Merged_dfnew = df.merge(CS_new, how='left', left_index=True, right_index=True)
Merged_dfnew = Merged_dfnew.merge(CO2_new, how='left', left_index=True, right_index=True)
```

```
Merged_dfnew = Merged_dfnew.merge(CO2_PM_sensor1, how='left', left_index=True, right_index=True)
Merged_dfnew = Merged_dfnew.merge(CO2_PM_sensor2, how='left', left_index=True, right_index=True)
Merged_dfnew = Merged_dfnew.merge(CS_TEMP_sensor2, how='left', left_index=True, right_index=True)
Merged_dfnew = Merged_dfnew.merge(CS_TEMP_sensor1, how='left', left_index=True, right_index=True)
Merged_dfnew = Merged_dfnew.merge(Weather_new, how='left', left_index=True, right_index=True)
Merged_dfnew = Merged_dfnew.merge(Out_PM25_100_new, how='left', left_index=True, right_index=True)
Merged_dfnew = Merged_dfnew.drop(columns=['value', 'PM10_1', 'PM10_2'])

#REMOVE WRONG VALUES
Merged_dfnew.loc[Merged_dfnew['Temp_room'] == -100, 'Temp_room'] = np.nan
Merged_dfnew.loc[Merged_dfnew['Temp_1'] == -100, 'Temp_1'] = np.nan
Merged_dfnew.loc[Merged_dfnew['Temp_2'] == -100, 'Temp_2'] = np.nan

Merged_dfnew.loc[Merged_dfnew['Temp_room'] < 15, 'Temp_room'] = np.nan
Merged_dfnew.loc[Merged_dfnew['Temp_1'] < 15, 'Temp_1'] = np.nan
Merged_dfnew.loc[Merged_dfnew['Temp_2'] < 15, 'Temp_2'] = np.nan

Merged_dfnew.loc[Merged_dfnew['RH_room'] == 0, 'RH_room'] = np.nan
Merged_dfnew.loc[Merged_dfnew['RH_1'] == 0, 'RH_1'] = np.nan
Merged_dfnew.loc[Merged_dfnew['RH_2'] == 0, 'RH_2'] = np.nan

Merged_dfnew.loc[Merged_dfnew['CO2_room'] == 0, 'CO2_room'] = np.nan
Merged_dfnew.loc[Merged_dfnew['CO2_1'] == 0, 'CO2_1'] = np.nan
Merged_dfnew.loc[Merged_dfnew['CO2_2'] == 0, 'CO2_2'] = np.nan

Merged_dfnew.loc[Merged_dfnew['Rain'] == -1, 'Rain'] = 0.05

Merged_dfnew.loc[~Merged_dfnew['Window 1'].isin([0, 1]), 'Window 1'] = np.nan
Merged_dfnew.loc[~Merged_dfnew['Window 2'].isin([0, 1]), 'Window 2'] = np.nan
Merged_dfnew.loc[~Merged_dfnew['Window 3'].isin([0, 1]), 'Window 3'] = np.nan
Merged_dfnew.loc[~Merged_dfnew['Window 4'].isin([0, 1]), 'Window 4'] = np.nan
Merged_dfnew.loc[~Merged_dfnew['Window 5'].isin([0, 1]), 'Window 5'] = np.nan

#Additional columns mean
Merged_dfnew['Temp_mean'] = Merged_dfnew[['Temp_1', 'Temp_2']].mean(axis=1)
Merged_dfnew['RH_mean'] = Merged_dfnew[['RH_1', 'RH_2']].mean(axis=1)
Merged_dfnew['CO2_mean'] = Merged_dfnew[['CO2_1', 'CO2_2']].mean(axis=1)
Merged_dfnew['PM25_mean'] = Merged_dfnew[['PM25_1', 'PM25_2']].mean(axis=1)
Merged_dfnew['PM100_mean'] = Merged_dfnew[['PM100_1', 'PM100_2']].mean(axis=1)

#Additional columns threshold exceeded
Merged_dfnew['Win_act'] = np.where((Merged_dfnew[['Window 1', 'Window 2', 'Window 3', 'Window 4',
'Window 5']] == 0).any(axis=1), 13, np.nan)

Merged_dfnew['Out_PM25'] = Merged_dfnew['Out_PM25'].interpolate()
Merged_dfnew['Out_PM100'] = Merged_dfnew['Out_PM100'].interpolate()
Merged_dfnew['Wind_Speed01'] = Merged_dfnew['Wind_Speed01'].interpolate()
Merged_dfnew['Rain'] = Merged_dfnew['Rain'].interpolate()
```

```
Merged_dfnew['Temp_thr'] = np.where(Merged_dfnew['Temp_mean'] > 24.1, 11, np.nan)
Merged_dfnew['RH_thr'] = np.where(Merged_dfnew['RH_mean'] < 30, 10, np.nan)
Merged_dfnew['CO2_thr'] = np.where(Merged_dfnew['CO2_mean'] > 800, 9, np.nan)
Merged_dfnew['PM25_thr'] = np.where(Merged_dfnew['PM25_mean'] > 5, 8, np.nan)
Merged_dfnew['PM100_thr'] = np.where(Merged_dfnew['PM100_mean'] > 15, 7, np.nan)
Merged_dfnew['Rad_act'] = np.where((Merged_dfnew[['Rad 1', 'Rad 2', 'Rad 3', 'Rad 4']] >
30).any(axis=1), 6, np.nan)

Merged_dfnew['Out_PM25_thr'] = np.where(Merged_dfnew['Out_PM25'] > 20, 4, np.nan)
Merged_dfnew['Out_PM100_thr'] = np.where(Merged_dfnew['Out_PM100'] > 30, 3, np.nan)
Merged_dfnew['Wind_thr'] = np.where(Merged_dfnew['Wind_Speed01'] > 32.4, 2, np.nan)
Merged_dfnew['Rain_thr'] = np.where(Merged_dfnew['Rain'] > 0, 1, np.nan)

Merged_dfnew.loc['2023-04-07 09:00:00':'2023-04-10 19:00:00', 'Wind_thr'] = np.nan

#NEW ORDER
new_order = ['Time', 'Out_temp', 'Temp_room', 'Temp_1', 'Temp_2', 'Temp_mean', 'Temp_thr', 'Out_RH',
'RH_room', 'RH_1', 'RH_2', 'RH_mean','RH_thr', 'CO2_room', 'CO2_1', 'CO2_2', 'CO2_mean','CO2_thr',
'Out_PM25', 'Out_PM25_thr', 'PM25_1', 'PM25_2', 'PM25_mean', 'PM25_thr', 'Out_PM100', 'Out_PM100_thr',
'PM100_1', 'PM100_2', 'PM100_mean', 'PM100_thr', 'Window 1', 'Window 2', 'Window 3', 'Window 4',
'Window 5', 'Win_act', 'Rad 1', 'Rad 2', 'Rad 3', 'Rad 4', 'Rad_act', 'Wind_Speed01',
'Wind_thr',  'Rain', 'Rain_thr']
Merged_dfnew = Merged_dfnew.reindex(columns=new_order)

#CHANGE NAMES
Merged_dfnew = Merged_dfnew.rename(columns={'Temp_room': 'Temp_r', 'Window 1': 'Win_1', 'Window 2':
'Win_2', 'Window 3': 'Win_3', 'Window 4': 'Win_4', 'Window 5': 'Win_5', 'Wind_Speed01': 'Wind',
'CO2_room': 'CO2_r', 'RH_room': 'RH_r'})

#***ADDITIONAL RELEVANT COLUMNS***

#temperature
mean_temp_tablenew = Merged_dfnew[['Temp_1', 'Temp_2']].mean(axis=1)
diff_temp_tablenew = abs(Merged_dfnew['Temp_1'] - Merged_dfnew['Temp_2'])
diff_temp_romtabnew = abs(Merged_dfnew['Temp_r'] - mean_temp_tablenew)

#relative humidity
mean_RH_tablenew = Merged_dfnew[['RH_1', 'RH_2']].mean(axis=1)
diff_RH_tablenew = abs(Merged_dfnew['RH_1'] - Merged_dfnew['RH_2'])
diff_RH_romtabnew = abs(Merged_dfnew['RH_r'] - mean_RH_tablenew)

#CO2
mean_CO2_tablenew = Merged_dfnew[['CO2_1', 'CO2_2']].mean(axis=1)
diff_CO2_tablenew = abs(Merged_dfnew['CO2_1'] - Merged_dfnew['CO2_2'])
diff_CO2_romtabnew = abs(Merged_dfnew['CO2_r'] - mean_CO2_tablenew)

#PM25
mean_PM25_tablenew = Merged_dfnew[['PM25_1', 'PM25_2']].mean(axis=1)
diff_PM25_tablenew = abs(Merged_dfnew['PM25_1'] - Merged_dfnew['PM25_2'])
```

```
#PM100
mean_PM100_tablenew = Merged_dfnew[['PM100_1', 'PM100_2']].mean(axis=1)
diff_PM100_tablenew = abs(Merged_dfnew['PM100_1'] - Merged_dfnew['PM100_2'])

#Total number of open windows
Merged_dfnew['Window_sum'] = (Merged_dfnew['Win_1'] == 0).astype(int) + (Merged_dfnew['Win_2'] ==
0).astype(int) + (Merged_dfnew['Win_3'] == 0).astype(int) + (Merged_dfnew['Win_4'] == 0).astype(int) +
(Merged_dfnew['Win_5'] == 0).astype(int)
print(Merged_dfnew.loc['2023-04-25 13:00:00':'2023-04-25 14:00:00', 'Window_sum'])

#Dataframes per measured day
Day24n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-04-24').date()]
Day25n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-04-25').date()]
Day26n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-04-26').date()]
Day28n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-04-28').date()]

Day1n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-05-01').date()]
Day2n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-05-02').date()]
Day3n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-05-03').date()]
Day4n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-05-04').date()]

Day8n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-05-08').date()]
Day9n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-05-09').date()]
Day10n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-05-10').date()]
Day11n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-05-11').date()]
Day12n = Merged_dfnew.loc[Merged_dfnew.index.date == pd.to_datetime('2023-05-12').date()]

Day24n = Day24n.copy()
Day25n = Day25n.copy()
Day26n = Day26n.copy()
Day28n = Day28n.copy()

Day1n = Day1n.copy()
Day2n = Day2n.copy()
Day3n = Day3n.copy()
Day4n = Day4n.copy()

Day8n = Day8n.copy()
Day9n = Day9n.copy()
Day10n = Day10n.copy()
Day11n = Day11n.copy()
Day12n = Day12n.copy()

def time_to_hours(t):
    return t.second / 3600 + t.minute / 60 + t.hour

Day24n['Time'] = Day24n['Time'].apply(time_to_hours)
Day25n['Time'] = Day25n['Time'].apply(time_to_hours)
```

```
Day26n['Time'] = Day26n['Time'].apply(time_to_hours)
Day28n['Time'] = Day28n['Time'].apply(time_to_hours)

Day1n['Time'] = Day1n['Time'].apply(time_to_hours)
Day2n['Time'] = Day2n['Time'].apply(time_to_hours)
Day3n['Time'] = Day3n['Time'].apply(time_to_hours)
Day4n['Time'] = Day4n['Time'].apply(time_to_hours)

Day8n['Time'] = Day8n['Time'].apply(time_to_hours)
Day9n['Time'] = Day9n['Time'].apply(time_to_hours)
Day10n['Time'] = Day10n['Time'].apply(time_to_hours)
Day11n['Time'] = Day11n['Time'].apply(time_to_hours)
Day12n['Time'] = Day12n['Time'].apply(time_to_hours)



#Mean of measured days
Day_meannew = Merged_dfnew

def time_to_hours(t):
    return t.second / 3600 + t.minute / 60 + t.hour
Day_meannew['Time'] = Day_meannew['Time'].apply(time_to_hours)

Day_meannew = Day_meannew.groupby('Time', as_index=False).mean()
Day_meannew = Day_meannew.sort_values('Time')
#Dataframe days without nan values
Day24nann = Day24n.copy()
Day25nann = Day25n.copy()
Day26nann = Day26n.copy()
Day28nann = Day28n.copy()

Day1nann = Day1n.copy()
Day2nann = Day2n.copy()
Day3nann = Day3n.copy()
Day4nann = Day4n.copy()

Day8nann = Day8n.copy()
Day9nann = Day9n.copy()
Day10nann = Day10n.copy()
Day11nann = Day11n.copy()
Day12nann = Day12n.copy()



Day24nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day25nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day26nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act',
'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
```

```
Day28nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)

Day1nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day2nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day3nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day4nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)

Day8nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day9nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day10nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day11nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day12nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)


Day24nann.dropna(inplace=True)
Day25nann.dropna(inplace=True)
Day26nann.dropna(inplace=True)
Day28nann.dropna(inplace=True)

Day1nann.dropna(inplace=True)
Day2nann.dropna(inplace=True)
Day3nann.dropna(inplace=True)
Day4nann.dropna(inplace=True)

Day8nann.dropna(inplace=True)
Day9nann.dropna(inplace=True)
Day10nann.dropna(inplace=True)
Day11nann.dropna(inplace=True)
Day12nann.dropna(inplace=True)

#Mean of measured days without nan values
Day_mean_nann = Day_meannew.copy()
Day_mean_nann.drop(columns=['Win_act', 'Temp_thr', 'RH_thr', 'CO2_thr', 'PM25_thr', 'PM100_thr', 'Rad_act', 'Out_PM25_thr', 'Out_PM100_thr', 'Wind_thr', 'Rain_thr'], axis=1, inplace=True)
Day_mean_nann.dropna(inplace=True)
```