HUMAN WINDOW INTERACTION

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How can a satisfactory window feedback system be created that provides energy savings, human multi-domain comfort and indoor air quality in open-plan workplaces?

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2 Introduction

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 difference between the predicted and real energy use of buildings proves this lack of understanding. Studies have shown that this difference is mainly caused by human behaviour by investigating identical houses with different occupants (Buso et al., 2015). 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 thermal comfort, indoor air quality, energy efficiency and the occupant's perception of the indoor environment. 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 completely 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 is the other way around, it provides 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 on which window feedback system is able to provide a successful cooperation between occupants and windows.

This report proposes a research framework to create a better understanding of window feedback systems which is provided in chapter 10. The other chapters relate to the literature review that has been carried out to get a better understanding of window feedback systems and their affect on the occupants' satisfaction and indoor climate. Chapter 3 provides the methodology. Chapter 4 to 6 provides information about window feedback and operation. Chapter 7 to 9 provides information on how to measure and evaluate thermal comfort, indoor air quality and energy consumption.

LITERATURE RESEARCH

3 Literature research methodology

Different literature has been examined to get a better understanding of window feedback systems and their affect 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 science 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	1. (Human OR occupant OR behaviour) AND window AND (interaction OR operation OR strategies OR efficiency) AND (building OR façade) 2. Occupant AND Feedback AND Window AND Building
Thermal comfort	1. (Thermal comfort OR heat balance OR adaptive approach) AND window AND (operation OR opening OR closing OR interaction)
Indoor Air Quality	1. (Indoor air quality OR IAQ) AND parameters AND (indoor climate OR offices OR perception)
Energy efficiency	1. 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.

4 Existing studies window feedback

In chapter 3: 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. From these six studies, four are related to the project MOBISTYLE which is part of the Horizon 2020 programme and is funded by the European Commission. This chapter will discuss the methodology, findings and limitations of these studies to get a better understanding of the state-of-the-art.

4.1 16 office buildings in the US

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 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 1. 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 6.2. In addition, this research is one of the few studies that provide an understanding of occupants' reasoning for window operation.

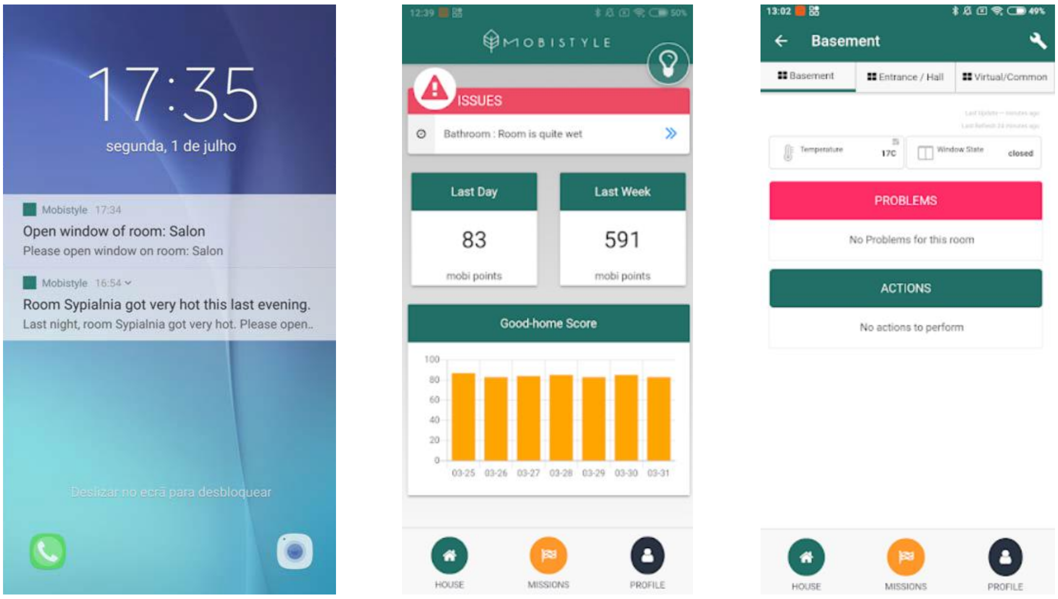
Figure 1: Encountered signalling devices by Ackerly and Brager which are not placed effectively and are easily overlooked when working. The shown signalling devices are placed far from the window and/or on the opposite side of the window (Ackerly & Brager, 2011)

4.2 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.

4.2.1 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 2 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

Last Day: 83 mobi points
Last Week: 591 mobi points

Temperature 17C
Window State closed

PROBLEMS
No Problems for this room

ACTIONS
No actions to perform

Figure 2: 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).

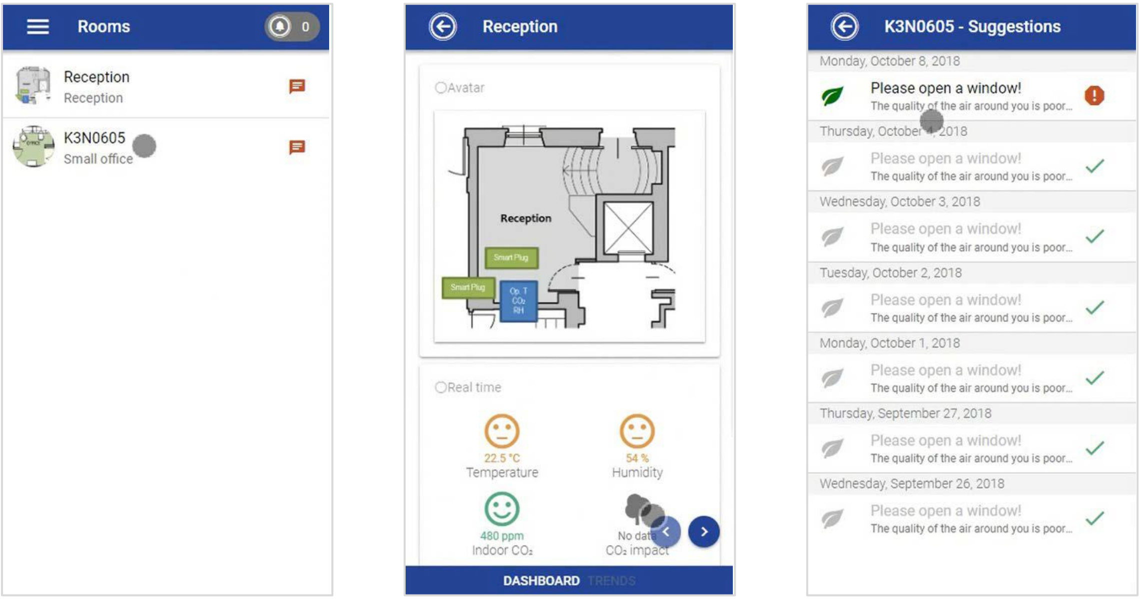
The case study in Denmark tested the game interface in 17 apartments which varied in size from 67-130 m^2 and in occupancy between 1-5 persons. The study measured besides the indoor environmental conditions also the energy consumption related to heating and domestic hot water usage. The experiment lasted 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 0.5°C;
- 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).

4.2.2 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 3 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 3: 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 4. 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 4: 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 5 which shows the overall measured CO_2 concentration and Figure 6 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).

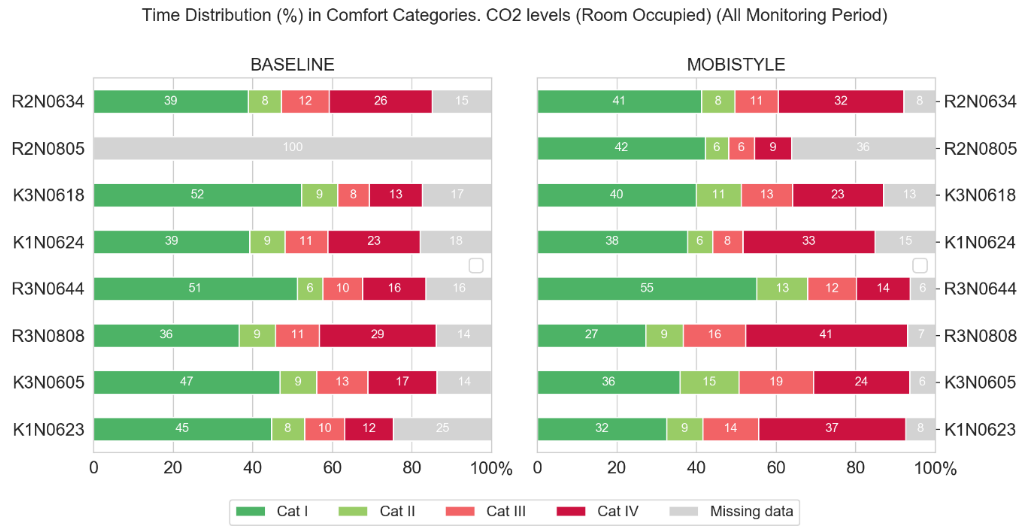


Figure 5: Overall measured CO_2 concentration (Mobistyle, 2020a)

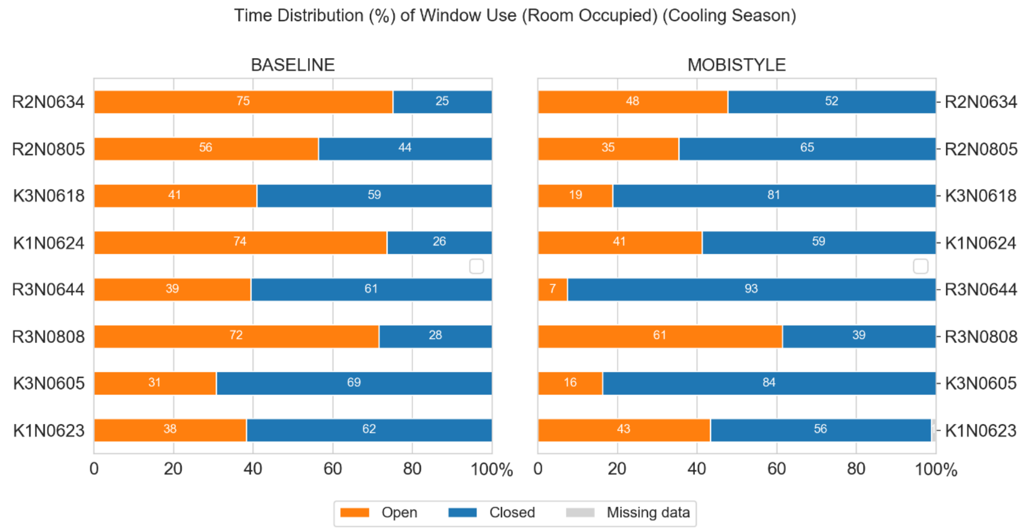


Figure 6: window opening time during the heating and cooling season (Mobistyle, 2020a)

4.3 CO_2 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).

4.4 Conclusion

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 also 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

	Office buildings in the US	**Apartments, Denmark**	**University, Slovenia**	**Schools, Italy**
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

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.

5 Drivers of window operation

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” (Buso et al., 2015). However, the choices they make are not always logical and 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.

5.1 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).

5.1.1 External drivers

Physical environmental:
This aspect refers to the external physical conditions. Examples of drivers are outdoor temperature, indoor temperature, humidity, air velocity, CO_2 concentrations, $PM_{2.5}$ concentrations, solar radiation, noise and smell (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 7. 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 affect 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 time period (Fabi et al., 2012). Also the distance from the window to the occupant's workplace affect 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).

5.1.2 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.

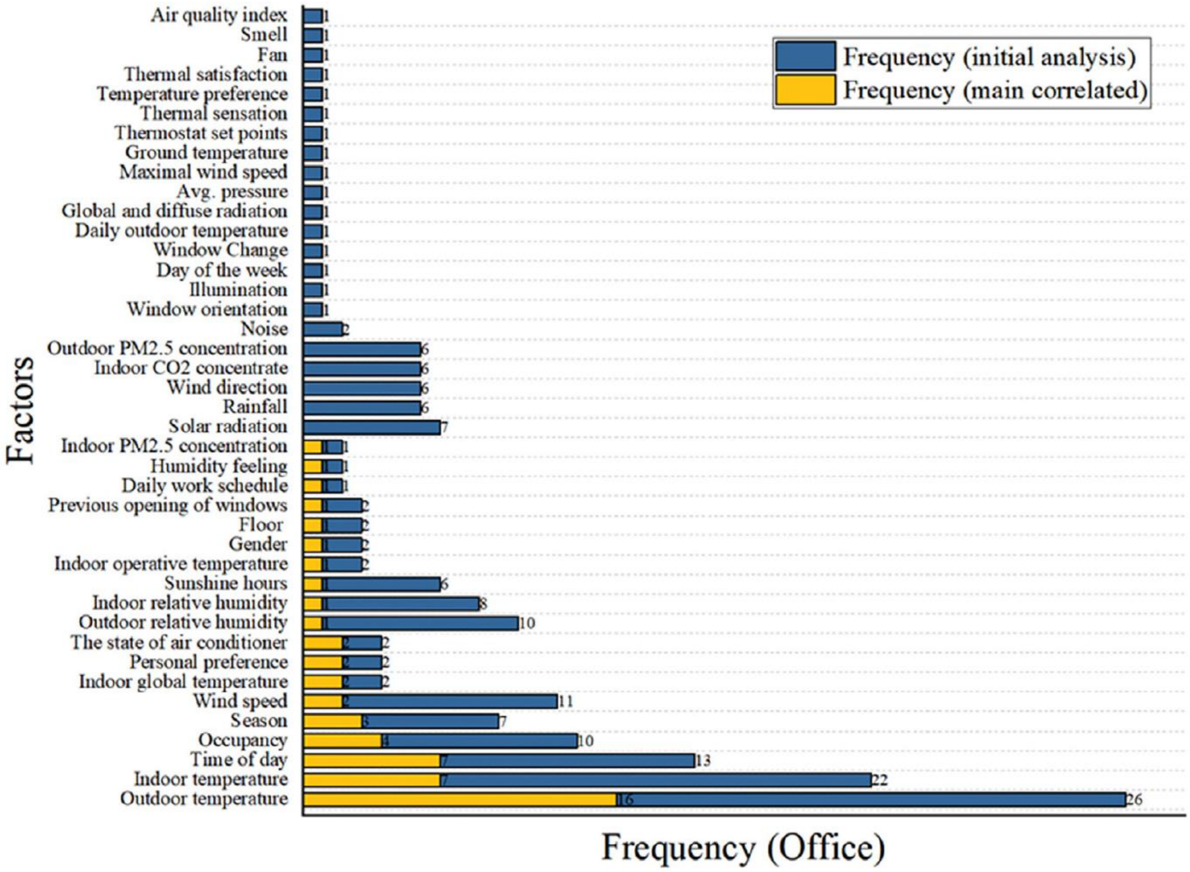


Figure 7: Frequency of factors associated with window opening behaviour in offices in the existing literature by Liu et al. (2022)

5.2 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 8. 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.

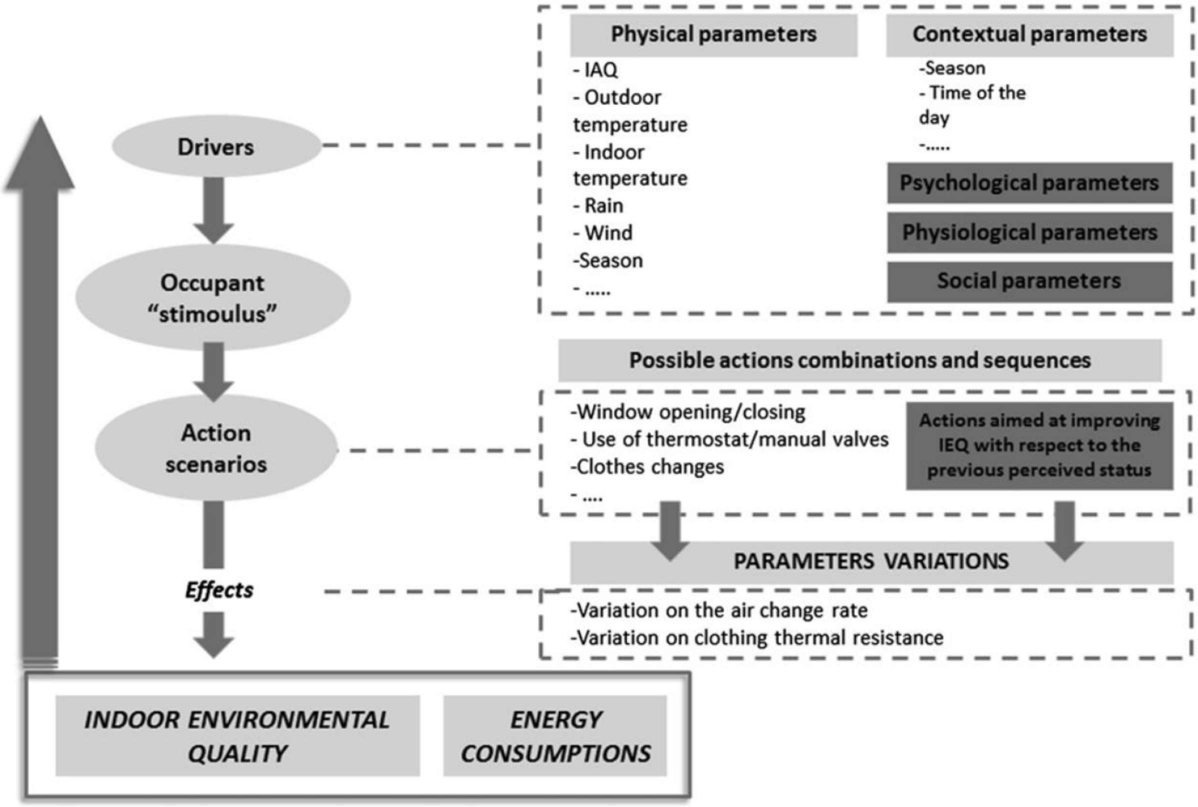


Figure 8: Diagram from drivers to energy consumption and the indoor environment by Fabi et al. (2012)

5.3 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.

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 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

6 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 relates to the human behaviour. Both will be explained in this chapter.

6.1 Control

On the extreme ends of 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 some 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).

6.2 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).

6.2.1 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 9 (Day et al., 2020; Ackerly et al., 2011).

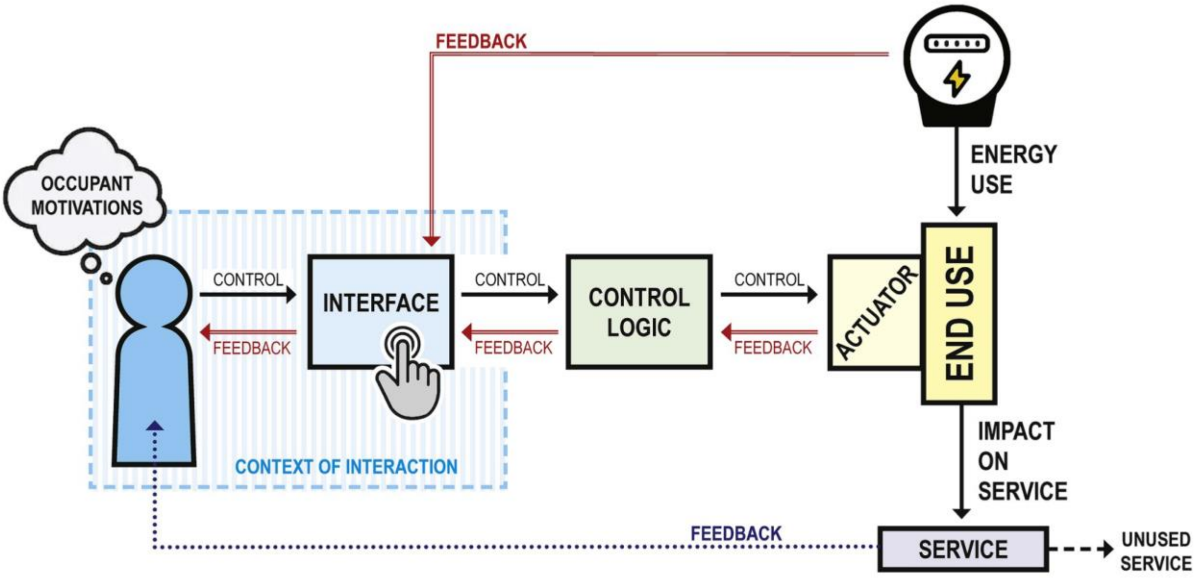


Figure 9: Conceptual model for understanding the occupant engagement with building interfaces by Day et al. (2020)

6.2.2 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 10. Note that in some cases the window signalling system were easily overlooked because of the placement in the room. A good example is Figure 11 in which the signalling system is attached to the ceiling and far from the window. In another case, see Figure 12, the window signalling system did consists 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.

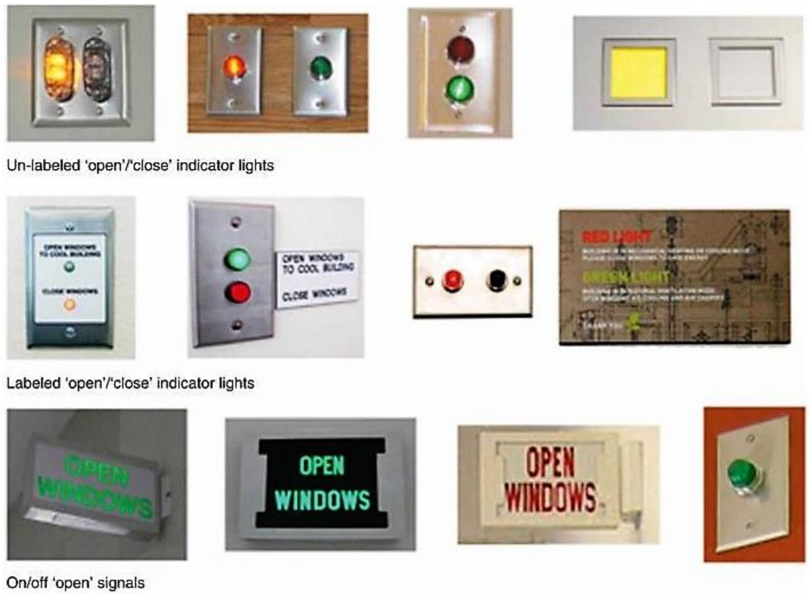


Figure 10: Different types of window signalling systems by Ackerly and Brager (2013)

Figure 11: 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 12: 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).

6.2.3 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).

6.2.4 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).

6.3 Conclusion

On the extreme ends of 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 are the other way around, it results in 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).

7 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.

7.1 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.

7.1.1 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 13 (Hoof, 2010; van der Linden et al., 2018, pp 87-89).

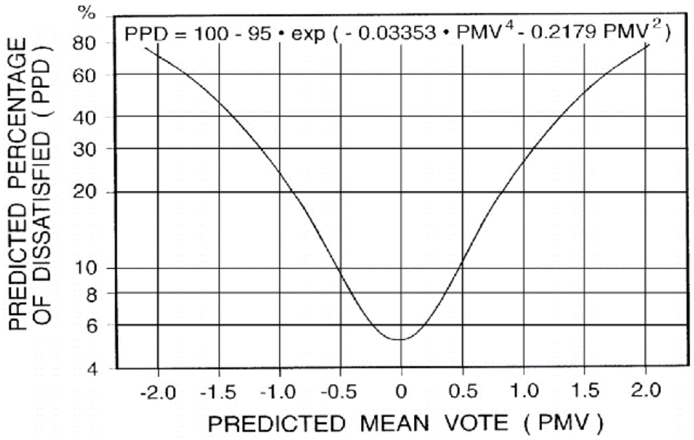


Figure 13: PPD as a function of PMV (ASHRAE 55, 2017, pp 39)

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)

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

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)

$$S = M \pm W \pm R \pm C \pm K - E - RES \tag{2}$$

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

7.1.2 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

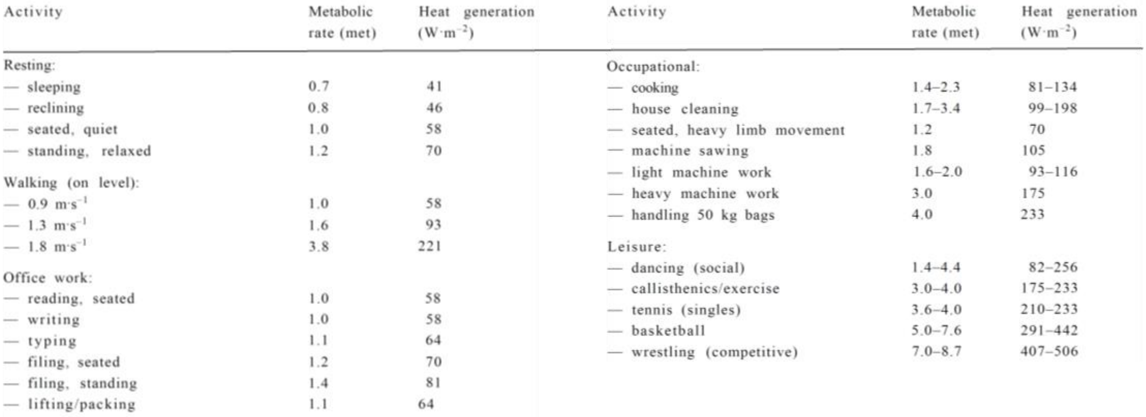
Air humidity relates to the moisture content of the air and is often expressed through the relative humidity. This parameter indicates the amount of water vapour in the air in relation to the maximum amount of vapour that the air can contain at a given temperature and pressure. The air humidity affects 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).

7.1.3 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)



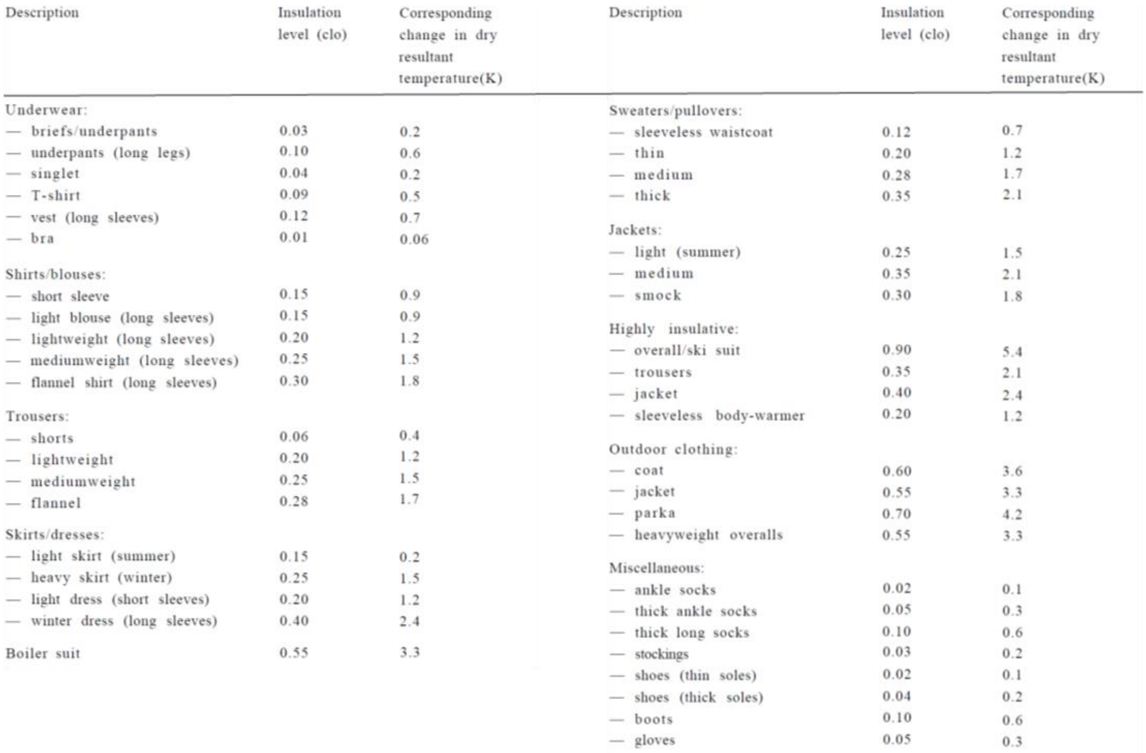
Activity	Metabolic rate (met)	Heat generation (W·m^{-2})
Resting:		
— sleeping	0.7	41
— reclining	0.8	46
— seated, quiet	1.0	58
— standing, relaxed	1.2	70
Walking (on level):		
— 0.9 m·s^{-1}	1.0	58
— 1.3 m·s^{-1}	1.6	93
— 1.8 m·s^{-1}	3.8	221
Office work:		
— reading, seated	1.0	58
— writing	1.0	58
— typing	1.1	64
— filing, seated	1.2	70
— filing, standing	1.4	81
— lifting/packing	1.1	64

Activity	Metabolic rate (met)	Heat generation (W·m^{-2})
Occupational:		
— cooking	1.4–2.3	81–134
— house cleaning	1.7–3.4	99–198
— seated, heavy limb movement	1.2	70
— machine sawing	1.8	105
— light machine work	1.6–2.0	93–116
— heavy machine work	3.0	175
— handling 50 kg bags	4.0	233
Leisure:		
— dancing (social)	1.4–4.4	82–256
— callisthenics/exercise	3.0–4.0	175–233
— tennis (singles)	3.6–4.0	210–233
— basketball	5.0–7.6	291–442
— wrestling (competitive)	7.0–8.7	407–506

<u>Clothing</u>

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)
Underwear:		
— briefs/underpants	0.03	0.2
— underpants (long legs)	0.10	0.6
— singlet	0.04	0.2
— T-shirt	0.09	0.5
— vest (long sleeves)	0.12	0.7
— bra	0.01	0.06
Shirts/blouses:		
— short sleeve	0.15	0.9
— light blouse (long sleeves)	0.15	0.9
— lightweight (long sleeves)	0.20	1.2
— mediumweight (long sleeves)	0.25	1.5
— flannel shirt (long sleeves)	0.30	1.8
Trousers:		
— shorts	0.06	0.4
— lightweight	0.20	1.2
— mediumweight	0.25	1.5
— flannel	0.28	1.7
Skirts/dresses:		
— light skirt (summer)	0.15	0.2
— heavy skirt (winter)	0.25	1.5
— light dress (short sleeves)	0.20	1.2
— winter dress (long sleeves)	0.40	2.4
Boiler suit	0.55	3.3

Description	Insulation level (clo)	Corresponding change in dry resultant temperature(K)
Sweaters/pullovers:		
— sleeveless waistcoat	0.12	0.7
— thin	0.20	1.2
— medium	0.28	1.7
— thick	0.35	2.1
Jackets:		
— light (summer)	0.25	1.5
— medium	0.35	2.1
— smock	0.30	1.8
Highly insulative:		
— overall/ski suit	0.90	5.4
— trousers	0.35	2.1
— jacket	0.40	2.4
— sleeveless body-warmer	0.20	1.2
Outdoor clothing:		
— coat	0.60	3.6
— jacket	0.55	3.3
— parka	0.70	4.2
— heavyweight overalls	0.55	3.3
Miscellaneous:		
— ankle socks	0.02	0.1
— thick ankle socks	0.05	0.3
— thick long socks	0.10	0.6
— 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

7.1.4 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.

7.2 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.

7.2.1 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

$$T_{comf} = A \cdot T_{a,out} + B \qquad (3)$$

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 14 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).

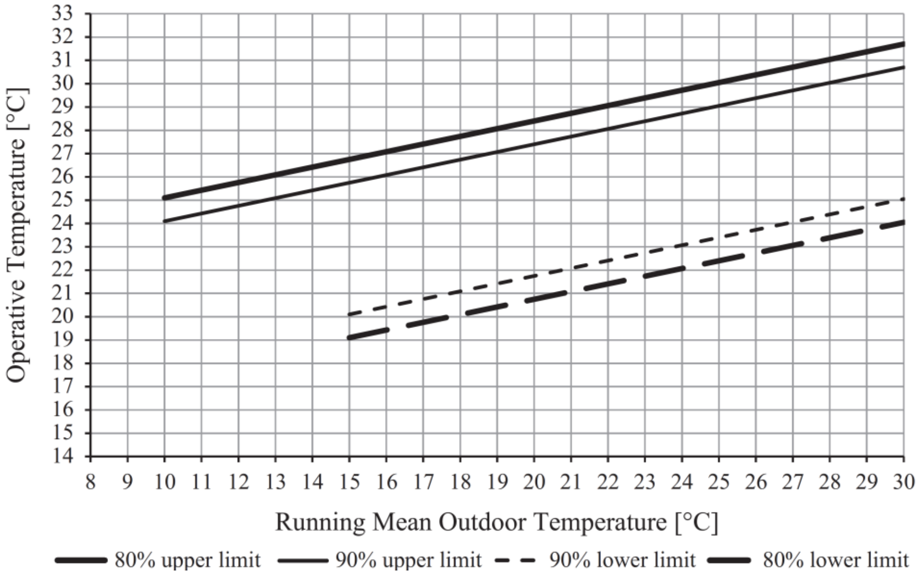


Figure 14: Comfort bandwidths according to the EN 15251

Equation 4: Adaptive approach according to EN 15251

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

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

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

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

7.2.2 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).

7.3 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 on 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.

8 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 5.1. 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.

8.1 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 15 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 15. 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).

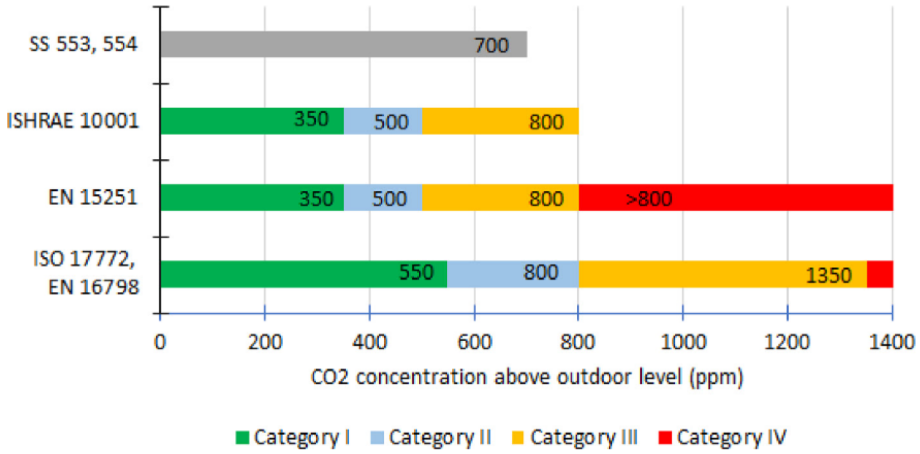


Figure 15: Acceptable CO_2 concentrations for non-residential buildings according to different standards (Khovalyg et al., 2020)

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).

8.2 Conclusion

The indoor environment contains a wide range of pollutants which can affect 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.

9 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 4 and 6. 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.

9.1 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 4. 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/m³ 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).

9.2 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

RESEARCH FRAMEWORK

10 Research Framework

10.1 Problem statement

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

10.2 Objective

Main objective

The objective of this research is to create a better understanding of what a satisfactory window feedback system is by comparing different kinds of feedback displays and their affect on the indoor climate and occupants' satisfaction. Therefore, it is expected to deliver a report with the following:

1. The most important drivers and reasons for window operation;
2. The affect of window feedback on energy efficiency, human comfort and indoor air quality;
3. Design recommendations for window feedback systems concerning the algorithm and the type of information display.

This report will be used to make an attempt in creating a satisfactory window feedback system design for open-plan workplaces. This design will be the final product together with the report.

10.3 Research Questions

Main question

How can a satisfactory window feedback system be created that provides 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. What is the occupants' reasoning for window operation with and without a feedback system, and how does it relate to the drivers?
6. How is the energy efficiency, human multi-domain comfort and indoor air quality affected with and without a feedback system?
7. What is a satisfactory feedback display?

10.4 Approach and methodology

The methodology to conduct the research is divided into two parts and consists of literature research and research by experimentation. Section 10.4.3 gives a visualisation of the approach and methodology.

10.4.1 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 feedback system by providing design considerations and a satisfactory algorithm. The experiment is only valid to start when the literature review is complete and finished.

10.4.2 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 two open-plan workplaces in which three situations will be tested out and include:

1. A neutral situation for both open-plan workplaces. This will serve as a benchmark.
2. A situation with a 'light indicator' feedback system.
3. A situation with a 'dashboard and notification' feedback system.

In all situations both objective and subjective measurements will be conducted and include surveys, interviews, observations and indoor and outdoor environmental measurements. Each situation will be ideally conducted for a period of 2 weeks. See Figure 16 for a visualisation.

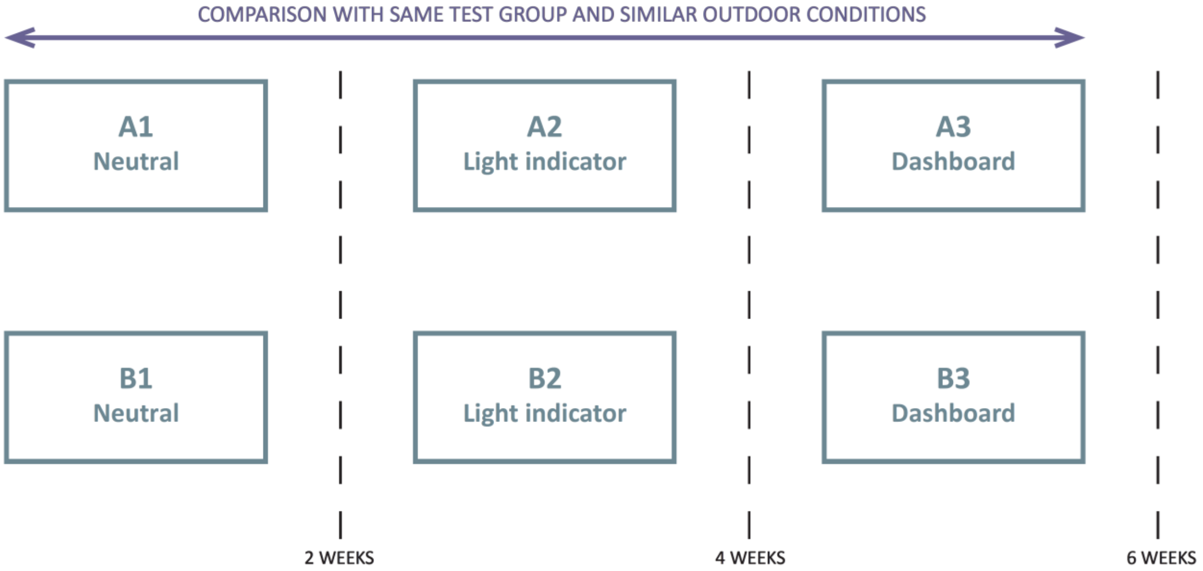


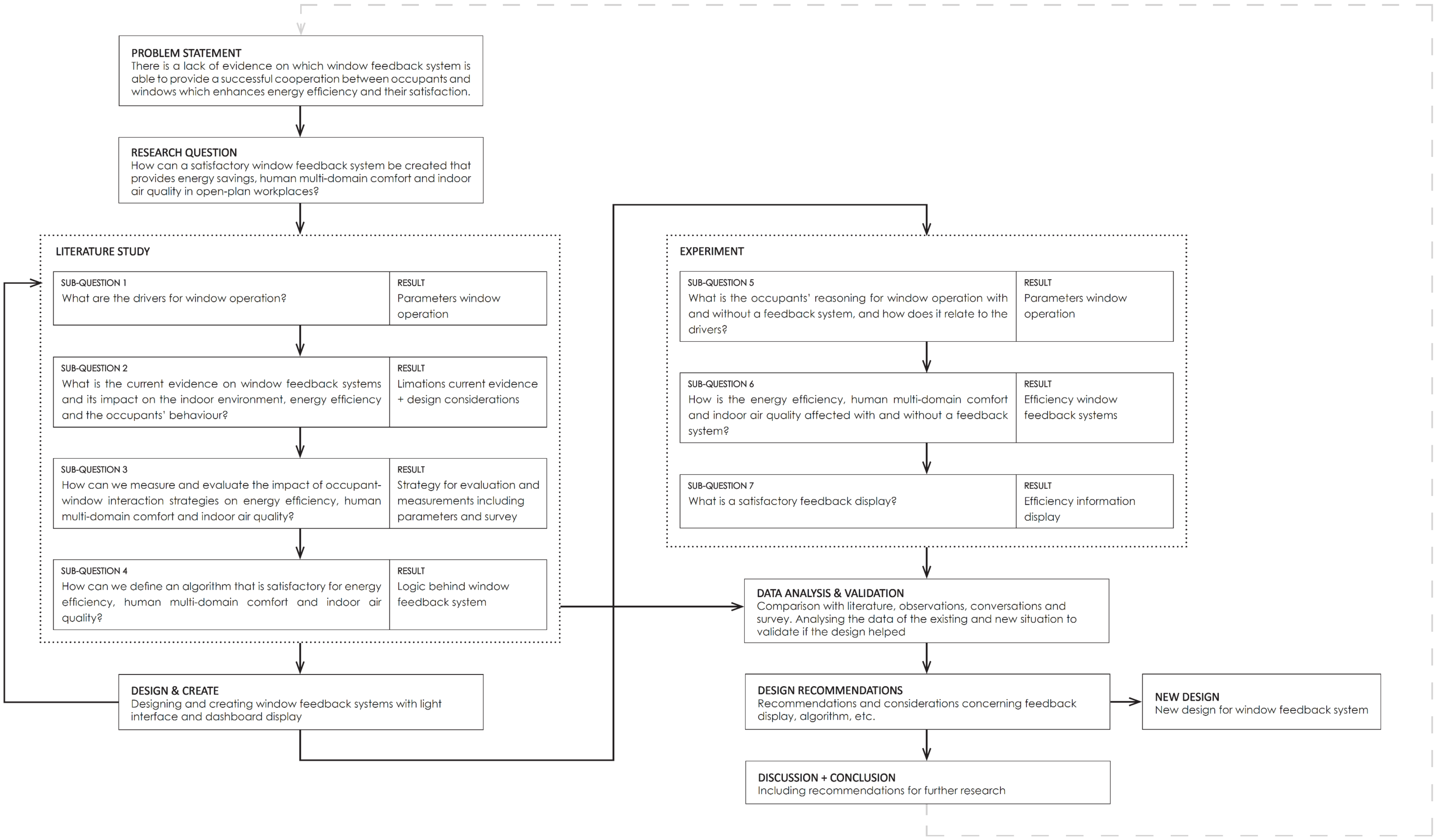
Figure 16: Visualisation experiment

The survey serves to find out what the reasons for window operation are, what the personal factors are (e.g., age, gender, clothing, metabolism), and what the satisfaction levels are with the indoor environmental conditions related to thermal comfort, indoor air quality and window opening. Concerning the latter, the survey will be conducted for those who operate the window and for those who sit nearby in order to measure the average satisfaction and comfort of the room. This will also help in identifying the social impact of the window operation. The results of the survey will be used to find important drivers and to determine the occupants' comfort levels. The results will be compared with the literature.

Regarding the indoor and outdoor environmental measurements, the intention is to measure the following parameters: indoor and outdoor air temperature, indoor radiant temperature, indoor air velocity, indoor and outdoor air humidity, indoor and outdoor carbon dioxide, indoor and outdoor particulate matter, window opening state and window opening time. However, this could change if certain measurement devices are not available. These parameters will be used to determine the level of thermal comfort and indoor air quality based on the thresholds of the literature review. The results will be compared with the results of the survey to validate the answers. In addition, these parameters will be used to calculate the energy efficiency of the window operation.

Based on the gathered data, it should be possible to answer the research questions by comparing the results of all three situations.

10.4.3 Visualisation approach and methodology



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

RESEARCH QUESTION
How can a satisfactory window feedback system be created that provides 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?

RESULT
Parameters 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?

RESULT
Limations current evidence + design considerations

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?

RESULT
Strategy for evaluation and measurements including parameters and survey

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

RESULT
Logic behind window feedback system

DESIGN & CREATE
Designing and creating window feedback systems with light interface and dashboard display

EXPERIMENT

SUB-QUESTION 5
What is the occupants' reasoning for window operation with and without a feedback system, and how does it relate to the drivers?

RESULT
Parameters window operation

SUB-QUESTION 6
How is the energy efficiency, human multi-domain comfort and indoor air quality affected with and without a feedback system?

RESULT
Efficiency window feedback systems

SUB-QUESTION 7
What is a satisfactory feedback display?

RESULT
Efficiency information display

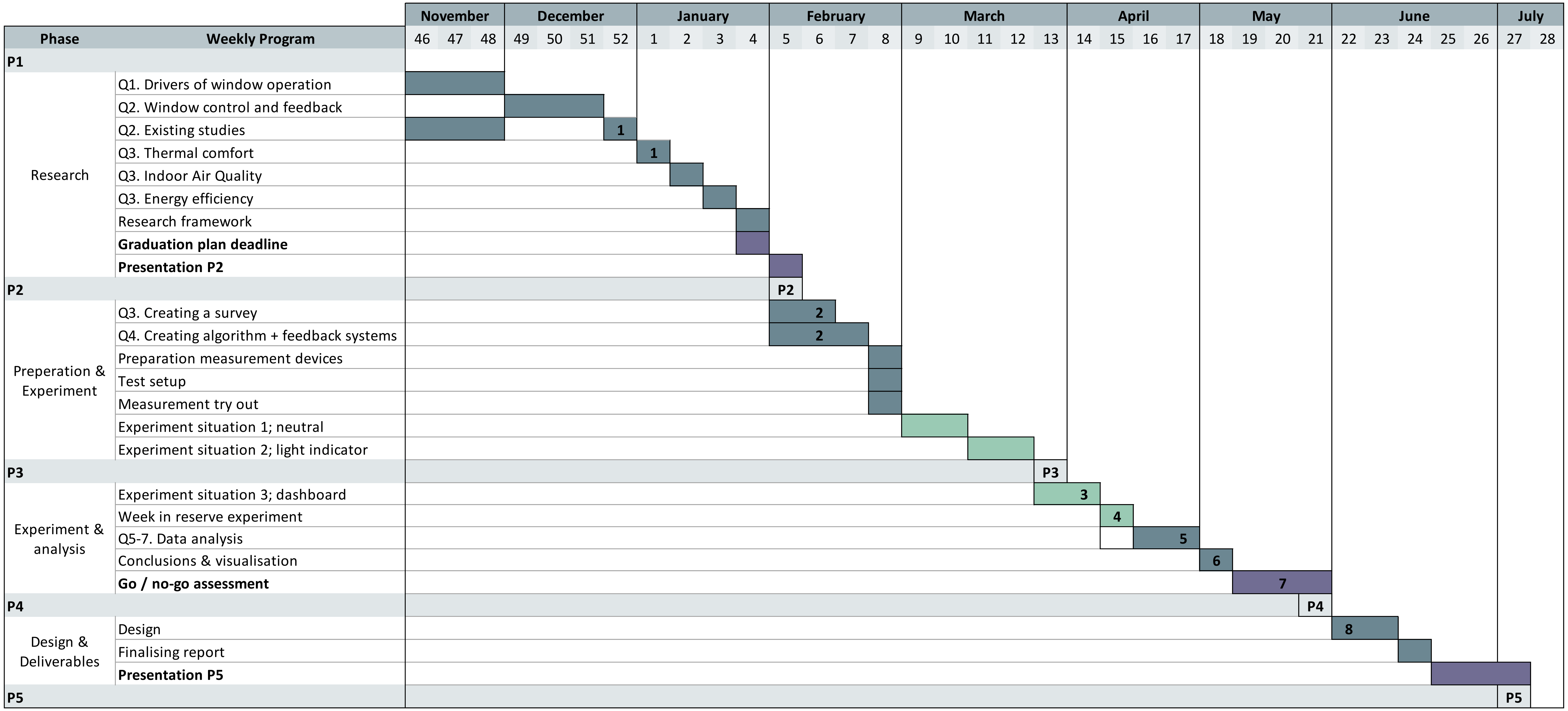
DATA ANALYSIS & VALIDATION
Comparison with literature, observations, conversations and survey. Analysing the data of the existing and new situation to validate if the design helped

DESIGN RECOMMENDATIONS
Recommendations and considerations concerning feedback display, algorithm, etc.

NEW DESIGN
New design for window feedback system

DISCUSSION + CONCLUSION
Including recommendations for further research

10.5 Planning and organisation



		November			December				January				February				March					April				May				June					July	
Phase	**Weekly Program**	46	47	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
P1																																				
Research	Q1. Drivers of window operation	■	■	■																																
	Q2. Window control and feedback				■	■	■																													
	Q2. Existing studies	■	■	■				■ 1																												
	Q3. Thermal comfort								■ 1																											
	Q3. Indoor Air Quality									■																										
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P2													P2																							
Preperation & Experiment	Q3. Creating a survey												■	■ 2																						
	Q4. Creating algorithm + feedback systems												■	■ 2	■																					
	Preparation measurement devices															■																				
	Test setup															■																				
	Measurement try out															■																				
	Experiment situation 1; neutral																🟩	🟩																		
	Experiment situation 2; light indicator																		🟩	🟩																
P3																					P3															
Experiment & analysis	Experiment situation 3; dashboard																				🟩	🟩 3														
	Week in reserve experiment																						🟩 4													
	Q5-7. Data analysis																						□	■	■ 5											
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1. Christmas period; Dec. 26 - Jan. 6
2. Spring break; Feb. 6 - Feb 10
3. Good Friday; April 7
4. Easter April 9 and 10
5. Kingsday; April 27
6. Liberation day; May 5
7. Ascension Day; May 19
8. Whit Monday; May 29

10.6 Relevance

With the increasing awareness of the occupants' impact on the energy consumption and their well being inside buildings, this thesis could be relevant for a larger social and scientific framework.

From a social perspective, this research could contribute towards more efficient behaviour that enhances the energy consumption and indoor climate in various kinds of buildings. It would help towards a society which behaves more environmentally friendly and which is more conscious of their well being. Improving the occupants' behaviour could 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.

From a scientific perspective, this research could be helpful in creating a better understanding of window feedback systems and their affect on the energy efficiency, occupants' comfort and indoor climate. It will provide a better understanding of the drivers and the occupants' reasoning for window operation. It will also contribute to the further development of window feedback systems. This research will be in particular helpful by conducting both subjective and objective measurements to validate the results, and by comparing different window feedback displays.

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