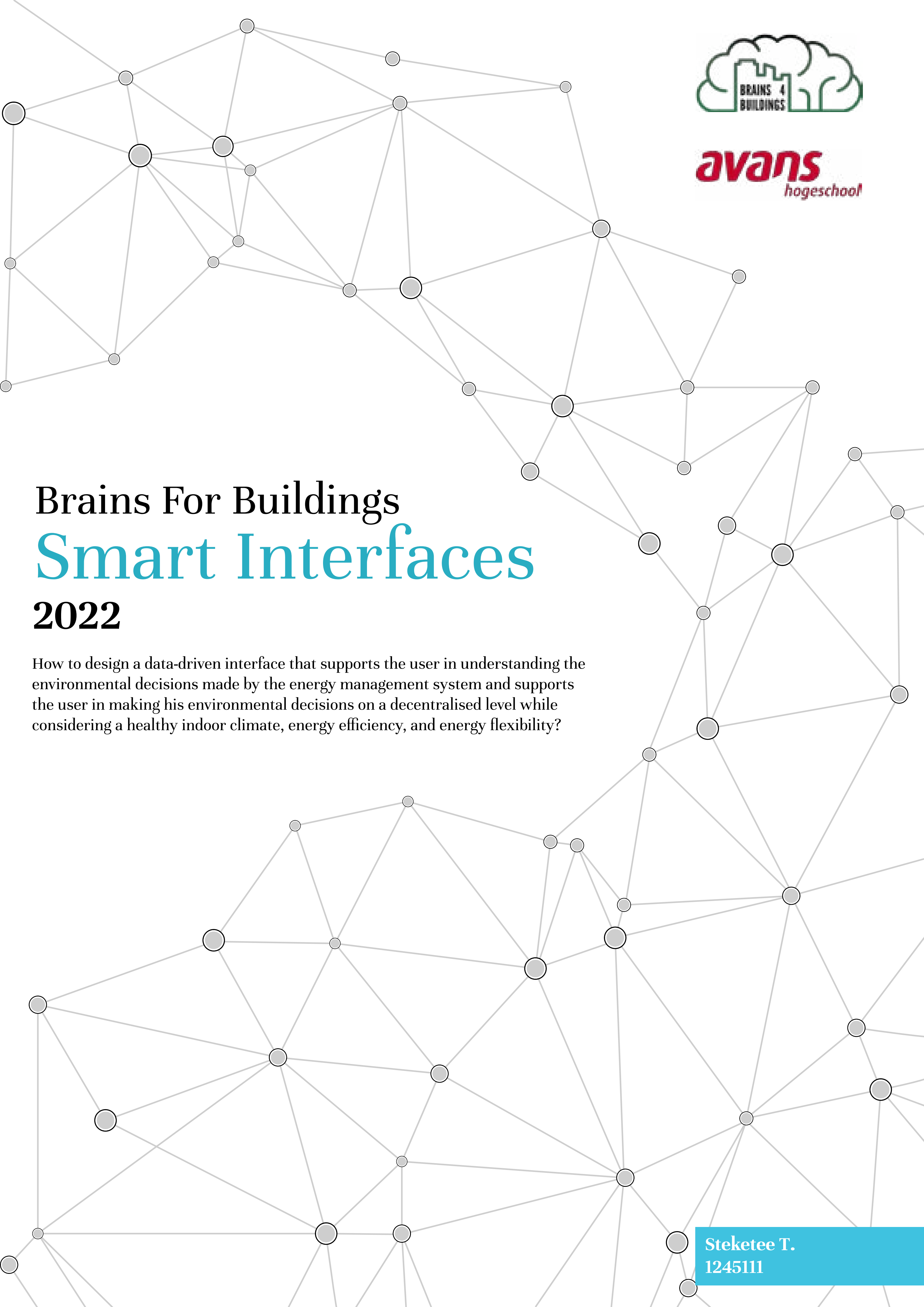


Brains For Buildings
Smart Interfaces
2022

How to design a data-driven interface that supports the user in understanding the environmental decisions made by the energy management system and supports the user in making his environmental decisions on a decentralised level while considering a healthy indoor climate, energy efficiency, and energy flexibility?

Steketee T.
1245111

TABLE OF
CONTENTS

WELCOME
INTRODUCTION

“Brains for Building’s Energy Systems (B4B) is a multi-year, multi-stakeholder project focused on developing methods to harness big data from smart meters, building management systems, and the Internet of Things devices to reduce energy consumption, increase comfort, respond flexibly to user behaviour and local energy supply and demand, and save on installation maintenance costs. This will be done by developing faster and more efficient Machine Learning and Artificial Intelligence models and algorithms. The project is geared to existing utility buildings such as commercial and institutional buildings.” [1]

In most modern utility buildings, 10-30 per cent of the energy is wasted by malfunctioning installations and unexpected user behaviour. Also, the indoor environment is inadequate, and the operational costs are high. Smart meters, facility management systems, and the Internet of Things allow the gathering of extensive amounts of data. By implementing Smart Systems like Machine Learning and Artificial Intelligence, this real-time data can be analysed and used to reduce energy consumption while optimising the user’s comfort. The goal of Brains4Buildings is to add operational intelligence to the buildings’ energy management system (EMS) to accomplish the transition to energy efficiency and design a scalable and modular solution to realise 20-30 per cent energy saving in buildings.

This research concerns the development of smart user interfaces and acquiring user feedback to accomplish an energy-efficient and healthy indoor climate. The focus will be on the user’s role in energy efficiency and his comfort in utility buildings. The user’s role in energy efficiency includes helping the user understand his environment and understand his impact on his environment.

The main research question concludes: *“How to design a data-driven interface that supports the user in understanding the environmental decisions made by the energy management system and supports the user in making his environmental decisions on a decentralised level while considering a healthy indoor climate, energy efficiency, and energy flexibility?”*

Project plan

The user is centred in this research on the energy efficiency of utility buildings. Therefore, the EMS should base its decisions on the user's comfort in addition to the energy efficiency of the building. Comfort is a broad concept and must be defined for the EMS to base its decisions on the users' comfort preferences. Also, using comfort as a basis for the user to communicate with the EMS ensures an intuitive interaction.

Visualisations of the decisions made by the EMS are crucial for the communication between the user and the EMS. Using the proper visualisation techniques can make an intuitive and understandable interaction for the user, thus adding to the user's experience. Therefore, visualisation techniques will be researched to use the proper visualisation.

The user must be able to give feedback to the EMS regarding their comfort levels to set up bidirectional communication. An interaction plan will be set up to design an intuitive interaction for the user. The research will conclude with a proof of concept. This proof of concept will contain all the research done and implement this research in a final design. The proof of concept will answer the main question.

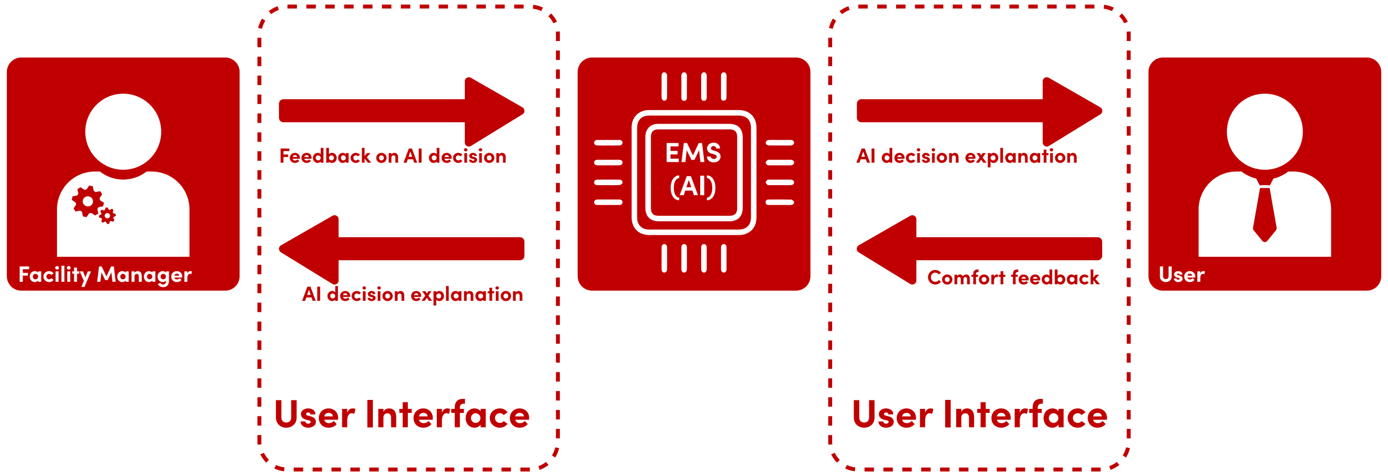
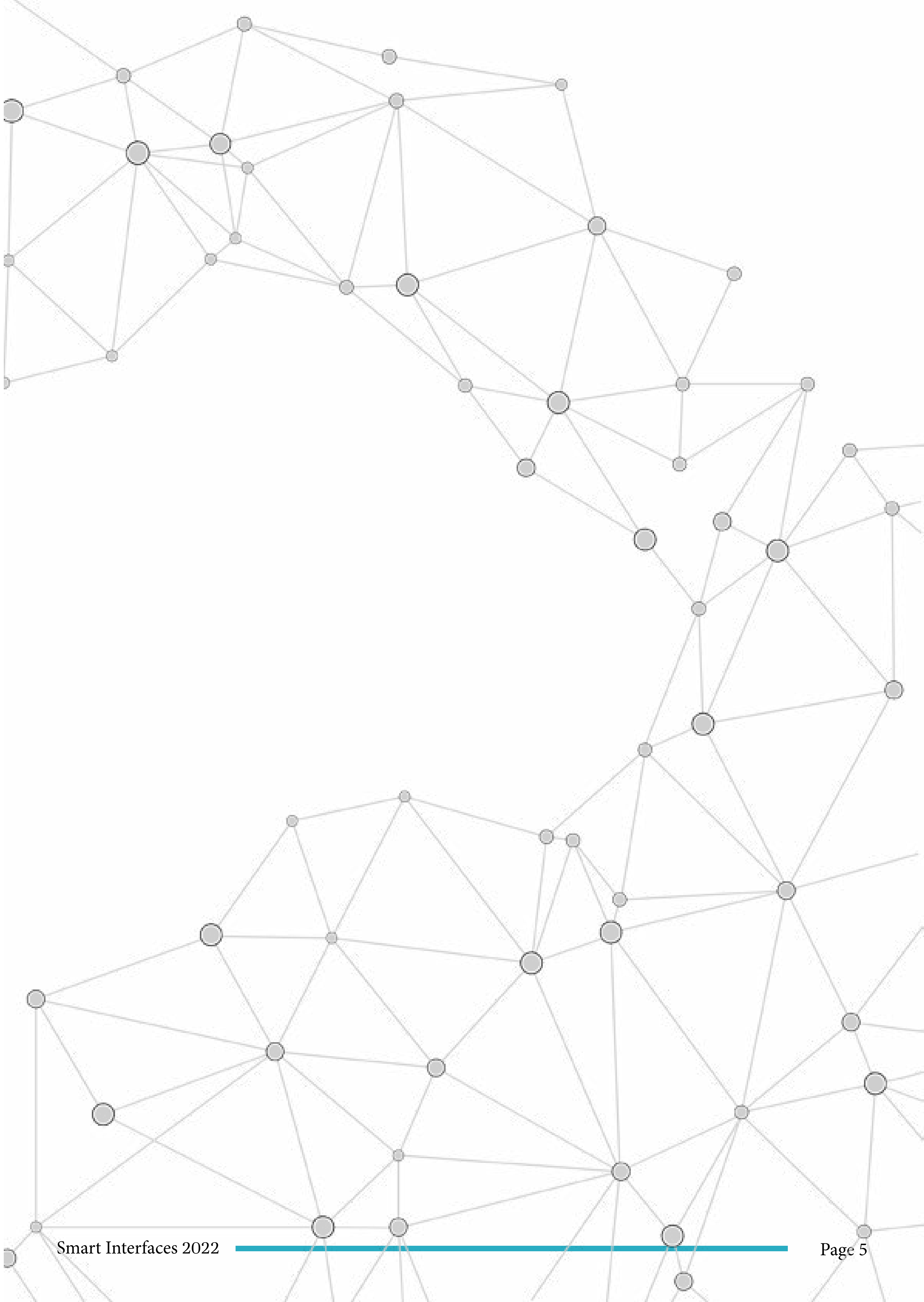


Figure 0: Project communication setup



GENERAL HOLISTIC
COMFORT

The comfort structure is complex because it entails a multidimensional personal experience with differing degrees of intensity. Multiple approaches can be used to measure comfort. A common approach is to measure comfort in specific situations. For example, in the case of public buses, comfort is measured by making a comfort index based on vibration and noise pollution.[2] These situation-specific conditions can provide a general overview of the user's comfort.

Another approach to measuring a user's comfort is defining comfort as the direct experience of having met basic human needs for relief, ease, and transcendence in physical comfort, psychospiritual comfort, environmental comfort and social comfort. [3] These comfort aspects are interrelated and can be diagrammed on a two-dimensional grid.

The first dimension of the grid is the intensity of the comfort needs. These intensities are defined as relief, ease, and transcendence. Relief is the low end of the spectrum, implying an immediate comfort need that has been relieved. For example, this could be the stopping of pain. Ease lives in the middle of the spectrum and implies a state of contentment and well-being. Transcendence is at the high end of the spectrum. It implies a comfort need that has been met so that the occupant is energised or inspired to perform optimally.

The second dimension consists of internal and external comfort needs. These comfort needs can be subdivided into four categories. Physical, psychospiritual, environmental, and social. Physical comfort implies the comfort of bodily sensations. Psychospiritual comfort implies the internal awareness of self, including esteem, concept, sexuality, and meaning in one's life. It can also encompass one's relationship to a higher order of being. Environmental comfort implies comfort in the external background of the human experience. It encompasses light, noise, ambience, colour, temperature, and natural versus synthetic elements. Social comfort implies comfort in interpersonal family and societal relationships.

USER-TEST COMFORT

The representational grid of holistic comfort can be used to define specific experiences of comfort. A survey was developed based on the representational grid of holistic comfort to determine the personal comfort of users in the utility building context. This survey aimed to map the occupants' personal comfort experiences to the holistic comfort grid to derive a general understanding of the occupant's comfort.

SETTING

In the preparatory part of the survey, the users are asked to disclose their personal information and their contextual situation. This information is needed to delineate the research and derive a general understanding of the users' context. Subsequently, the main part of the survey consists of four sections: physical comfort, psychospiritual comfort, environmental comfort, and social comfort. The users could address their comfort experience based on relief, ease, and transcendence in each section. This research was qualitative to track the users' personal experience of comfort and provide the user with the ability to give a detailed description of his experience. The responses were assessed and grouped to get a general overview of the responses. [4]

RESULTS

The most significant results are in social comfort and environmental comfort. The most common response to social comfort is the presence or lack of quiet workplaces and social interaction. This social interaction is, for example, a good relationship with their colleague or boss. The most common responses to environmental comfort were the lighting conditions and the thermal sensation.

Based on these answers, further research will be done on social/auditive comfort, visual comfort (lighting conditions), and thermal comfort.

VISUAL
COMFORT

Visual comfort or lighting conditions are an essential facet of the holistic comfort of the indoor environment. It can be helpful to implement lighting control systems to improve visual comfort and reduce energy consumption. Also, improving lighting conditions can lead to a higher perceived level of user productivity. [5]

STANDARD NEN 12464-1
Current recommendations regarding the lighting of offices are posed in the European stand NEN 12464-1. [6] These lighting requirements are determined by the satisfaction of three human needs: Visual comfort (the feeling of well-being). Visual performance (the ability of the occupants to perform their visual tasks). Safety (the visual safety of the occupants.
The main criteria determining the luminous environment are luminance distribution, illuminance, glare, the directionality of light, colour appearance, flicker, and variability of light (levels and colour of light).

LUMINANCE
The illuminance and its distribution on the task area and its immediate surrounding area significantly impact how quickly, safely, and comfortably a person perceives and carries out the visual task. Too high luminance and too high luminance contrast can result in a glare. This glare will negatively affect the user's comfort. On the other hand, too low luminance will result in a dull and non-stimulating working environment. Too much variation in luminance can cause fatigue due to constant re-adaption of the eyes.
All surfaces in a room must be considered to create a well-illuminated area. They are determined by the reflectance of and the illuminance on the surfaces. High surface reflectance contributes to energy savings and better visual comfort.

FLICKER
Flicker or stroboscopic effect (temporal light artefacts - TLA) can reduce visual comfort and task performance. Also, it can lead to physiological effects such as fatigue or headaches. Flicker is specified by using the IEC short-term flicker indicator. Flicker can be measured by applying a flickermeter to verify the voltage fluctuation levels. [7]

DIRECTION OF LIGHT
A specific direction of light can define the edges of objects in the working area. This effect can result in a better working area for specific tasks. Also, this can lead to unintended reflections. Light from multiple directions can cast multiple shadows, resulting in a confusing visual effect.

GLARE
Glare can occur by reflecting a bright light on surfaces on windows or mirrors. Glare can also occur directly from the luminaire. It produces an unpleasant sensation and fatigue, and it can cause accidents. Glare can be experienced as discomfort glare or as disability glare. It can be avoided by limiting the luminance of luminous surfaces or by shielding the light source directly. The glare of the luminaire can be estimated using the Unified Glare Rating (UGR) method.

Usertest Visual Comfort

INTRODUCTION
A user test is developed to validate the occupant's comfort. This test aims to take the standards from the NEN 12464-1 into consideration and validate them in the context of a utility building. The test consists of a sensor box to capture the lighting condition in a room and a survey to capture the occupant's comfort at a specific moment. With these components, the effect of the lighting condition on the occupant's comfort can be estimated.

SETTINGS
The test will be performed whilst the occupants are working or studying. Initially, the occupants are asked to fill in the survey as a base measurement. Then, when the occupants experience a difference in their visual comfort, they can address their sense of visual comfort via the survey.

Simultaneously, the sensor is placed close to the occupants. This sensor captures the overall luminance in a room and the main direction of the light source. It uses a real-time clock (RTC) to capture the current real-time. With this captured time, the measured data can be connected to the visual comfort declared through the survey. A delay is considered when connecting the survey answers and the sensor data due to the time it takes for the occupants to notice the change in visual comfort and address their sensations through the survey.

DESIGN SENSOR BOX
The luminance of the room is measured with a luminance sensor. This sensor outputs a voltage between 0 and 1024, which must be converted to a luminance value. The luminance sensor is provided with a dataset to map the sensor values to luminance. [8] Based on this dataset, a linear regression model is used to create the equation to convert the voltage output to luminance (lx).

The flickering of the light can be estimated by analysing the dataset on abrupt, significant changes in luminance. The data is measured every 100 milliseconds. A change of light can be labelled a flicker if an abrupt, significant light intensity change occurs in less than 500 milliseconds. Therefore, this method can measure the flickering of the light.

The direction of light is measured with four Light Dependent Resistors (LDR). These LDRs are separated into four positions: north, east, south, and west. The sensors are separated by walls to block the light from other directions. [Figure 1] The light direction can be noted as a vector by calculating the relative difference of the opposing sensor positions.

$$L_d = [v_n - v_s, \quad v_e - v_w]$$

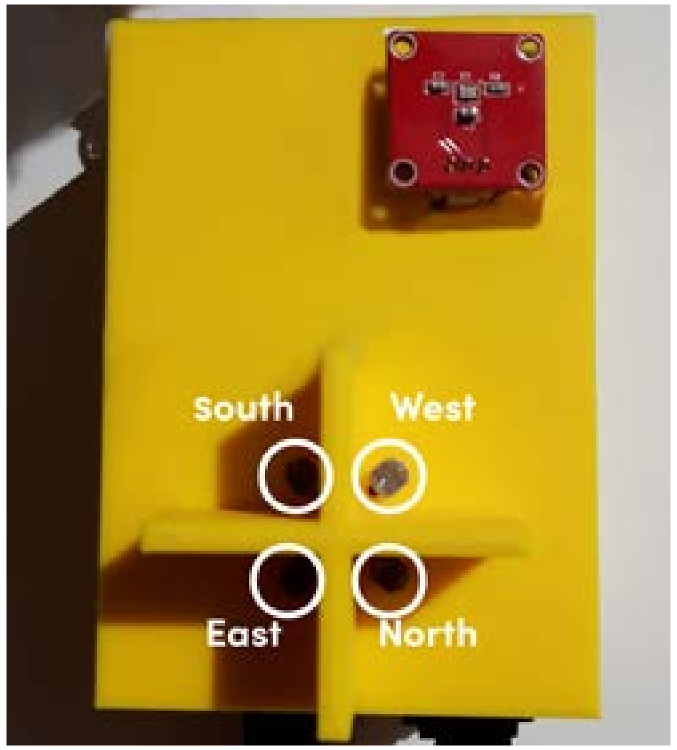


Figure 1: Sensor Box

Validation Sensors

The light directionality sensor is tested to validate its reliability and its usability. Therefore, the sensor was placed in an area where the light source moved from the southeast to the southwest in 2 hours. The data was captured and graphed on a 2-dimensional grid.

The north side is taken as the occupant's viewing direction, and the time is visualised by colour. The graph shows that the light source starts in the southeast and moves to the southwest, which was the case in the testing context. [Figure 2]

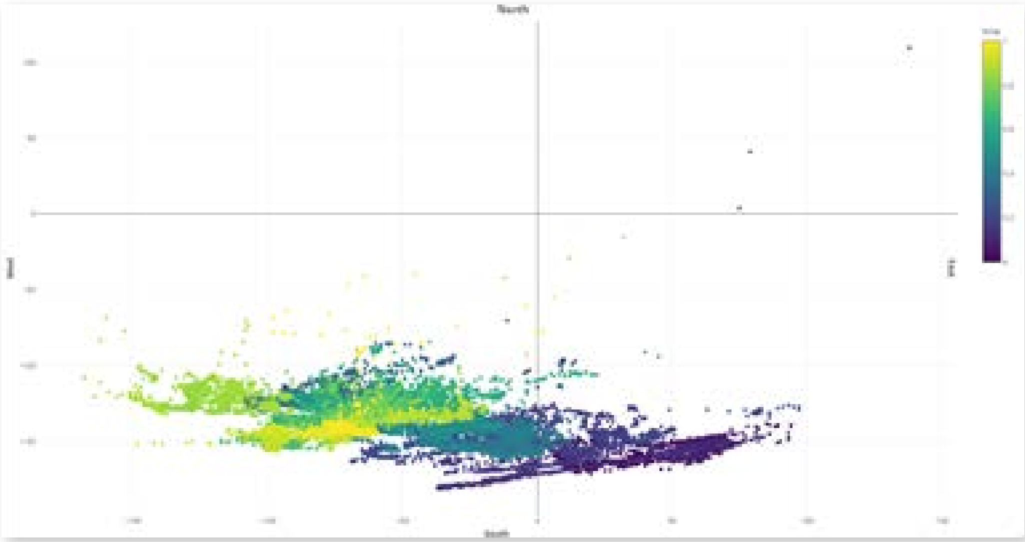


Figure 2: Directional sensor validation

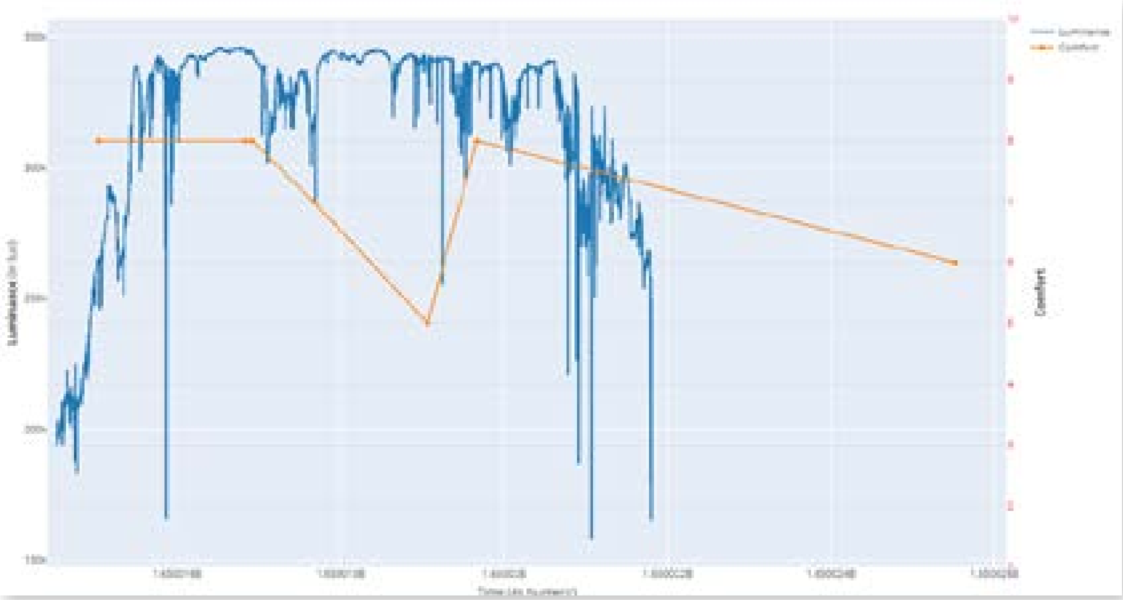


Figure 3: Directional sensor validation

Data Analysis

The user test was performed in a room where the light was highly directional from the occupant's perspective. The sensor is positioned so that the occupants are looking in the north direction. The source of light was natural sunlight. Therefore, the light source moved from the south to the southeast over two hours from the occupants' perspective, as shown in figure 4.

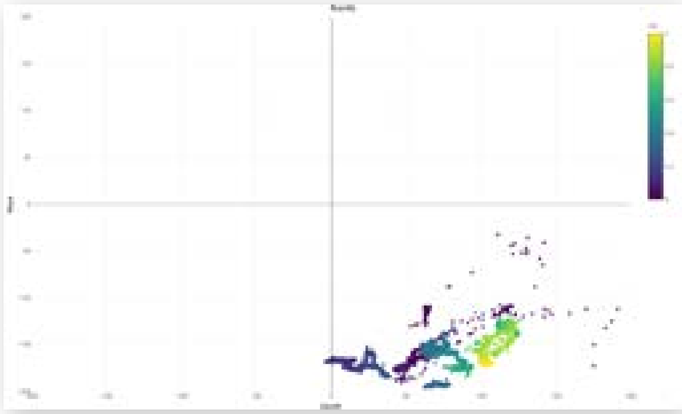


Figure 4: Direction sensor user test 1 - Time

The results show that all occupants in this test have reported two comfort values, 6 and 8. Figure 5 shows that the higher comfort values positionally surround the lower comfort values. This is due to outliers caused by the occupant's shadow covering the sensor. Therefore, figure 6 uses an adjusted opacity to remove the outliers and show a clear overview of the actual direction of the light source. This graph visualises that the light source directly from the back is considered more comfortable than a light source coming from the side.

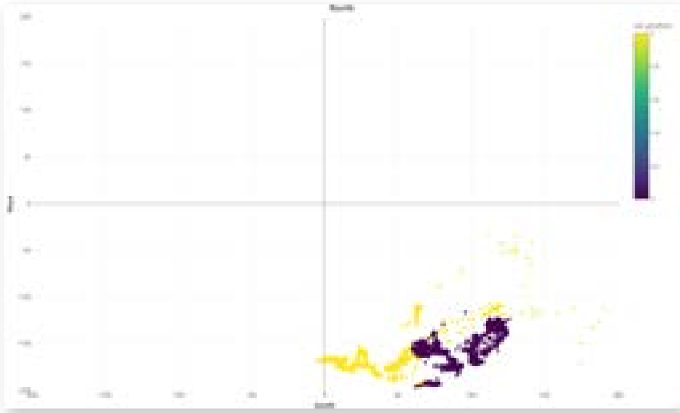


Figure 5: Direction sensor user test 1 - Values

This data is analysed by applying machine learning to the dataset. A random forest algorithm is applied to the dataset to create the machine learning model. The model is trained to predict a comfort value utilising the north, east, south and west values. This resulted in a machine learning model with an accuracy of 0.9991, a recall of 0.99905 and a precision of 0.99995. The high accuracy, precision and recall outcomes prove a significant correlation between the directionality of the light source and the occupant's comfort in this user test.

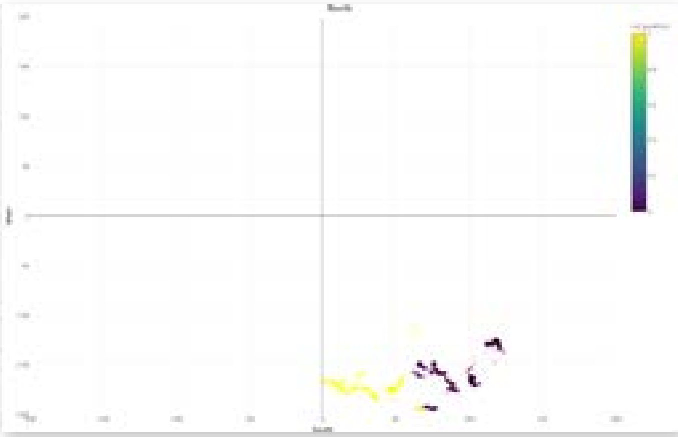


Figure 6: Direction sensor user test 1 - Values adjusted opacity

Data Analysis

Figure 7 shows the measured luminance values and the comfort feedback on a time scale of two hours. The occupants in this test have reported three comfort values, 6, 7, and 8. A smoothing algorithm is applied, which smooths out the measured values by calculating the mean value of their neighbours to remove outliers that the occupants can cause by casting a shadow over the sensor. The smoothing in this dataset is accomplished by a factor of 25.

The graph suggests a positive correlation between the luminance and the reported visual comfort of the occupant. It shows a lower comfort value when the measured luminance is lower and a higher comfort when the luminance is higher. The correlation between the measured luminance and the comfort values is approximately 0.89.

These changes in comfort are relative and can be different in other lighting conditions. For example, when the measured value in a room is already significantly high, an increase in luminance can cause a decrease in comfort, which will result in a negative correlation between the measured luminance and comfort. Although the test does not show the exact correlation between luminance and comfort because of the possibility of varying conditions, the test does show a significant correlation between luminance and comfort. Therefore, the test shows that the direction of light and the overall luminance significantly impact occupants' comfort.

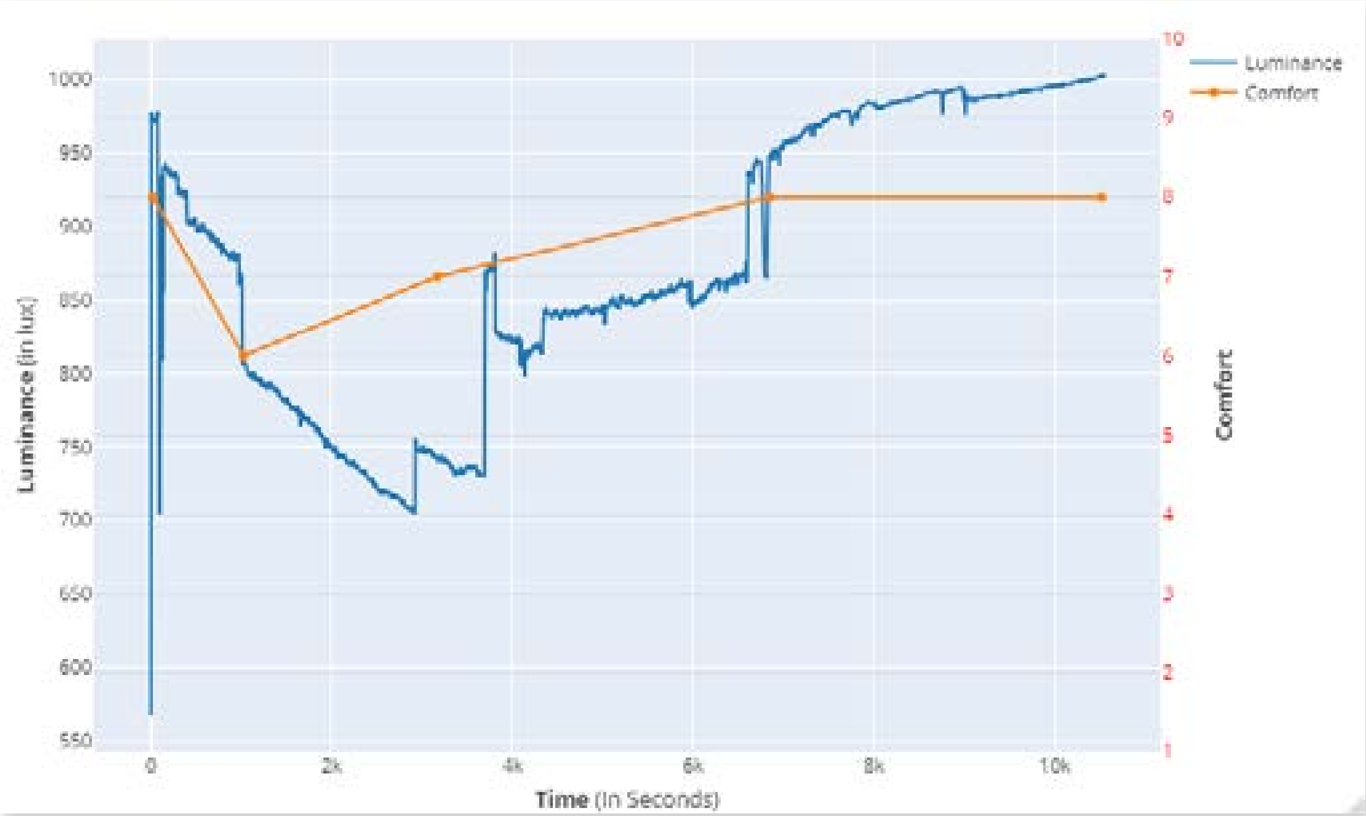
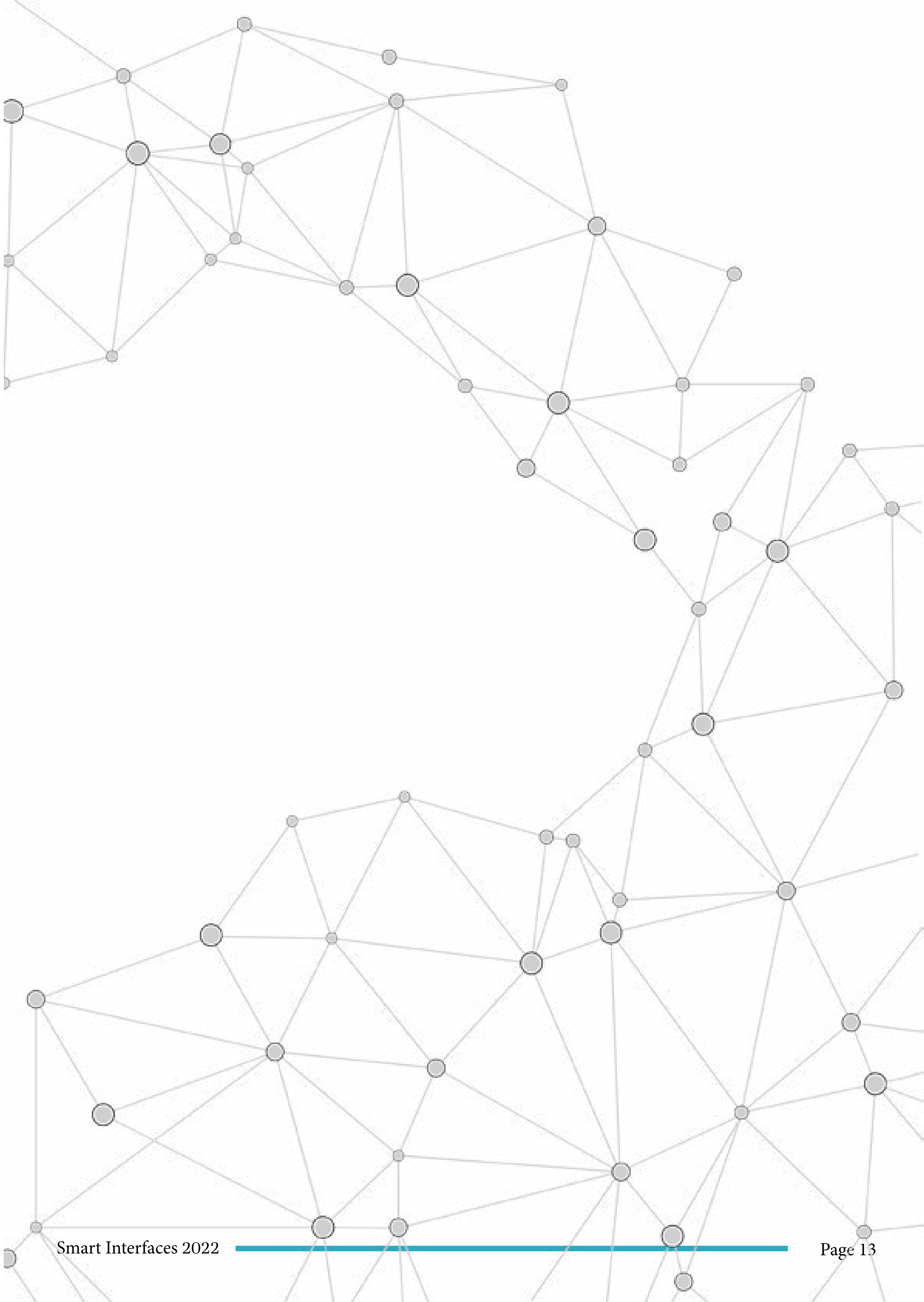


Figure 7: Luminance & visual comfort user test 1



SOCIAL | AUDITIVE
COMFORT

User test 1 (Holistic comfort) concluded that having a calm working place contributes to a comfortable working environment. While performing the user test, calmness was mainly defined as the absence of noise or social interactions. Auditive and social comfort concepts must be considered to create a comfortable working environment.

AUDITIVE COMFORT

Research has reported lower satisfaction and lower work productivity in offices in open-plan offices compared to traditional offices. The research indicates that most of the adverse effects are associated with the increase in background noise. [15] Also, research indicates a significant better cognitive performance in low noise conditions compared to high noise conditions. Ambient noise has a significant impact on tiredness and lack of motivation. [16]

Other research on noise in the physical working environments reports that the participants noticed the noise but that the noise was not bothersome. [17] The majority of the noise measurements were found to exceed 85 dBA. According to Dutch legislation, the workers are obligated to wear protective noise-cancelling gear at this level of noise, and a plan of action must be constituted. [18], [19]

A study published in the Journal of Consumer Research states that an appropriate level of ambient noise triggers the mind to think more creatively. [20] Process measures show that an intermediate level of noise, unlike a low level of noise, increases processing difficulty, causing a higher construal level and thus promoting abstract processing, which leads to higher creativity.

SOCIAL COMFORT

Research suggests that the lack of personnel space and crowded workplaces negatively affect productivity and morale. An intrusion of their personnel space increases the occupant's anxiety and decreases productivity. The psychosocial environment of the occupant is an essential factor for productivity. When the occupants like their work and colleagues, it positively affects their morale and productivity. [21]

Higher levels of social interaction increase overall productivity due to the social nature of humans. This phenomenon is called the 'water cooler effect'. Also, increased cohesion increases shared attitudes, work habits, and social support. [22] On the other hand, due to a heterogeneous population in terms of extroverted and introverted people, quarantining and social distancing may also boost the productivity of extroverted people. [23]

A worker's productivity can also be affected by their coworkers' productivity. Its effort is positively related to the productivity of workers who observe him but not workers who do not observe him. Additionally, the presence of coworkers with whom they frequently interact enhances this effect tremendously. [24]

Social | Auditive Comfort

Multiple aspects of social and auditive comfort must be considered to create a calm working environment. The auditive comfort consists of three levels of noise. Low noise conditions indicate a significant better cognitive performance. Intermediate noise conditions can trigger the mind to think more creatively. High noise conditions can cause severe damage to workers' ears and should be avoided.

Social interaction between workers has a significant influence on their morale and productivity. It can cause increased shared attitudes, work habits, and social support. Also, the workers' coworkers can affect their productivity. When creating an auditive and socially comfortable working environment, considering the research, noise levels and social interactions should be appropriately arranged to achieve the desired intention for a specific space.

THERMAL

COMFORT

Thermal comfort has a significant impact on performance and health. In a survey done across Europe, the initial complaint reported was a lack of thermal comfort. Furthermore, studies have been conducted on the impact of learning capability on students. These studies concluded that students who have never experienced high indoor temperatures achieved higher scores on tests than students who have experienced high indoor temperatures. Additionally, high temperatures have been linked to negative moods, heart rate, respiratory symptoms and feelings of fatigue. [25]

FANGER METHOD

Thermal comfort can be measured by using the Fanger method. This method consists of the predicted mean vote (PMV) and the predicted percentage of dissatisfaction (PPD). These indices are based on the perception of a broad group of people of metabolic rate, clothing insulation and environmental conditions. [26]

PMV & PDD

An individual's thermal sensation is strongly related to the thermal balance of his or her body. This balance is influenced by physical activity, clothing, and environmental parameters: air temperature, mean radiant temperature, air velocity, and air humidity. By estimating these factors, the thermal sensation for the body as a whole can be predicted by calculating the predicted mean vote. [27] The predicted mean vote aims to predict the mean value of votes of a group of occupants on a seven-point scale. The seven-point scale ranges from -3 to +3 and represents the group's relative thermal sensation, where -3 means cold, +3 means hot, and 0 is the thermal equilibrium. A thermal equilibrium occurs when an occupant's internal heat production is the same as his heat loss. [28]

The following formula calculates the PPD.

$$PMV = (0{,}303e^{-2.100M} + 0{,}028) \cdot [(M - W) - H - E_c - C_{res} - E_{res}]$$

- **M**
  The metabolic rate, in Watt per square meter (W/m2).
- **W**
  The adequate mechanical power, in Watt per square meter (W/m2)
- **H**
  The sensitive heat losses
- **Ec**
  The heat exchange by evaporation on the skin
- **Cres**
  Heat exchange by convection in breathing
- **Eres**
  The evaporative heat exchange in breathing

The predicted percentage dissatisfied (PPD) can be extracted from the PMV. The PPD Index provides a method to predict the percentage of people who experience thermal discomfort in a room. The following formula calculates the PPD. [27]

$$PPD = 100 - 95 \cdot \exp\left(-0{,}03353 \cdot PMV^4 - 0{,}2179 \cdot PMV^2\right)$$

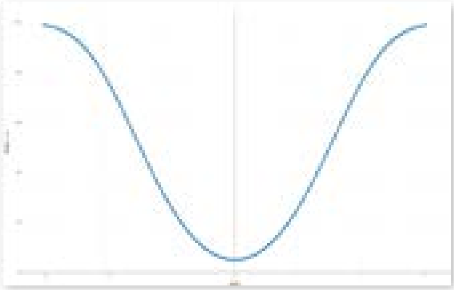


Figure 8: PPD Graph

Standards

Organisations use standards that integrate the PMV and PDD calculations to determine the climate satisfaction in a room. The most common thermal standards are ASHRAE 55 and ISO 7730.

ASHRAE standard 55

ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy was published in 1966 by the American Society of Heating, Refrigerating and Air-Conditioning. It was first expanded upon by P. O. Fanger based on experiments done in the 1960s at Kansas State University. The original standard was built based on temperature and humidity. However, the standard grew to include PMV, PPD, Metabolic rate, air turbulence, and clothing isolation. With these additional indicators, the ASHRAE 55 became an institutionalised standard for predicting climate in America. [29]

ISO 7730

ISO 7730: Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria is an international standard published by the Standard Setting Organisation (ISO). The 7730 standard presents methods for predicting the general thermal sensation and degree of thermal dissatisfaction of healthy people exposed to moderate thermal environments. The ISO 7730 standard extends the ASHRAE 55 by including cultural, national, and geological factors. [27] Furthermore, occupants' physical handicaps must be considered when estimating thermal comfort. Physically disabled people tend to have lower activity levels than standard people. They also cannot easily adjust clothing to the thermal level. [30]

CONCLUSION

The PMV and the PPD provide a basic understanding of the occupant's thermal satisfaction. Additional factors must be considered to acquire a deeper understanding of the occupant's thermal satisfaction. The ASHRAE 55 provides a better understanding by adding air temperature, mean radiant temperature, air velocity, and air humidity as factors to calculate estimate thermal comfort. ISO 7730 builds on top of that and provides the most comprehensive explanation of thermal comfort by considering cultural, national, and geological factors. ISO 7730 is momentarily the best and most complete method of estimating thermal comfort.

MEANINGFUL

DATA VISUALISATION

Codes are institutionalised rules which carry a specific meaning. Codes can be icons, colours, or images to communicate data in an easily understandable manner. A crucial question for the understanding of data visualisation is whether the codes used are intuitively understandable or are based on widely known conventions. There can be many good reasons to choose design elements for such communication strategic reasons. However, choices can also confuse the reader since he will initially assume that all the visual elements and their different characteristics mean something. For example, when only one form or one colour is used, it is assumed that form does not matter in itself. When there is more than one form or colour, it is assumed that the form or colour has meaning. On the other hand, it is not immediately clear which variables carry compositional and figurative meanings with multiple forms of complex coding systems. [9]

A well-designed data visualisation contains multiple levels of reading. At the first level, the reader can understand all key codes well enough to read the basic visualisation message. The second level, which requires more time and mental effort, adds more nuanced information about exact numbers, source ratios, and advanced functions. [9]

Specific communications methods such as logos, website designs, and an organisation's digital presence can also affect the organisation's credibility. For example, logos are considered an essential part of the organisation's identity.[10]

Reader position in visualisation design

Data visualisation belongs to the type of text that appears impersonal and objective. However, every visualisation reflects and influences the relationship between the reader and the sender. This relationship can take multiple forms.

Data visualisation most often supports a relationship where the sender appears as a "teacher", and the reader appears as a "learner". In other words, a solid asynchronous power relationship occurs. Depending on the initial relationship of trust with the sender, some readers will face the visualisation with a fundamentally critical or even sceptical view. This phenomenon is based on the precondition that data visualisations are highly suitable for manipulating the truth. To enhance the effectiveness of the visualisation, it is therefore essential to build trust between the parties and balance the power relationship. It is required that the sender shows who she is to obtain this trust. She should communicate the steps taken to transform the data and design the visualisation. [9]

Using popup information to inform the reader is a way to give the reader an insight into the actual data. The reader is enabled to do more thorough research. Also, it is easier to understand the meaning of the used codes in the data visualisation. [9]

In a personalised interactive visualisation, the reader can use their input to manipulate the data. This way, the reader is partly given control over the visual representation of the data.[9]

Adding a description of the original data can provide insight into the process behind the visualisation design. The reader can take a critical view of the procedure of the design process and assess the sender's competence. The reader can have a sceptical view of the visualisation when their perception and the graphic representation do not correspond. [9]

Providing access to the source data is a way to give the user complete control to validate the visualisation. The reader can take the position of a critical accessor and validate the sender's competence. When the data is not provided, it fails to give the perception that the visual representation is objective and not shaped by the sender's perception.[9]

An important side note to this is that most readers will not make an effort to assess the visualisation. Enabling them to do so does contribute to the trusting relationship between the sender and the reader. [9]

The value of good data visualisation is defined by Vitruvius based on three components by which the quality of the visualisation is measured. These components are utility, soundness and beauty.

The utility of data visualisation is measured by how the visualisation reaches its objective, which is to convey information. Two approaches for data visualisation are explorative visualisation and narrative visualisation. These approaches are unique approaches and, thereby, non-hierarchical.

Explorative visualisations provide information in an unbiased fashion, enabling viewers to analyse it and construct their conclusion. This approach is best used when comprehension of collected insights is a priority, for example, in scientific and academic applications.

Narrative visualisations guide the reader through a specific set of information that tells a predetermined story. This approach is best used to convey a specific message to the user. It focuses on audience appeal and information retention.

The soundness of data visualisation is defined by how meaningful it is. A cohesive and interesting story must be present for visualisation to become meaningful. The information should be complete, trustworthy, and engaging.

Beauty describes how the appearance matches the visualised data. It is defined in format and design quality. An inappropriate format or design will result in an inferior outcome. The visualisations design must be prescribed regarding the appropriateness and effectiveness of the objectives and the displayed information. [11]

Figure 9: Triangle of vitruvius
Source: Adapted from [11]

In the next section, multiple data visualisations are reviewed using the literature gathered.

The first example is the visualisation **Going Gray** from Reuters Graphics. [12] This visualisation shows the shift in overall age over the years in multiple countries. The code used in this graph is a line. The height of the line shows the percentage of 65 years and older people in a population in a specific year. The numbers explain this code on the axes. Also, a brief explanation is given on the first page of the visualisation.

The visualisation is not interactive, and the user cannot give their input. Also, the source data is not given, and the process of transforming the data is not shown. Therefore, the reader cannot assess the dataset on validity and correctitude.

The visualisation uses a narrative design. The predetermined story is presented linearly, and the data cannot be explored. This visualisation has a social interest and interestingly presents the information. The design of the visualisation is kept timid. It does not use many animations or visual effects. Arguably, this is the right choice for this visualisation because the object is rather severe.

Commute / Metronome is a visualisation of the ambient noise during subway journeys. [13] The codes used in this visualisation are circles, colours, and sound. The codes are not conventionalised or generally known. Despite an explanation of the meaning of the codes being present, it is not directly comprehensible what they mean. This is due to the absence of a comprehensive explanation of the visualisation. The reader cannot interact with the data, the data transformation process is not described, and the source data is not mentioned. Therefore, the reader is not able to assess the data visualisation.

The visualisation uses a narrative design. The predetermined story is presented linearly, and the data cannot be explored. This visualisation has a social interest and interestingly presents the information. The use of sound to visualise commute ambient noise complements the overall meaning of the visualisation.

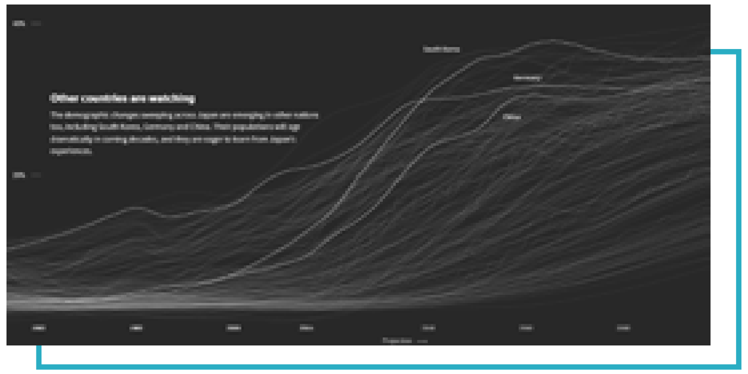


Figure 10: Going Gray
Source: Adapted from [11]

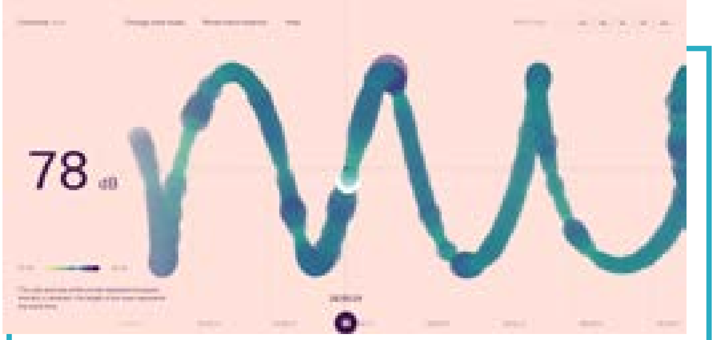


Figure 11: Commute / Metronome
Source: Adapted from [12]

U.S. Gun Deaths is a visualisation designed by Periscopic. [14] The visualisation shows the United States of America's deaths by gun violence. It also shows the lost years based on the victims' life expectancy. The codes used are colours and lines. In a quick animation at the start, the codes are visually explained. Also, the colour of the lines is conventionalised. These conventionalised codes make for clear and coherent visualisation.

This visualisation uses popup information on the lines to give the reader more information. Also, a description is present about the method and the source data are mentioned. Therefore, the reader can take the position of a critical accessor and validate the sender's competence.

The visualisation has a narrative design. The predetermined story is presented linearly, and the data can not be explored. This visualisation has a social interest and interestingly presents the information. The design of the visualisation is moderate. It does not use many animations or visual effects. This is the right choice for this visualisation because the topic has a serious tone. [7]

Figure 12: U.S. Gun Deaths
Source: Adapted from [13]

USER

INTERACTION

Every user has preferences for thermal comfort, visual comfort, and social comfort. These preferences can vary for different locations within utility buildings, for different activities, or in different contexts. Also, these preferences can change over time. The EMS must consider the user's varying personal preferences to make a well-considered decision about the building's environment. Therefore, the communication between the user and the EMS must be established wherein the EMS can explain its choices, and the user can constantly report his feedback about these choices. This two-way communication makes for an interactive experience.

The first step for the user is to know the environmental status of the room they are occupying. Based on that status, the user can place their own experience of the room in context. For example, when the user experiences a cold sensation but the room is 22 C°, the user can adjust his perception of the room's temperature. In addition, the EMS must explain the decision-making process to provide the user with a deeper insight that can alter their perception of comfort. [31]

The system should speak the user's language, with words, phrases, and concepts familiar to the user rather than system-oriented terms. Also, the user has to be able to give feedback in the user's language. Using a familiar language will result in understandable and intuitive communication for the user. [32]

Finally, the EMS should save the user's information. The EMS can use this information to understand the user's personal preferences better. It can use the information to make a better preliminary decision about the user's comfort. The EMS should give feedback that the user's feedback is saved and incorporated into the system's decision-making to enhance the trusting relationship between the user and the EMS. [32]

VERSION 1

PROOF OF CONCEPT

The main question reads: "How to design a data-driven interface that supports the user in understanding the environmental decisions made by the energy management system and supports the user in making his environmental decisions on a decentralised level while considering a healthy indoor climate, energy efficiency, and energy flexibility?" A proof of concept (POC) has been designed to conclude the research in one concept and answer the main question. The POC is a mobile application that the user can use to see the EMS's environmental choices. The choices of the EMS are based on a predictive AI model that considers the user input based on visual, social and thermal comfort and considers the data from a specifically designed smart sensor that can measure multiple aspects of visual, social and thermal comfort. The user can provide his feedback on the EMS using this mobile application. That way, two-way communication occurs between the user and the EMS.

SENSOR
The designed smart sensor consists of a temperature and a humidity sensor to sense the thermal conditions in a room from which the thermal comfort can be estimated. The smart sensor is provided with a luminance sensor to estimate the user's visual comfort in a room. The social comfort data is captured using an ESP32 camera with software to count the number of people in a room. The noise level in a room will be sensed with a sound sensor(dB). All the data will be saved on a local database where the machine learning model can use it.

AI
The AI is designed to predict the user's comfort based on sensory data and feedback from the user. This AI will be trained using a TPOT algorithm to extract the best fitting model for the data. The underlying AI model for the EMS ensures that the user's feedback and personal data can be used and incorporated.

MOBILE APPLICATION
The user interface will be executed as a mobile application. A mobile application can be personalised without the need for login screens. Also, a mobile application is easily accessible for immediate comfort feedback and is highly distributional. Using different user interfaces like a central access point on room level would make it harder to accomplish a personal experience and require the user more steps to commit their comfort feedback.

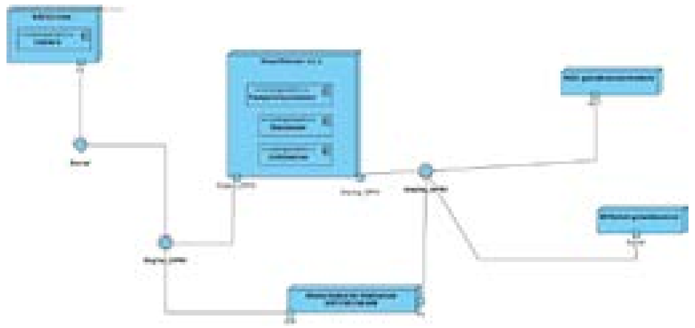


Figure 13: Sensor design diagram

The mobile application consists of 4 views. These views all serve a purpose in providing the user with sufficient data or the ability to input their personal preferences.

MAIN VIEW
The main view gives the user an overview of the EMS choices divided into thermal comfort, visual comfort and social comfort. The choices of the EMS are visualised using recognisable and conventionalised codes. Also, the codes are explained with additional numeric data. Clause: 3.0

The user can get more information about the decision-making of the EMS by tapping one of the three types of comfort. The information on this page is structured by first showing the visualised decision of the EMS. Next, the decision-making is explained. With this information, the user can commit valid feedback on their comfort. Clause: 7

LIST VIEW
The list view gives the user an overview of all rooms with their respective comfort values per comfort type. This view is built to extend the idea of moving occupants in a building based on their environmental preferences instead of adjusting the environmental settings. In some cases, like social comfort, the building cannot make environmental adjustments based on users' preferences.

The user can see all the rooms and their respective environmental values listed in this view. He can decide which room to occupy based on his environmental preferences. Therefore, the EMS has to make fewer adjustments while the users' overall comfort rises.

Figure 14: Main view

Figure 15: Main view

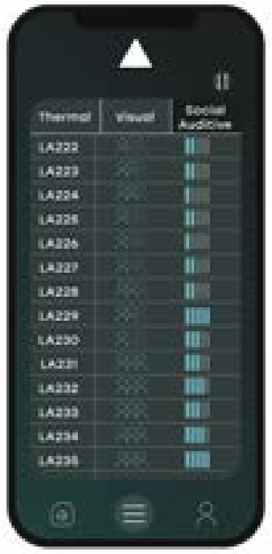


Figure 16: List view

Figure 17: List view

Figure 18: Personal view

Figure 19: Personal view

PERSONAL VIEW
The personal view consists of two sections. A first section is a form where users can fill in their cultural, national, and geological information based on ISO 7730. This data is used in the decision-making on the users' thermal comfort. Clause: Thermal
The second section consists of displaying the users' measured comfort feedback. This part adds to the sender-reader relationship by providing insight into the process of data processing. Clause: 6.0

Figure 20: About view

ABOUT VIEW
The about view is designed to add to the reader-sender relationship. The view explains how the users' data is being used and how the EMS comes to a decision. Also, this view consists of a button that leads the users to the original data. This button allows the users to take the position of a critical accessor and validate the EMS. Clause: 6.0

User Validation

The POC is validated on a group of occupants. The POC was presented to the occupants and validated on understandability and usability. Also, varying visualisations were used based on the visualisation theory to test which type of visualisation was best to convey information.

RESULT

The most important results of the user test were that the best scoring visualisations were based on recognisability and the use of a frame of reference. Using recognisable or conventionalised visualisations can help the user better understand the visualisation. A good example is the visualisation of the blinds, where the users found a regular percentage bar to be confusing due to the direction of the blinds. When a recognisable visualisation of the blinds was used, the confusion cleared.
Using a frame of reference helped the user put the presented data into perspective. A good example was the noise level. Noise levels are measured in decibels (dB) which is complex for a regular user to understand because it is not regularly used. When providing the user with a frame of reference, the user can better understand the auditive conditions.

An information button is added to every comfort type. This button triggers a popup that provides the user with more reference material about the presented data. For example, the popup of the social comfort shows a recognisable situation that produces the same level of decibel. Therefore, the user can better understand the visualised data.

Figure 21: User validation thermal comfort

Figure 22: User validation visual comfort

Proof of Concept Version 2

Combining the given feedback with the first POC, a new version of the POC is designed.

Comfort theory is studied and defined into three essential factors. These factors help the users understand their comfort and enable them to provide comfort feedback quickly. The users' usability, understandability, and recognizability are considered while designing the mobile application. Also, the openness of the EMS's data is provided to build a trusting relationship between the users and the EMS. The mobile application is designed to be easily accessible for quick comfort feedback and scalable to be broadly applicable.

Therefore, this design combines comfort theory, the visualisation theory and the interaction design to create a validated, data-driven interface that supports the users in understanding the environmental decisions made by the energy management system and supports the users in making their environmental decisions on a decentralised level while considering a healthy indoor climate, energy efficiency and energy flexibility.

Figure 23: New Proof of Concept Design

DISCUSSION

While research and the general standards suggest a correlation between light conditioning and comfort levels, it does not supply relative applied research. The user test on visual comfort proves this hypothesis by measuring light conditions and occupants' feedback. These two measurements are highly correlated.

The user test does not take some possible errors into account. The luminance sensor can cause an error because the luminance sensor is set up to measure the overall luminance of a room. The research suggests that comfort can be affected by the difference in luminance of the working area and the background luminance. [6] This sensor does not include the difference in luminance.

Another error can occur because the sensor is not placed directly on the user's eyes. While performing the user test, lighting can be highly local. Therefore, dissimilarities can occur in the user's comfort feedback and the measured lighting conditions.

The flickering of the light was estimated by measuring significant changes in the luminance sensor over a short time. Due to the placement of the luminance sensor, these changes in luminance could be caused by the occupant's shadow. Therefore, flickering can not be considered for estimating user comfort. The overall correlation between the users' comfort and the luminance was 0.80. Also, the machine learning model used to predict comfort by the direction of light gave an accuracy, recall and precision of over 0.99. While these are exceedingly high results, the results are not very representative. These high results are caused by testing with a small group of occupants. The results will presumably be lower if the group of occupants is increased. However, this would result in a more reliable and valid result.

The user can use the interface to commit comfort feedback by signing into a room and committing their feedback to that specific room. This feedback will most likely be given when the user feels uncomfortable or notices a change in comfort. When users feel comfortable in a room, they would probably not give feedback on their comfort. Therefore, the EMS does not know how many people feel comfortable or uncomfortable in a room. A possibility is to use a sensor that measures the occupancy in a room. However, the amount people who do not use the mobile application should be considered.

OUTLOOK

This research is based on the idea that users commit their comfort feedback to how they experience it. While this can be an effective way to measure comfort, this feedback can be biased because the experienced comfort can be caused or influenced by other factors. Other methods can be used to estimate user comfort.

One example is to study estimating user comfort by using physiological information obtained from wearable devices. Although this might be an interesting perspective, research suggests that adding these physiological sensors to the environmental sensors only leads to a 3% - 4% higher accuracy in estimating comfort. [33]

The use of existing sensors in a building can estimate users' comfort. For example, the light switch in a room can be used as a sensor. Whenever the light switch is not used, the users in a room would be comfortable. Whenever the light switch is turned off or on, it can be assumed that the previous state of the light was uncomfortable. This methodology can apply to multiple sensors or interfaces in a room. The disadvantage of using this method is the lack of personal information. The EMS does not know who switched the button, so it cannot consider the users' cultural and national background and physical ability, as stated in ISO 7730.

While this research takes the cultural, national, and geological differences into account for estimating user comfort, this research does not take the sex differences of the user into account. Sex differences can influence the user's thermal comfort and social comfort. Further research can study the effects of sex differences on multiple comfort fields.

The interaction design in this research is based on the ten heuristics of Jakob Nielsen. Further research can study different interaction techniques to improve the interaction between the user and the EMS.

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