# Linked data-based Digital Twins for increasing the Indoor Environmental Quality (IEQ) of individuals working from home

**A proof-of-concept use-case leveraging both measurement data and direct feedback to provide task-based improvements of the IEQ**

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# Preface

Dear reader,

What you are currently reading is the final project of a period of long and hard work. I am glad that this topic is what I could dive into, I learned much. Even more so during the course of the graduation period. I came to learn about my own wishes and desires for my future, for after all that was the reason why I chose a master in the first place.

This thesis is the conjunction of my years of study, and my years of learning in the working field. One person from my history of building houses I especially have to thank is Niels, a bright mind who is never afraid to see a new opportunity. I learned much from him, but most noticeably to work your ass off if you wish to make something work.

Furthermore, I want to thank Alex for this thesis was never possible without his help. I learned a lot from him too. Most noticeably that something can always be improved, but that you have to enjoy the process as well. Dujuan, thank you for helping with the initial launch. Without you there would never have been a proposal to begin with. Thank you for everything from premaster to graduation.

Then there is Sara, my master buddy, and close friend. Sara and I collaborated on almost all projects and assignments, and in doing so achieved great results. Sara above all you made my master a fun process. I am always grateful and found a friend for life.

To my family and friends, thank you for your support. Thank you for always being there with me, and thank you for being part of this journey.

Jelle van Midden

## Summary

On average people spend around 90% of their time in an indoor environment. On a societal basis, this amount is only increasing and will pose lasting challenges for the coming decades when left unchecked. The influences of a poor indoor environment often result in detrimental health effects, such as those associated with sick building syndrome. Due to the Covid-19 crisis, an increased amount of work hours is spent in a working from home (WFH) situation. This results in individuals being prone to an Indoor Environmental Quality (IEQ) that was never intended for this purpose. A solution to this problem is required, as the combination between WFH and working from office (WFO) is likely to stay.

In the academic field, much research has been done on the effects of IEQ on an individual’s feeling of comfort. Many determine this comfort by accounting for individual IEQ parameters groups and stating that if none are in a state of discomfort, that the general IEQ is comfortable. These IEQ parameter groups are subdivided into thermal, visual, acoustic, and indoor air quality (IAQ). More recent studies link these parameter groups to the representative IEQ parameters of temperature and humidity (thermal), light intensity and visual quality (visual), sound pressure level (acoustic), and CO2 levels (IAQ).

Additionally, there is an increase in technologies available to influence and measure these IEQ parameters. An increasing amount of Internet of Things (IoT) technologies is integrated into the work and living environments so that data becomes more readily available. One technology that has been increasingly gaining more track is the Digital Twin (DT) paradigm. The DT paradigm focuses on the interplay between the virtual and the physical linked through data. Combined are these entities able to create a loop of learning, where the virtual and physical are able to influence each other to create value. An effective method of building the relations is linked data. Linked data is a method of storing data, where information is stored in a subject, predicate, object relation (RDF-triple). As linked data is both flexible and effective in its applicability, a combination between these and Digital Twins is provided. It was for this reason that the main research question was formulated as: “*How can a linked data-based Digital Twin model be used to improve the Indoor Environmental Quality (IEQ), based on air-, temperature-, noise- and light parameters, of an at-home situated hybrid working- and living environment of the occupant(s), while also accounting for occupant(s) feedback?”.*

To answer this research question a methodological approach was constructed based on a literature study. Within this approach, the current state of the IEQ parameters, linked data, and Digital Twins are combined. Alongside this methodological approach, an application is developed which is used in a proof-of-concept use-case. This application aims to provide occupants with IEQ information and allow for user feedback to be integrated. A back-end will then combine the measurement and input information and select a corresponding response.

The IEQ parameter thresholds are based on the values from the literature and then connected to an activity level that groups threshold values with similar requirements. To obtain these IEQ measurements a combination of different individual IEQ parameter sensors are placed in the use-case location. Their results are then combined and stored in a relational database on a secure server on the TU/e campus. Then a Python script will query the required information from the linked data-based Digital Twin, and use it to query the relational database. Additional information required for the IEQ assessment is queried directly from the linked data model. These measurement values are compared to the threshold values corresponding with the current task. Additionally, direct input (i.e. prompt response, current task, and current discomfort) from the occupant are compared and, based on a hierarchical system, will result in an information prompt on the user interface (build in Angular).

This application is then placed on a test location called the OpenFamilyHome, which will function as the case study location. During a period of five days, two occupants will perform their WFH task and provide direct input to the application. This application will then either provide IEQ information, provide a request (e.g. open the window), or ask a survey question to determine and influence the occupant's comfort. After this period of five days, the data is analyzed and compared to the current literature. These results are evaluated from both an IEQ point of view, and a linked data-based DT point of view. The use-case covers both a hybrid work and living environment (living room) and a dedicated work environment (converted bedroom to an at-home office).

Regarding the IEQ of a WFH situation, this research found that from the measured IEQ parameters both temperature and sound pressure levels are non-impactful and based on the literature should not result in discomfort. However, from the direct input, it is shown that temperature is primarily experienced as neutral or negative even when within boundaries. Additionally, the at-home situation makes temperature the easiest to adapt to as there is both direct control over the room temperature and the occupant has access to clothing in order to adjust their insulation value. The other parameters have shown to be dire from a measurement perspective. For light intensity, CO2, general IAQ, and humidity almost all activity levels show a significant level of measurement values to be out of boundary. This corresponds with the responses since over 40% were about the light intensity being either too light or too dark, 22% about IAQ, and 25% about humidity. Light intensity was worse in the living room, while the rest was worse in the bedroom (which signifies a relation to room size).

The linked data-based DT performed as expected. Providing the required data through a SPARQL query, which could then be used directly as Python variables to perform an SQL query to gain the measurement results. These results were then used as input, which worked as intended. This allowed the application to generate the required prompts. Showing that the current implication of the hybrid model, proposed by Tang et al. (2019), of linked data and relational databases works as a Digital Twin format. This approach allows for expansion by expanding the information stored in the RDF-triples of the linked data-based DT. Providing a valid solution to the IEQ WFH situation.

The research ends with a discussion and conclusion, which provides the societal relevance, scientific relevance, and recommendations for future research.

## Samenvatting

Gemiddeld spendeert men rondom 90% van zijn of haar tijd in een binnen omgeving. Dit aantal groeit alleen nog maar op een maatschappelijk niveau, en zal langdurige uitdagingen met zich meebrengen indien hier niets mee gedaan wordt. De invloeden van een kwalitatief slecht binnen klimaat (BK) resulteren vaak in nadelige gezondheidseffecten, zoals die van het sick building syndroom. Vanwege de Covid-19 crisis spendeert men een toenemend aantal werkuren in een thuiswerk situatie. Dit resulteert erin dat individuen vatbaar zijn voor een binnenklimaat die nooit bedoeld was voor deze functie. Een oplossing voor dit probleem is noodzakelijk, aangezien de combinatie tussen thuiswerken en het kantoor zal blijven.

In de academische wereld zijn veel onderzoeken gedaan over de effecten van een BK met betrekking tot het gevoel van comfort van de individu. Vele stellen dit comfort vast door middel van gegroepeerde BK parameters, en geven aan dat wanneer geen van deze parameters wordt ervaren als oncomfortabel de stelling kan worden gemaakt dat het BK comfortabel is. Deze BK parameter groepen worden onderverdeeld in thermisch, zicht, akoestisch en luchtkwaliteit. Meer recente studies geven aan dat deze groepen kunnen worden gerepresenteerd door het gebruik van de BK parameters: temperatuur en luchtvochtigheid (thermisch), licht intensiteit en zich kwaliteit (zicht), geluidsdruk niveaus (akoestisch) en CO2 niveaus (luchtkwaliteit).

Hiernaast is er een toenemende hoeveelheid technologieën beschikbaar die in staat zijn om deze BK parameters te meten en beïnvloeden. Een toenemend aantal Internet of Things (IoT) technologieën worden geïntegreerd in de thuis- en werk omgevingen zodat meer data beschikbaar is. Eén technologie die toenemend is de Digital Twin (DT) paradigma. Deze DT paradigma focust op de samenwerking tussen het virtuele en het fysieke door middel van data communicatie. Gezamenlijk zijn deze entiteiten in staat om een cirkelwerking tot stand te brengen waar het virtuele kan leren van het fysieke en andersom, met het doel om meerwaarde te creëren. Een effectieve manier van het bouwen van relaties is linked data. Linked data is een methode waar data word opgeslagen in de zogeheten RDF-triples, die bestaan uit een onderwerp, predikaat, en een object. Aangezien linked data zowel flexibel als effectief in haar toepasbaarheid, is de combinatie tussen DT en linked data een logische stap. Vanwege deze reden is er gekozen voor de volgende hoofdvraag: *"Hoe kan een linked data gebaseerd Digital Twin model worden gebruikt voor het verbeteren van het binnenklimaat, gebaseerd op de lucht-, temperatuur-, geluids-, en lichtparameters van een hybride werk- en leef thuiswerk situatie voor de inzittende(n), terwijl er ook gebruikt wordt gemaakt van terugkoppelingen door de inzittende(n)?."*

Om een antwoord te geven op deze onderzoeksvraag is een methodologische benadering opgesteld gebaseerd op een literatuur onderzoek. Binnen deze benadering zijn de huidige statussen van de BK prameters, Linked data en Digital Twins gecombineerd. Naast deze methodologische benadering is een applicatie ontwikkeld die gebruikt wordt in een bewijs van concept gebruikscasus. Het doel van deze applicatie is om de inzittende inzicht te geven in hun BK informatie, en hierbij de mogelijk te bieden voor input wat geïntegreerd wordt. Een back-end zal deze input en de meetdata combineren en een passende prompt aanbieden.

De BK parameters drempelwaarden zijn gebaseerd op de waarden gevonden in de literatuur, en zijn daarna verbonden aan een activiteitsniveau die de drempelwaarden groepeert gebaseerd op vergelijkbare voorwaarden. Om deze BK metingen te verkrijgen is een combinatie van verschillende individuele BK parameter sensoren geplaats op locatie. Hun resultaten zijn hierna gecombineerd en opgeslagen in een relationele databank op een beveiligde server locatie op de TU/e. Een Python script zal de benodigde waardes opvragen via de linked data DT, vanuit de relationele databank. Extra benodigde informatie is direct opgevraagd uit het linked data model. Deze meetingswaarden worden hierna vergeleken met de drempelwaarden en de huidige taak. Verder wordt ook de directe input (i.e. promptreacties, huidige taak, en huidige discomfort) van de inzittende vergeleken. Deze worden via de gebruikersomgeving getoond aan de inzettende, gebaseerd op een rangorde.

Deze applicatie is geplaats in een test omgeving genaamd OpenFamilyHome (open familie huis), wat functioneert als de test casus van deze studie. Over een tijdsperiode van vijf dagen zullen twee inzittenden hun thuiswerk taken verrichten samen met het leveren van input met betrekking tot hun BK. De applicatie zal gebaseerd op de input informatie verschaffen in de vorm van: BK informatie, een verzoek tot actie (e.g. open een raam), of een vraag uit een vooropgestelde vragenlijst. Deze informatie wordt gebruikt m de huidige comfort van de inzittende te bepalen. Na deze vijf dagen zal de data worden geanalyseerd en vergeleken met de huidige literatuur. De resultaten zullen worden geëvalueerd vanuit een BK perspectief en een DT perspectief. De cases betrek zowel een hybride thuiswerk situatie (woonkamer) als één met een thuis kantoor (slaapkamer).

Dit onderzoek toont aan dat voor temperatuur en geluidsniveau, met respect tot het BK van een thuiswerk situatie, geen impactvolle metingen zijn aangetroffen wanneer deze vergeleken worden met de literatuur. Deze waardes zouden niet mogen leiden tot discomfort. Echter is dit voor temperatuur wel het geval, aangezien deze voornamelijk neutrale of negatieve waarden vindt binnen de directe input data. Zelfs wanneer deze binnen de gestelde marges valt. Hiernaast heeft de inzittende veel zeggenschap over deze waarde, aangezien inzittende in staat is om de thermostaat aan te passen of de kleding isolatie waarde te verander naar wens. De andere parameter waarden zijn erger vanuit een meetings perspectief. Voor licht intensiteit, CO2, luchtkwaliteit en luchtvochtigheid is het merendeel van de meeting buiten de gestelde grenswaarden. Dit is terug te zien in de discomfort input waar 40% van de reacties aangeeft dat het of te licht of te donker is, 22% aangeeft dat de luchtkwaliteit afwijkt, en 25% aangeeft dat de luchtvochtigheid afwijkt. Van deze set is licht intensiteit verreweg de slechts presterende in de woonkamer, terwijl alle andere het slechts presteerde in de slaapkamer (wat hint op een relatie tussen de kwaliteit en de kamergrote).

De linked data gebaseerde DT presteerde zoals verwacht. De benodigde informatie was goed aangeleverd via SPARQL en is naar wens geïntegreerd in de Python omgeving als variabelen. Deze konden dan worden gebruikt om de benodigde data op te vragen door middel van SQL uit de relationele databank zodat de meetdata kan worden gebruikt. Deze meetdata werd goed geïntegreerd in de applicatie. Wat ervoor zorgde dat de applicatie in staat was om prompts aan te leveren. Dit laat zien dat de hybride werkwijze van Tang et al. (2019), bruikbaar is als een Digital Twin format. De huidige werkwijze maakt het mogelijk verdere uitbreidingen toe te voegen aan de applicatie in de vorm van nieuwe RDF-triples. Wat aangeeft dat deze oplossing toepasbaar is als oplossing voor het BK en thuiswerken probleem.

Verder is er in dit onderzoek nog een discussie en een conclusie, die inzicht bieden in het wetenschappelijke-, maatschappelijke belang en de toekomstige onderzoeksmogelijkheden

## Abstract

This research aims to explore the possibility of using linked data-based Digital Twins for the Indoor Environmental Quality (IEQ). This is achieved through a proof-of-concept (PoC) case set in a working from home (WFH) environment. The IEQ is made measurable by using the IEQ parameters: temperature, humidity, light intensity, sound pressure level, and indoor air quality (IAQ) level. The emphasis of this PoC is placed on the individual's comfort as objective, with the integration of personal preference. Since the IEQ of a WFH environment is currently designed to facilitate leisure tasks, this now pressures the at-home environment to conform to both the needs of leisure and work tasks. This use was never the aim of the at-home environment and thus poses challenges aligned with the required shift of working from office (WFO) to WFH. A hybrid linked data and relational database approach have been used to facilitate the Digital Twin. Attached to this Digital Twin an application has been made in order to communicate with the occupants. This application provides the occupants with IEQ information or request prompts and receives direct input about their current discomfort, current tasks, and daily parameters. Combining measurement and direct input, which are then linked to a task activity level. The result is a response to help the occupants better their IEQ. To test this approach a case study has been done, spanning five days and covering two rooms. These are a hybrid leisure and work environment (living room), and a dedicated work environment (a bedroom converted into an at-home office). These results have thereafter been analyzed providing insights about IEQ in a WFH environment and the applicability of linked data-based Digital Twins, resulting in a proof-of-concept.


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Keywords: Indoor Environmental Quality, Linked data, Digital Twin, User feedback integration, Sensor Data

# Abbreviations

| | |
|---|---|
| ACL | Access Control Lists |
| ACM | Adaptive Comfort Model |
| API | Application Programming Interface |
| BIM | Building Information Management |
| BOP | Building Performance Ontology |
| BOT | Building Topology Ontology |
| CAD | Computer-Aided Design |
| CWA | Closed World Assumption |
| DB | Database |
| DBMS | Database Management System |
| DT | Digital Twin |
| FM | Facility Management |
| FOI | Feature Of Interest |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IAQ | Indoor Air Quality |
| IEQ | Indoor Environmental Quality |
| IFC | Industry Foundation Classes |
| IoT | Internet of Things |
| IRI | Internationalized Resource Identifier |
| LBD | Linked Building Data |
| LBDC | Linked Building Data Community |
| LoD | Level of Detail |
| OWA | Open World Assumption |
| OWL | Web Ontology Language |
| PMV | Predicted Mean Vote |
| PPD | Predicted Percentage of Dissatisfied |
| POE | Post Occupancy Evaluation |
| RDF | Resource Description Framework |
| RDFS | Resource Description Framework Schema |
| SBS | Sick Building syndrome |
| SHACL | Shapes Constrained Languages |
| SPARQL | SPARQL Protocol and RDF Query Language |
| SQL | Structured Query Language |
| Turtle | Terse RDF Triple Language |
| UI | User Interface |
| UID | Unique Identifier |
| UIR | Uniform Resource Identifier |
| URL | Uniform Resource Locator |
| WAC | Web Access Control |
| WFH | Working from home |
| WFO | Working from office |

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# Chapter 1. Introduction

*This chapter will elaborate on the background of the research (covering the societal and scientific importance of the research), provide a problem definition. State the main and sub-questions. Finally, the chapter ends with a reading guide for the thesis.*

## 1.1 Background

Over the past decades, technological advancement has pushed the (re)development of buildings from an energy- and technological perspective resulting in the creation of energetically and sustainably improved housing. The effects of this chance on individual health and well-being are less understood. An important benefactor to human wellbeing and physical comfort is the Indoor Environmental Quality (IEQ), which has a proven relationship with different detrimental health effects, such as those associated with sick building syndrome (SBS) and other negative health- and work-related effects such as respiratory illness and productivity loss (Seppänen & Fisk, 2006).

According to the US Bureau of Labor Statistics (BLS), people spend 90% of their time in a "closed" indoor environment, (Park et al., 2018). During this time people are prone to detrimental health effects originating in poor indoor environments. On a societal basis, this will result in a higher need for healthcare and an overall lower stage of average wellbeing. When taking into account that according to the World Health Organization (WHO), over two-thirds of the human population will be living in urban areas at the start of 2050 (a 10% increase in the coming thirty years), which means that the number of people exposed to these situations will only increase (WHO, 2019). Long-term diseases and lowered quality of life will be the result if the (re)development of building within the built environment will continue to focus on the energetical parts but neglects health. So the upcoming challenges regarding urbanization can also be an opportunity, where a more balanced approach will drive the built environment to not only a more sustainable, but also a more healthy future (Craft et al., 2017).

Therefore IEQ has become an increasingly interesting topic of research (Seppänen & Fisk, 2006; Park et al., 2018). Primarily six different indoor environmental quality indicators are relevant: Indoor Air Quality, Thermal comfort, Lightning (sunlight, daylight, and artificial light), Sound, View- and Spatial quality (Wang et al., 2021). These are measured by different variables and together contribute to the health and comfort of a user. Besides the physical health, there is also the mental health of the user originating from discomfort and the formation of stress. From a cognitive perception (*The ability to execute a task with different levels of difficulty which are part of the brain-based skillset known as cognitive functions*) this becomes increasingly important over time (Wang et al, 2020). Current research is mainly focused on the effects of IEQ in work-dedicated spaces, such as offices, or a dedicated work environment (Guo and Chen, 2020). However, access to a dedicated work environment when working from home is often not the case resulting in different levels of comfort which are experienced by the occupants due to an uncontrolled IEQ in their hybrid work and living space (Guo and Chen, 2020). The uncontrolled environment increases the experience of sick building syndrome, and subjects the occupant to a potential inhospitable work environment (Guo and Chen, 2020; Malmqvist, 2008; Aigbavboa et al., 2018).

This transition, of going from a work-dedicated environment to a hybrid environment, is accelerated due to the Covid-19 crisis where many employees are forcefully working in a working from home arrangement (Kramer & Kramer, 2020). Research has shown that there is a shift in workdays that are spent on the office location, and those that are spent in the at-home location, with a WFH to WFO split of 2 to 3 days, with 2 being the preferred mean (Tokumura et al., 2021). The split is dependent on leveraging the ability of the employee to do its tasks from a hybrid environment where both work and living activities are fulfilled. What in turn results in new challenges for the IEQ of both work- and living environments based on the individual's needs (Kramer & Kramer, 2020). The challenge being the balancing of the user's work- and living environment IEQ parameters.

New technologies allow the built environment to cope with upcoming challenges in a better way than before. At the moment, one of the most noticeable technologies is Digital Twin, which is a dynamic digital representation of real-world objects, processes, or systems that uses both historic and real-time data to allow for the predictive modeling, as-if modeling, visualization, data-bundling, and linkage (Dembski et al., 2020; Bolton et al., 2018). A Digital Twin is characterized by a bi-directional flow between the physical world and the Digital Twin, looping information, which can be linked to different applications and algorithms that make use of the semantic data integrated into the model (Lu et al., 2019; lu et al., 2020; Boje et al., 2020). Such a Digital Twin model collects information from sensors, databases, or other IoT (Internet of Things) tools, and will leverage the advantages of machine learning-, artificial intelligence- and analytical techniques to obtain and provide real-time insights with different purposes regarding physical assets (Vivi et al., 2019).

While the Digital Twin philosophy originated from aero-studies, it is more than applicable in the built environment. Currently, BIM (Building Information Management) and BMS (Building Management Systems) technologies are more embedded in the built environment (Tang et al., 2019) compared to Digital Twin technologies (Boje et al., 2020). BIM is a practice where information is transferred from one phase of the design and construction process to the next. Often during these handovers information is lost, as many use reference models in order to control and communicate information (Pauwels et al., 2017). BIM aims to use standardized computer-aided design philosophies and processes to generate and maintain information from start design to end-of-life. BMS is a controlling system to manage a building's internal systems. Digital Twins can use the BIM historic and as-is information, combined with the measurements and status information of the BMS system to create a representation of a building in a digital environment, which shows more potential, and goes beyond the initial standalone BIM and BMS usage (Pauwels et al., 2017; Boje et al., 2020). The increased benefit of Digital Twins would be the transition of singular information models to a semantic web of different sources, which allows for more complex and flexible data linkage and a more interoperable, domain crossing, and logical system (Pauwels et al., 2017). However such technologies still encounter challenges, specifically between systems, data management, storage, and standardization (Tang et al., 2019).

These technologies could aid the process of the management- and monitoring of buildings resulting in improvements, including in the IEQ management (Wang et al., 2021). Their implementation is, however, not without challenges. The management and monitoring of IEQ parameters are work-intensive and financially expensive (Adeleke & Moodley, 2015).

Furthermore, there is not a direct linear relationship between user satisfaction & perceived comfort, and the objective automated control of IEQ-parameters (Kim & De Dear 2012; Kwon et al., 2019). This lack of a direct linear relationship results in a mismatch between machine-operated solutions and the perceived benefits of the occupant (Salamone et al., 2018). To better understand the effects of the measured IEQ and the perceived IEQ a study is needed that looks into the connection between the technologic advancements and user feedback from a working from home setting, with a focus on a hybrid work and living environment.

To conclude, the shift from WFO (working from office) to WFH (working from home) poses challenges as occupants make use of environments designed for leisure activities as work environments. The occupants are then prone to a poor IEQ, and all negative consequences thereof. As it is predicted that this will become increasingly more common, a solution is needed. With the increased adoption of IoT (Internet of Things) technologies, linked data becomes a more valuable solution. Therefore a linked data-based Digital Twin could be a potential solution to the problem. A lack of research on the use of the Digital Twins in a WFH environment requires additional insight into the potential uses cases, as well as, a proof-of-concept.

## 1.2 Problem statement

An increasing amount of the working population is exposed to poor IEQ WFH environments, as this was never the intentional use of the occupied space. As individuals are increasing their time spend WFH, additional research is required in order to protect these individuals. The increase in affordability of sensor technologies and the availabilities of IoT technologies allows for better and more precise data measurement in a WFH environment. This with the rise in popularity of Digital Twin technologies and linked data results in the need for additional insight into the useability and applicability of these technologies. Opportunities are found in the understanding of measurable IEQ- parameters (Indoor Air Quality, Thermal comfort, Lightning, and Sound) combined with user feedback, as a potential use-case of these technologies. More understanding of the IEQ parameters is required, as to how these can be translated to a WFH situation to increase the wellbeing of the occupants. As there is little understanding of the certainty of how these hybrid WFO and WFH workweeks are going to be formalized a more general approach is needed. This results in the following main research question:

*How can a linked data-based Digital Twin model be used to improve the Indoor Environmental Quality (IEQ), based on air-, temperature-, noise- and light parameters, of an at-home situated hybrid working- and living environment of the occupant(s), while also accounting for occupant(s) feedback?*

To answer this research question the following sub-questions have been formulated:

1. How are the IEQ paraments derived and made measurable according to the literature, for both dedicated work environments and hybrid environments?
2. How is the occupant's experience of the IEQ parameters derived and made measurable according to the literature, for both dedicated work environments and hybrid environments?

3. What are the effects of the IEQ parameters on occupant comfort, and what is the effectual difference between a dedicated work environment and a hybrid environment?
4. How and what should the user communicate with the Digital Twin and vice versa?
5. What would be a suitable interface for user interaction and how can this dashboard provide suggestions based on the measurements?
6. For the Digital Twin and the selected use case, what system architecture is needed and how would this be implemented?
7. How is the model able to communicate the measurement information and suggestions with the user, in order to improve the IEQ of the occupant?
8. What are the benefits of linked data-based Digital Twins within a WFH situation, and how is this approach made scalable?

Sub-question one to six will be answered using current literature and will feed into the methodological design of the proof-of-concept case used to answer sub-question 7 and 8. Through answering these main and sub-questions this research aims to provide insights into the use-case of linked data-based Digital Twins in order to benefit the IEQ of a WFH environment. With the goal of providing occupants with a better IEQ, to support a healthier work environment.

## 1.3 Outline

This research is structured in such a way that one gains increasing insights into how IEQ parameters are handled, and how a linked data-based Digital Twin can be used. It maintains the structure of first stating any information about the IEQ parameters, before explaining the implementation thereof. Figure 1 provides a visual overview, where every chapter is represented by its corresponding number. Chapter 2 provides insight into the current standing of IEQ parameter measurement, the interactions between IEQ parameters and occupant comfort, and how this can be translated into a measurable method for WFH. Additionally, it provides an overview of the current standings of Digital Twins, linked data, and their use in the built environment, as well as, providing insights into the requirements of how a system should communicate the IEQ with the occupants. Chapter 3 provides an overview of the methodological design and how tasks can be represented comparatively to their corresponding IEQ requirements. Additionally, an overview of the application's architecture is provided. Chapter 4 provides an overview of how all available sources are prepared for the use-case and provides case-specific information used during the research. Then this chapter will go into the results of a measurement period of five days in a WFH environment. Chapter 5 reflects on the results and the application. Chapter 6 will reflect on this research, its relevance, and future research.

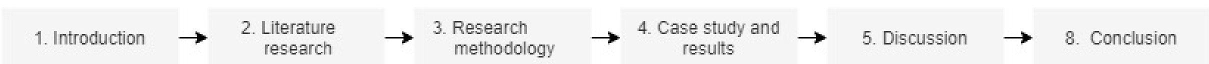


*Figure 1 Research visualization outline*

# Chapter 2. Literature review

*Through this literature review sub-questions, one to six will be answered. The study is divided into two sections. Section one is about IEQ parameters and will cover sub-questions one to three. Section two is about linked data and Digital Twins and will cover sub-questions four to six. First, the Indoor Environmental quality will be elaborated, which will then go into more depth with the sub-chapters each providing information about a parameter group. Then Digital Twin, linked data and their integration will be elaborated, with each subchapter providing additional information about the individual parts and how they connect.*

## 2.1 Indoor environmental quality of the work environment

The connection between workplace IEQ and an individual's comfort has been the subject of a large number of researches, many with different angles and focus points (e.g. health, productivity, learning, work performance, task completion, stress) (Seppänen & Fisk, 2006; Park et al., 2018; Wang et al., 2021). It is safe to state that a significant effect on occupant satisfaction can be derived from the influences of IEQ (Geng et al., 2017). The following subchapters will provide an overview of the current standing within the literature, how IEQ parameters are measured with an emphasis on occupant comfort, what additional influences are originating from an individual, and how this can be generalized into a method to apply this to a working from home situation.

### 2.1.1 IEQ parameter comfort

Indoor environmental quality (IEQ) is the conditional microclimate inside an indoor environment (e.g. a building, room, etc.), and covers six primary IEQ-parameters (i.e. thermal, air quality, visual (lighting and visual environment), acoustics, and spatial quality), where the primary measurable discomfort IEQ-paraments cover temperature, humidity, air quality, light intensity and noise (Sarbu & Sebarchievice, 2013; Park et al., 2018; Wang et al., 2020; Wang et al., 2021). To research, the effects of the IEQ on occupants two primary research methods are proposed in the literature. The first is a climate-controlled room, where parameter values are shifted to measure response. The second is field research, without any controlling parameters, and instead of measuring as-is situations (Geng et al., 2017). A WFH environment is never a controlled environment, making the second the preferred method of research for this study. The current most common method used to understand IEQ comfort during field research is via post-occupancy evaluation (POE), where point in time (PIT) measurement values are connected to subjective input (Geng et al., 2017; Park et al., 2018). Multiple studies have shown the ability to combine POE with building data to enhance occupant comfort and satisfaction (Bortolini & Forcada, 2021). This relation is further underpinned by a study done by Guo & Chen (2020), who evaluated occupant comfort and its relation to health in an indoor working environment. Overall the emphasis of these studies is on combining a POE in the form of a survey with a collection of measurements. A complete overview of relevant studies has been provided in table 1. This table covers both working from home (WFH) and working from office (WFO) related studies to show how these studies have a similar approach for IEQ. For a WFH situation, most studies originate from 2019 and onward, showing the influence of the Covid-19 crisis on academic research.

*Table 1 Overview of concepts and variables in current research on IEQ*

| | *Author* | Bae et al. | Geng et al. | Kang et al. | Antoniadou et al. | Herrera et al. | Lee et al. | Aigbavboa et al. | Che et al. | Andargie et al. | Altomonte et al. | Devitofranceso et al. | Finell & Nätti | Gou & Chen | Bellia et al. | Xiao et al. | Cuerdo-Vilches et al. | Tokumura et al. | Torresin et al. | Awada et al. | Wang et al. | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Year* | 2017 | 2017 | 2017 | 2017 | 2018 | 2018 | 2018 | 2019 | 2019 | 2019 | 2019 | 2019 | 2020 | 2021 | 2021 | 2021 | 2021 | 2021 | 2021 | 2021 | |
| | **Method** | | | | | | | | | | | | | | | | | | | | | |
| | Survey results | X | | X | | X | X | X | | | X | | | X | | X | X | X | X | | | 11 |
| | Sensor measurement | | X | | | X | X | | X | | X | X | | | | | | | | | | 6 |
| | **Focus of study** | | | | | | | | | | | | | | | | | | | | | |
| | Office Environment | X | X | X | X | X | X | X | X | X | X | X | X | | X | | | X | | | X | 15 |
| | Working from Home | | | | | | | | | X | | | | X | | X | X | X | X | X | | 7 |
| | Hybrid OE and WFH | | | | | | | | | | | | | | | | | X | | | | 1 |
| | **Focus of result** | | | | | | | | | | | | | | | | | | | | | |
| | Comfort | | | | X | X | | | X | X | | | | X | X | | | | X | | X | 8 |
| | Productivity | | X | X | | | | | | | X | | | | | | X | X | | | X | 6 |
| | Satisfaction | X | X | | | | | | | | X | | | | X | X | | X | | | | 6 |
| | Cognitive functioning | | X | | | | | | | | | | | | | | | | | | X | 2 |
| | (Mental) health | | | | | | | X | | | X | X | X | | | X | | | X | X | X | 8 |
| | Well-being | X | X | | | | | X | | | X | X | | | | X | | | | X | | 7 |
| | **IEQ Parameters and influencers** | | | | | | | | | | | | | | | | | | | | | |
| **Thermal comfort** | Room temperature | X | | | X | | X | | | X | | X | | X | X | X | X | X | | X | X | 12 |
| | Ability to control the temperature | X | | | | | X | | | X | | | | X | | | | | | | | 4 |
| | Air temperature | | X | | X | | | | | | | X | | | | | | | | | X | 4 |
| | Airspeed | | | | X | | X | | | X | | X | | | | | | | | | X | 5 |
| | Humidity | | X | | X | X | | | | | | | | | | | | | | | | 3 |
| | Humidity levels | | | | X | | | | | X | | X | | X | X | X | | X | | X | X | 9 |
| | Ability to control humidity | X | | | | | | | | X | | | | X | | | | | | | | 3 |
| **Visual comfort** | **Lighting** | | | | | | | | | | | | | | | | | | | | | |
| | Light intensity | X | X | X | X | X | X | | | X | X | X | | X | X | X | X | X | | X | X | 16 |
| | Artificial Lighting | X | | X | | | X | | | X | X | X | | X | X | X | X | | | X | X | 12 |
| | Ability to turn on/off lighting sources | X | | | | | X | | | X | X | | | X | | | | | | | | 4 |
| | Ability to adjust brightness of lighting sources | X | | | | | X | | | | X | | | X | | | | | | | | 4 |
| | Natural Lighting | X | | X | | | X | | | X | X | X | | X | X | X | X | | | X | X | 12 |
| | Ability to control natural lighting | X | | | | | X | | | X | X | | | X | | | X | | | | | 5 |
| | Availability of sun (direct) and daylight (indirect) | X | | X | | | X | | | | X | X | | X | | X | | | | X | X | 9 |
| | Glare level | | | | | | | X | | | | X | | X | | X | X | | | X | | 6 |
| | Color spectrum | | | | X | | | | | | | | | | X | | | | | | | 2 |
| | **Non-lighting** | | | | | | | | | | | | | | | | | | | | | |
| | Outside view | | | | | | | | | X | X | | | X | | | X | | X | | | 5 |
| | Area of space | | | | | | | | | | | | | X | | | X | | X | X | X | 5 |
| | Layout of space | | | | | | | | | | | | | X | | | | | | X | X | 3 |
| | Material texture | X | | | | | | | | | | | | | | | X | | | | X | 3 |
| | Material color | | | | | | | | | | | | | X | | | | | | | X | 2 |
| | Furniture texture | X | | | | | | | | | | | | | | | X | | | | X | 3 |
| | Furniture color | X | | | | | | | | | | | | X | | | | | | | X | 3 |
| | Furniture type (active or inactive) | | | | | | | | | | | | | | | | | | | X | | 1 |
| | Level of tidiness | X | | | | | | X | | | X | | | X | | | X | | | X | | 6 |
| | Level of maintenance | | | | | | | | | | | | | X | | | | | | | | 1 |
| | Availability to green (biophilic) | | | | | | X | | | | | | | | | | X | | | X | X | 4 |
| | Level of visual privacy | X | | | | | | | | X | | | | | | | | | | | | 2 |
| **IAQ comfort** | **Mechanical ventilation** | | | | | | | | | | | | | | | | | | | | | |
| | Level of mechanical ventilation | | | | | | | | X | X | X | X | | X | | X | X | | | X | X | 9 |
| | Ability to control mechanical ventilation | X | | | | | | | | X | X | | | X | | | | | | | | 4 |
| | **Natural ventilation** | | | | | | | | | | | | | | | | | | | | | |
| | Level of natural ventilation | | | | | | | | X | X | X | | | X | | | X | | | X | X | 7 |
| | Ability to control natural ventilation | X | | | | | | | | X | X | | | X | | | | | | | | 4 |
| | **Air Pollution** | | | | | | | | | | | | | | | | | | | | | |
| | Air pollution emission levels | | | | | | | | X | X | | | | X | | | X | | | X | X | 6 |
| | Ability to control air pollution emission | X | | | | | | | | | X | | | X | | | | | | | | 3 |
| | CO2 concentration level | | X | | X | X | X | | X | | X | | | | | | | X | | | | 7 |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Particle matter and dust intensity | | | | | | | | X | | X | | | | | | | | | | | | 2 |
| | **Air Freshness** | | | | | | | | | | | | | | | | | | | | | | |
| | Air freshness level | | | | | | | | X | | X | | | X | | | | | | | | | 3 |
| | Ability to control air freshness | X | | | | | | | | | X | | | X | | | | | | | | | 3 |
| | Air filtration level | | | | | | | | | | | | | | | | | | | | X | | 1 |
| | Smoke (tobacco) | | | | | | | X | | | X | | | | | | | | | | | | 2 |
| **Acoustic comfort** | Noise | X | | | | | X | | | X | X | X | | X | | X | X | X | X | X | X | | 12 |
| | (Air)traffic | | | | | | | | | | | | | | | | | | X | | X | | 2 |
| | Speech | | | | | | | | | | | X | | | | | | | X | | X | | 3 |
| | Public | | | | | | | | | | | | | | | | | | X | | X | | 2 |
| | Machinery | | | | | | | | | | | X | | | | | | | X | | X | | 3 |
| | Equipment | | | | | | | | | | | | | | | | | | X | | X | | 2 |
| | (Own) background music or TV | | | | | | | | | | | | | | | | | | X | | | | 1 |
| | Natural | | | | | | | | | | | | | | | | | | X | | | | 1 |
| | Reverberation | | | | | | | | | | | X | | | | | | | | | | | 1 |
| | Ability to control noise | X | | | | | | | | X | X | | | X | | | | | | | | | 4 |
| | Level of acoustic privacy | | | | | | | | | X | | | | | | | | | | | | | 1 |
| **EM** | Power frequency magnetic fields | | | | | | | | | | | X | | | | | | | | | | | 1 |
| | Radiofrequency and Microwave electromagnetic fields | | | | | | | | | | | X | | | | | | | | | | | 1 |
| **Work-related** | Type of work | | | | X | | | | | | | | | X | | | | | | | | | 2 |
| | Workload | | | | | | | | | | | | X | X | | | | | | | | | 2 |
| | Work schedule | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Company/institution policy | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Online platform | | | | | | | | | | | | | X | | | | | | | | | 1 |
| **Influencers of personal perception of work** | **Communication factors** | | | | | | | | | | | | | | | | | | | | | | |
| | In-person communication | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Online communication | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | **Personal- and work environment factors** | | | | | | | | | | | | | | | | | | | | | | |
| | Team working atmosphere | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Peer pressure | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Commuting time | | | | | | | | | | | | | | | | | X | | | | | 1 |
| | Interest in work | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Interruption by other people | | | | | | | | | | | | | X | | | X | | X | | | | 3 |
| | Relationship with partners | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Electronic facility | | | | | | | | | | | | | X | | | X | | | | | | 2 |
| | Ergonomic facility | | | | | | | | | | | | | | | | X | | | X | | | 2 |
| | Nourishment type | | | | | | | | | | | | | | | | | | | X | | | 1 |
| | Privacy preference | | | | | | | | | | | | | X | | | X | | | | | | 2 |
| | Clothing preference | | | | | | | | | X | | | | X | | | | | | | | | 2 |
| | Presence of children and young adults | | | | | | | | | | | | | | | | X | | | | | | 1 |
| **Personal influencers** | **Biological influencers** | | | | | | | | | | | | | | | | | | | | | | |
| | Age | | | X | | X | | | | | | | X | | | X | X | | | | | | 6 |
| | Sex | | X | X | | X | | | | | | | X | | | X | | | | | | | 6 |
| | Biorhythm | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Metabolism | | | | X | | | | | X | | | | | | | | | | | | | 2 |
| | Physical well-being | | | | X | | | | | | | | | X | | | | | | | | X | 3 |
| | Adaption rate | | | | X | | | | | X | | | | | | | | | | | | X | 3 |
| | **Psychological factors** | | | | | | | | | | | | | | | | | | | | | | |
| | Mental health | | | | | | | | | | | | | X | | | | | X | | | X | 3 |
| | Work stress | | | | | | | | | | | | | X | | | | | X | | | X | 3 |
| | Emotional health | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Self-regulation | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Self-efficacy | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Personal relationships | | | | | | | | | | | | | X | | | | | | | | | 1 |
| | Work-life balance | | | | | | | | | | | | | X | | | | | | | | | 1 |

Table 1 provides more insight into the current standing of the literature and shows that besides a pure IEQ measurement approach other aspects should be taken into consideration (i.e. direct work-related influencers, indirect personal perception on work, and personal influencers). From the IEQ perspective, a clear separation is made between sensor measurable IEQ parameters and survey input IEQ parameters. Most studies show a tendency towards the more general sensor-based measurement parameters (i.e. thermal (via temperature and humidity), visual (via light intensity), acoustic (via sound pressure intensity), and IAQ (via particle concentrations)). From a health perspective most direct relations are present in the combination between IEQ measurement values and personal influencers, most commonly age and sex (Herrera et al., 2018; Finell & Nätti, 2019; Guo & Chen, 2020; Awada et al., 2021; Wang et al., 2021). However, studies with a focus on WFH have an increased emphasis on work-related factors, personal perception of work, and personal health (Guo & Chen, 2020; Xiao et al., 2021; Cuerdo-Vilches et al., 2021; Tokumura et al., 2021; Torresin et al., 2021; Awada et al., 2021). Studies that mention detrimental health effects of a poor IEQ are most commonly directly associated with sick building syndrome (SBS). However, there are studies where an increased emphasis has been placed on mental health and well-being as well (Guo & Chen, 2020; Awada et al., 2021; Wang et al., 2021). Additionally, there is a psychological influence originating from the feeling of control which accumulates into less experienced IEQ discomfort when available (Guo & Chen, 2020; Tokumura et al., 2021). It is, however, hard to quantify the relations of IEQ parameters, as they are interdependent, and the influence of cognitive functioning, mental health, and personal perceived wellbeing, are still not completely understood. Furthermore, the influences of stress originating outside of the influences of IEQ still highly influence the perception of IEQ (Guo & Chen, 2020; Wang et al., 2021). Resulting in a highly personal perception of IEQ, that easily shifts depending on interaction with the occupant by outside sources and influencers. As these outside sources are hard to account for when measuring sensor data or requesting PIT survey results a more personal approach is required (Wang et al., 2021).

The keywords present in much of the studies in table 1 are focused on personal comfort (preference, perception, and satisfaction), personal well-being (stress, sleep quality, (mental) health, enjoyment, and workload), and work activity ( productivity, task completion, activity levels, and work efficiency). Additionally, there are biological influencers mentioned (biorhythm, metabolism, sex, age, adaption rate, and physical well-being (e.g. sickness and menstruation cycle)), which all together create a complex web of interdependencies. The aim of the studies is not to make these interdependencies measurable, but rather focus on the result of working towards a higher feeling of comfort and well-being. This in turn translates to an increased work satisfaction and task completion rate (Gou & Chen, 2020; Awada et al., 2021). Overall to determine the quality of the IEQ for the individual the most commonly used method is perceived occupant comfort (Krekel et al., 2019; Frontczak & Wargocki, 2011). However, the current efforts to quantify comfort as a measurable standard have been lacking (Herrera et al., 2018). Most definitions of perceived IEQ parameter comfort come down to the same inherent meaning, which is captured by Frontczak & Wargocki (2011) as seen in table 2. Figure 2 represents the connections of influencing factors and perceived IEQ parameter comfort based on the literature mentioned in table 1.

*Table 2 Definitions of perceived IEQ parameter comfort (Frontczak & Wargocki, 2011)*

| Concept | Definition |
|---|---|
| Thermal comfort | The condition of mind that expresses satisfaction with the thermal environment. |
| Visual comfort | A subjective condition of visual well-being induced by the visual environment. |
| Acoustic comfort | A state of contentment with acoustic conditions. |
| Air quality | Air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction. |

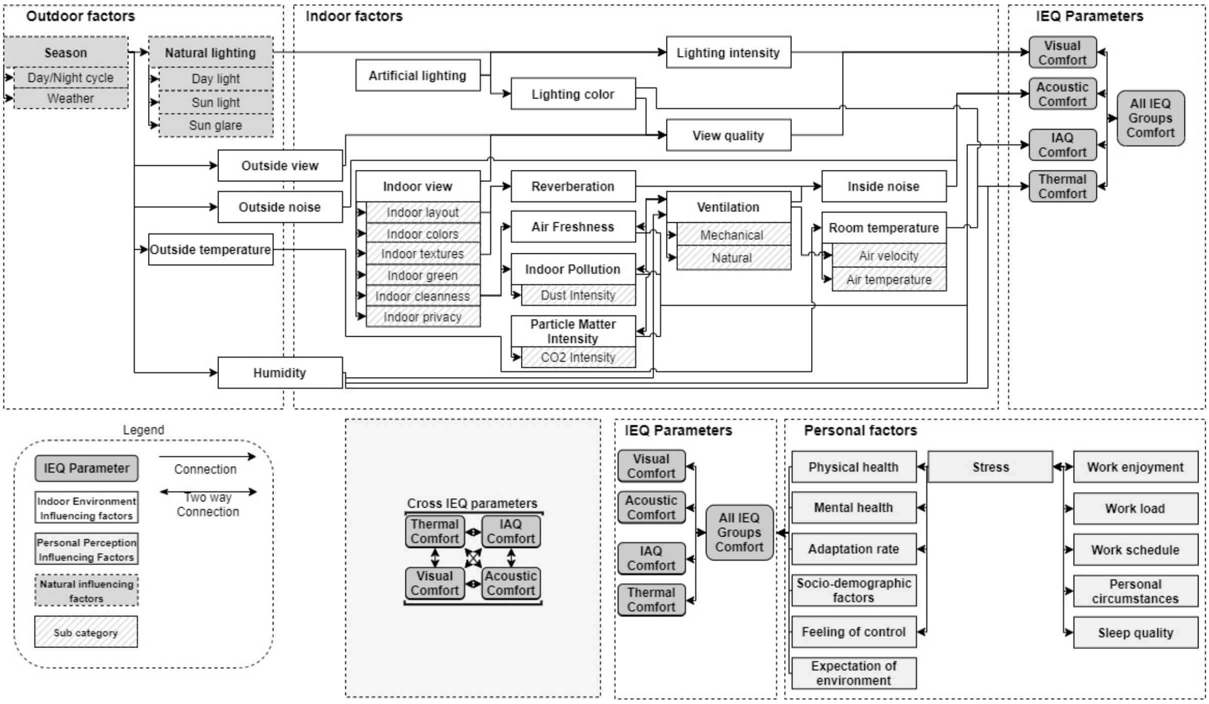


*Figure 2 Influencing factors on perceived IEQ comfort*

To conclude, there are many different factors influencing IEQ parameter comfort. The most prominently are separated into work-related and individual-related (grouped as personal factors), and senor measurable and survey input-based IEQ parameters (grouped in outdoor factors and indoor factors). It is shown that there is an interdependent relation of IEQ parameters on other IEQ parameters. Especially when the occupant already experiences discomfort with another IEQ parameter (Jayathissa et al., 2020). The next paragraphs will elaborate more in-depth on the most often studied IEQ parameters (i.e. thermal, visual, acoustic, and IAQ), and their most common measurement methods to achieve perceived occupant comfort.

## 2.1.1.1 Thermal comfort

Thermal comfort is expressed in the form of being satisfied, as an individual, based on the thermal environment (Frontczak & Wargocki, 2011). This expression is highly personal and subjective to influencing factors outside of the realm of the thermal environment. According to the ANSI/ASHRAE standard 55, the primary influencers are metabolism, activity level, clothing, air temperature, mean radiant temperature, airspeed, and relative humidity. Other influences are psychological in nature (Wang et al., 2021). This personal expression of perceived thermal comfort is both present in the Dutch regulated national standard (Dutch European Standard, 2005) and the US standards (American National Standard Institute, 2017; American National Standard Institute, 2020)

Overall are there two types of thermal comfort assessments. Objective-subjective and objective-criteria assessments. The first tries to combine measurement data with subjective input, the latter compares measurement data with performance measurement protocols. Where for occupant IEQ parameter comfort the objective-subjective assessment results in the most reliable outcomes. However, both show drawbacks to predicting IEQ parameter comfort correctly (Jayathissa et al., 2020).

*Table 3 Overview of studies explaining thermal comfort measurement methods*

| Measurement method | Threshold values in °C | Source |
|---|---|---|
| PMV, with a 7 scale criteria (thermal sensation). Starting from a threshold-based comfort range. Adjusting for grouped comfort with a maximum 5% dissatisfaction rate. | 18 – 24 (*average of 21*). The result of the study average dropped to 19. With a mean comfort vote of 20,4. | Ormandy & Ezratty, (2011) |
| PMV, with a 7 scale criteria (thermal sensation and satisfaction level). Individuals were informed of the temperature at the start test. Comparative PMV prediction model versus actual results. | 16 – 28 (*average of 22*). The result of the study average jumped to 24. With the highest satisfaction around 25. | Geng et al., (2017) |
| Sensor measurement (near body and environment), heart rate (individual), time (cycle habits), room (comfort profile), and preference history. | - | Jayathissa et al., (2020) |
| 5 scale subjective questionnaire (thermal discomfort) accounting for adaption, and task completion. Compared directly with relative humidity (RH) levels. All are compared to a theoretical PMV. | 18 – 24 (*Average of 21*). The results of study 24 are better paired with 40% RH. Deviation from the average should max 3 in any direction. | Liu et al., (2021) |
| PMV, with a 7 scale criteria (thermal sensation). Adjusting for grouped comfort with a maximum 5% dissatisfaction rate. | - | Antoniadou & Papadopoulos, (2017) |
| PMV, with a 7 scale criteria (thermal sensation). Compared together with lighting color. | Average of 20. Results show a perceived difference of 1,7 when working with colored lighting in both directions (cool and warm). | Bellia et al., (2021) |
| Comparing multiple studies, based on popular topics and cross-reference the results. Use of computerized tests to test cognitive functioning. Comfort originates from PMV. | Average of 24. Results show the best memory performance range of 22 – 26, while attention and reaction are shown to be optimal at 26. | Wang et al., (2021) |

Table 3 provides an overview of selected studies that explain their method of accounting for thermal comfort. Overall two approaches are most commonly used. The predicted mean vote (PMV), and the adaptive comfort model (ACM) (in general, the PMV is more dominant in a research capacity) (Halawa & Hoof, 2012; Geng et al., 2017; Jayathissa et al., 2020). The PMV is a multi-condition parameter indicator (e.g. accounting for the influencers stated by the ANSI/ASHRAE standard 55) (Antoniadou & Papadopoulos, 2017). While the adaptive model is comprised of the difference between the inside and outside temperature (also accounting for air velocity and metabolic rate). However, the occupant freely adapts by influencing their clothing insulation value and thus accounting for a range of clothing insulation values based on individual adaption. Both account for occupant feedback via the implementation of a thermal sensation scale. Most commonly used is the 7-point thermal sensation scale of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). This defines the thermal sensation based on discomfort. Scaling as followed: +3 Hot, +2 Warm, +1 Slightly warm, 0 neutral, -1 slightly cool, -2 cool, and -3 cold (Geng et al., 2017). Even though the PMV is quite able to incorporate measurement values and individual perceived comfort, it still is only accurate 34% of the time (Jayathissa et al., 2020). To provide a solution Jayathissa et al. (2020) propose to use the occupant-as-a-sensor approach, tagging data to enrich the value of supplementary sensors. Rather than subjecting an occupant to large surveys (which might result in survey fatigue), an occupant provides directional input (i.e. neutral, too warm, too cold). Combined with additional measurements in the area of, and close to, the occupant. This study highlights the flaws of one-size-fits-all comfort models such as the PMV and ACM.

Additional insight is provided about influencing factors of perceived thermal comfort. So is a significant relation between relative humidity (RH) and air temperature proven, where the PMV was significantly higher than the predicted model (Liu et al. 2021). Additionally, humidity strongly correlates with thermal comfort and affects the occupants' perceived wellbeing and health (Geng et al., 2017; Xiao et al., 2021). Furthermore, sex related sensitivity to temperature was also significant, where "too warm" for males, resulting in faster discomfort votes, than "too warm" for females. The contrast of "too cold" is similar, in that females are twice as likely to state discomfort as males. Overall, "too cold" is more impactful than "too warm", especially for longer exposure durations (Liu et al. 2021). Both males and females show a comfort range of around 3°C of their preferred mean. Additionally, light warmth (scale red to blue, corresponding with warm to cold) shows a significant relation with thermal comfort, resulting in increased clothing insulation values (thus more clothing) when light color is colder, and a faster discomfort response when color ranges are not in line with the desired temperature (warmer during the winter, colder during the summer) (Bellia et al., 2021; Liu et al., 2021). In the same line, material color also influences the perception of thermal comfort where warmer colors result in a decreased rate of stating discomfort, and colder colors show an increased rate of stating discomfort (neutral colors, such as green shown no significant direction) (Wang et al., 2021). Overall there is a clear distinction between perceived thermal comfort and predicted thermal comfort on a personal level.

To conclude an average air temperature of 20 – 22 °C is used as a starting point for thermal comfort based, with a maximum deviation of 3°C in any direction, but an optimal cognitive functioning around 26°C. The PMV is most commonly used for thermal comfort prediction. While there are multiple ways of accounting for individual influencers, none have been proven to be completely accurate, highlighting the flaws of one-size-fits-all prediction models. An alternative proposed to this problem is the occupant-as-a-sensor approach. Allowing the occupant to tag PIT data, to enrich current measurements. The premise of this approach is the ability to incorporate available data alongside directional input ("too warm", "neutral", "too cold") of individuals. All studies use air temperature as an adjustable value to influence thermal comfort. Additional influencers are stated (i.e. humidity, airspeed, metabolism, clothing insulation, activity level, sex, and light color).

#### 2.1.1.2 Visual comfort

Visual comfort is expressed in the form of being satisfied, as an individual, based on the visual environment (Frontczak & Wargocki, 2011). The visual environment is subjected to both lighting (e.g .color range, intensity, day/night cycle) and non-lighting parameters (e.g. material color, material texture, view, biophilia) (Gou & Chen, 2020; Cuerdo-Vilches et al., 2021). Lightning is especially important, as it is inherently connected to the human day/night cycle and functioning of the human body and its ability to complete tasks. It is for this reason that both light intensity and light color are closely correlated with cognitive performance, and hormone-enforced activity patterns (e.g. biorhythm, attention, and energy) (Bellia et al., 2021; Wang et al., 2020; Wang et al., 2021).

*Table 4 Overview of studies explaining visual comfort measurement methods*

| Measurement method | Threshold values in lux | Source |
|---|---|---|
| Measuring light intensity, light color range, and accounting for non-lighting parameters survey input. | 300 – 500 for normal activities, 200 minimum, and a maximum of 1500. Preference is 300 lux from a warm colored light source. | Wang et al., (2021) |
| Measuring light intensity and light color range. Increased focus on 15-30 minute task cycles. Results based on activity levels, physical and emotional health. | 300 – 500 for normal activities, with a minimal requirement of 6,5 hours of blue light (daylight) per day. | Shishegar & Boubekri, (2016) |
| Measuring light intensity and light color to understand effects on thermal comfort alongside visual comfort. | 300 on average, but based on task concentration increases up to 1000 for medical tasks. | Bellia et al., (2021) |
| Measuring light intensity. Combined with temperature, humidity, IAQ, and noise for an overall view. | 200 – 1500 based on the required concentration level. | Lai et al., (2009) |
| Overview of light intensity levels per common space, with additional reference to the international standards. | 200 – 600 based on location. | Zhivov & Lohse, (2020) |
| Survey-based, adequate or not adequate. | - | Cuerdo-Vilches et al., (2021) |

Table 4 provides an overview of different studies which are measuring visual comfort. Most studies only encompass lighting parameters (i.e. intensity and color range), but some focus on non-lighting parameters as well. However, measuring light intensity is by far the most common method and is present in all mentioned studies about visual comfort. Overall the assumption is that light intensity, direct glare, color spectrum are the primary indicators of visual comfort (Bae et al., 2017; Bellia et al., 2021; Wang et al., 2020; Wang et al., 2021). As for the distribution of light intensity, table 5 provides an overview of required lux per activity intensity level (Dutch European Standard, 2011).

*Table 5 Overview of activity intensity related to required light intensity (adopted from BS-EN-12464-1:2011)*

| Activity intensity | Example task | Illumination requirement in lux |
|---|---|---|
| Non-active | Sleep | < 8 |
| Almost non-active | Relaxation | 8-50 |
| Slightly active | Refreshment | 50-200 |
| Active | Preparation | 200-300 |
| Focused | Information processing | 300-500 |
| Concentration | Knowledge processing | 500-750 |
| High concentration | Inspection of goods | ≥ 750 (*1000 optimum*) |

For non-lighting parameters, a general standard for measurement is harder to establish, as it is mainly personal preference. There is an interaction between material color and material texture when compared to light intensity resulting in visual discomfort (especially attention) depending on the orientation of the work environment, and the reflection of glare (Cuerdo-Vilches et al., 2021; Wang et al., 2021). Overall a survey method is preferred. Additionally, in a WFH scenario, the occupant has more influence on non-lighting parameters, such as furniture, colors, and view. However, the occupant often makes these design choices with a non-working purpose in mind. These choices might result in a suboptimal visual environment, even though the occupant is able to influence the environment.

To conclude, most perceived visual comfort studies emphasize light intensity. Addition focus is placed on color range, where especially warmer colors are connected to cognitive functioning. Further, a 6,5 minimum hours of daylight is required when accounting for energy levels and health, accounting for 15-30 minute tasks as an optimum. For normal tasks, the light intensity ranges from 200 to 400 lux. With the scaling of optimal ranges based on task activity level. Non-lighting parameters are measured via survey input but are difficult to influence. Especially in a WFH environment, any decisions are made on personal preference, but with leisure activities in mind. Resulting in potential visual discomfort, which is hard to interact with.

## 2.1.1.3 Acoustic comfort

Acoustic comfort is expressed in the form of being satisfied, as an individual, with the acoustic conditions of the environment (Frontczak & Wargocki, 2011). Most commonly, acoustics is expressed in noise and has many detrimental health effects originating from the stress caused due to exposure (Wang et al., 2021; Cuerdo-Vilches et al., 2021; Aigbavboa et al., 2018). The perceived stress becomes worse when accounting for crucial periods (e.g. relaxation, concentration, sleep), and can fuel extensive stress even when the noise exposure has been stopped. Noise can be particularly difficult due to the higher inability to control the noise levels compared to other IEQ parameters, this is especially true during an activity as it can be disrupting due to its interrupting capacity (Wang et al., 2021). Depending on available resources and the quality of sound insulation, there might be an increased potential of acoustic disturbance (Cuerdo-Vilches et al., 2021).

*Table 6 Overview of studies explaining acoustic comfort measurement methods*

| Measurement method | Threshold values in dB | Source |
|---|---|---|
| Case study. Main emphasis sound pressure levels, combined with measuring reverberation time, and special delay. All is then compared to the simulation model. | Average of 34, with a range of 30 to 40 for small offices and conference rooms, and 35 to 45 for landscape offices and cubicles. Exceeding these thresholds results in acoustic discomfort over time. | Macchie et al., (2018) |
| Noise measurement, based on sound pressure levels. | 55 is the max during daytime and is stated as poor, 55 during night time cause health risks. 80 is the threshold for hearing impairment, 120 being max peak value. 40-45 is suitable for work tasks. | Berglund et al., (1999) |
| Sound pressure level, including peak values. | 45 as background, 75 as peak value, with 95 being at risk for hearing impairment. 135 is stated as the max peak value. | Jafari et al., (2019) |
| Sound pressure levels, including peak values | - | Wang et al., (2021) |
| Sound pressure level, survey response input. | - | Aigbavboa et al., (2018) |

Table 6 provides an overview of how acoustic comfort is represented in the literature. Most indicate sound pressure levels in dB to be the representative factor. These measurements are made in close proximity to the occupant, requiring a 4-meter range. Everything within that 2,5-meter range is as if it originated at the location of the occupant itself due to the special decay. Within 4 meters is experienced as distracting when exceeding sound pressure levels of 30 dB to 45 dB (Macchie et al., 2018). General peak values are stated to be around 80 dB to 90 dB with long-term exposure resulting in hearing impairment. 120 dB – 135 dB is the max peak value, causing pain and permanent damage. Acoustic comfort is experienced within a 30 dB to 45 dB range for work activities, and up to 40db for leisure activities (Jafari et al., 2019; Macchie et al., 2018). Additionally, socially related activities have an accepted sound pressure level of 5 dB more than concentration activities (Macchie et al., 2018).

Time of day is an important factor of acoustic comfort, as these periods correspond with important aspects of an individual's biorhythm. Therefore European standards consider $L_{den}$ (day, evening, night), whereas US standards consider $L_{dn}$ (day, night). Represented in formula 1. $L_{den}$ has increased weight factors for acoustic discomfort during evening and night, based on a lower acceptance rate of noise during these times of the day. Table 7 provides an overview of acoustic comfort categories with their corresponding threshold values.

$$L_{den} = 10 * \mathrm{Log}_{10} \frac{1}{24} * \left(12 * 10^{\frac{L_{day}}{10}} + 4 * 10^{\frac{L_{evening}+5}{10}} + 8 * 10^{\frac{L_{night}+10}{10}}\right) \quad [1]$$

*Where: day = 07:00-19:00, evening = 19:00-23:00, and night = 23:00-07:00*

*Table 7 Overview of acoustic comfort categories with corresponding threshold values (adapted from Macchie et al., 2018)*

| Category (quality) | Sound pressure levels in dB |
|---|---|
| A (High) | ≤ 35 |
| B (Medium) | 35 - 40 |
| C (Moderate) | 40 - 55 |
| D (low) | ≥ 55 |

To conclude, much of the research is focused on measuring noise discomfort through the use of sound pressure levels. Especially concentration, relaxation, and sleep are prone to noise discomfort. Social events have by nature a higher accepted sound pressure level than concentration activities.

## 2.1.1.4 IAQ comfort

Indoor air quality (IAQ) comfort is expressed in the form of being satisfied, as an individual, based on the absence of harmful concentrations of contaminants within the environment (Frontczak & Wargocki, 2011). As air quality is closely linked to detrimental health effects and pollution, a large number of studies have been conducted on making it measurable (Guo & Chen, 2020; Wang et al., 2020, Wang et al., 2021). Especially air quality indicators related to heat, ventilation, and air conditioning (HVAC), air pollution (such as CO2, formaldehyde, and particulate matter (PM)) humidity, and freshness (Lou & Ou, 2019; Gou & Chen, 2020). Since the effects of concentrated pollutants are causing distress to the occupant, dilution is required to maintain comfort levels. Both natural and mechanical ventilation allows for controlling the concertation of pollutants and are essential for a comfortable Indoor Air Quality (IAQ). IAQ is incorporated into the US (American National Standard Institute, 2019a; American National Standard Institute, 2019b) and EU standards (Dutch European Standard, 2007).

*Table 8 Overview of studies explaining IAQ comfort measurement methods*

| Measurement method | Threshold values in ppm | Source |
|---|---|---|
| CO2, combined with $NO_x$ as indicator used for IAQ. In a controlled environment, performing tasks with increasing levels of CO2. | For CO2, 1000 results in a decrease in choice reaction and decision-making. No statistical effect on other cognitive functions has been present. | Wang et al., (2021) |
| CO2 and/or ventilation levels were controlled. | 500, 1000, 3000 were used as threshold values. Where 500 was under healthy conditions, 1000 increased and 3000 stress indulging. | Zhang et al., (2017) |
| CO2 as a general indicator, $NO_2$, BaP, $SO_2$, $O_3$, $PM_{2,5}$, and $PM_{10}$ as additional indicators. | For CO2, 5000 max over 8 hour average, with a high quality of max 400. | Ortiz & Guerreiro, (2020) |
| Survey-based, satisfied or not satisfied. | - | Gou & Shen (2020) |
| CO2 levels in a controlled environment. With computer-based validation of office activities. | 600 as acceptable, with 1000+, has a significant effect on decision-making performance | Satish et al.., (2012) |
| CO2 levels tested on office employees during a workday. With computer-based validation of office activities. | 1000 as a break of point, thereafter influences are becoming noticeable. 950 is average. | Allen et al., (2016) |

Table 8 provides an overview of different studies that incorporated IAQ. Of these studies, many tend to focus on concentration levels (compared to outdoor air levels), and their effects on individuals. CO2 is often used combined with ventilation to proxy and indicate the IAQ of a space (Wang et al., 2021). Most studies, therefore, tend to use CO2 combined with symptoms (e.g. dry mouth, dry through, dry eyes, bad odor, dizziness) to determine IEQ comfort as most effects are not directly noticeable by the occupant (Liu et al. 2021; Wang et al., 2019; Wang et al., 2020). All studies then keep a benchmark value of 1000 ppm to determine low IAQ. To make these values measurable table 9 presents air quality levels per threshold level. Furthermore, CO2 should be kept below 500 ppm as a benchmark of good quality (CEN, 2007; Lai et al, 2009)

*Table 9 Overview of IAQ quality categories with corresponding threshold values (CEN, 2007)*

| Category (quality) | CO2 levels above outdoor air in ppm (Default value) |
|---|---|
| IDA 1 (High) | ≤ 400 (350) |
| IDA 2 (Medium) | 400-600 (500) |
| IDA 3 (Moderate) | 600-1000 (800) |
| IDA 4 (low) | >1000 (1200) |

Additionally, a significant relations between perceived IAQ quality and humidity can be found, where levels of humidity that are too high or too low directly influence an occupant's perception of air quality (Wang et al., 2021). This is due to a dry environment evoking discomfort by females, and a wet environment evoking discomfort by males (Liu et al., 2021)

To conclude, CO2 is used as a proxy for measuring IAQ. Accepted CO2 levels are maxed at 1000 ppm. When this threshold is crossed results in significant negative effects on health and cognitive functioning. A poor IEQ is hard to discern by the occupant and would benefit from symptom analysis rather than direct discomfort input.

### 2.1.2 Working and leisure task

Due to the shift from WFO to WFH, a noticeable split between concentration-oriented tasks and socially-oriented tasks can be seen (Tokumura et al., 2021; Torresin et al. 2021). Where concentration tasks are completed within a therefore suitable location (depending on the WFH situation this might still be at the office), and the social tasks (such as meetings, etc.) which are almost exclusively on office sites. The exact effect of the Covid-19 crisis is still unclear, as is its effect on work location with relation to specific tasks. The work culture, expected work attitude, and working atmosphere can shift the preference of specific tasks to either be completed at the office or not at the office (such as WFH) (Wu & Chen, 2020; Tokumura et al., 2021; Wang et al., 2021). Figure 3 provides an overview of the interplay of IEQ parameters on cognitive functioning, through task types on work and leisure tasks.

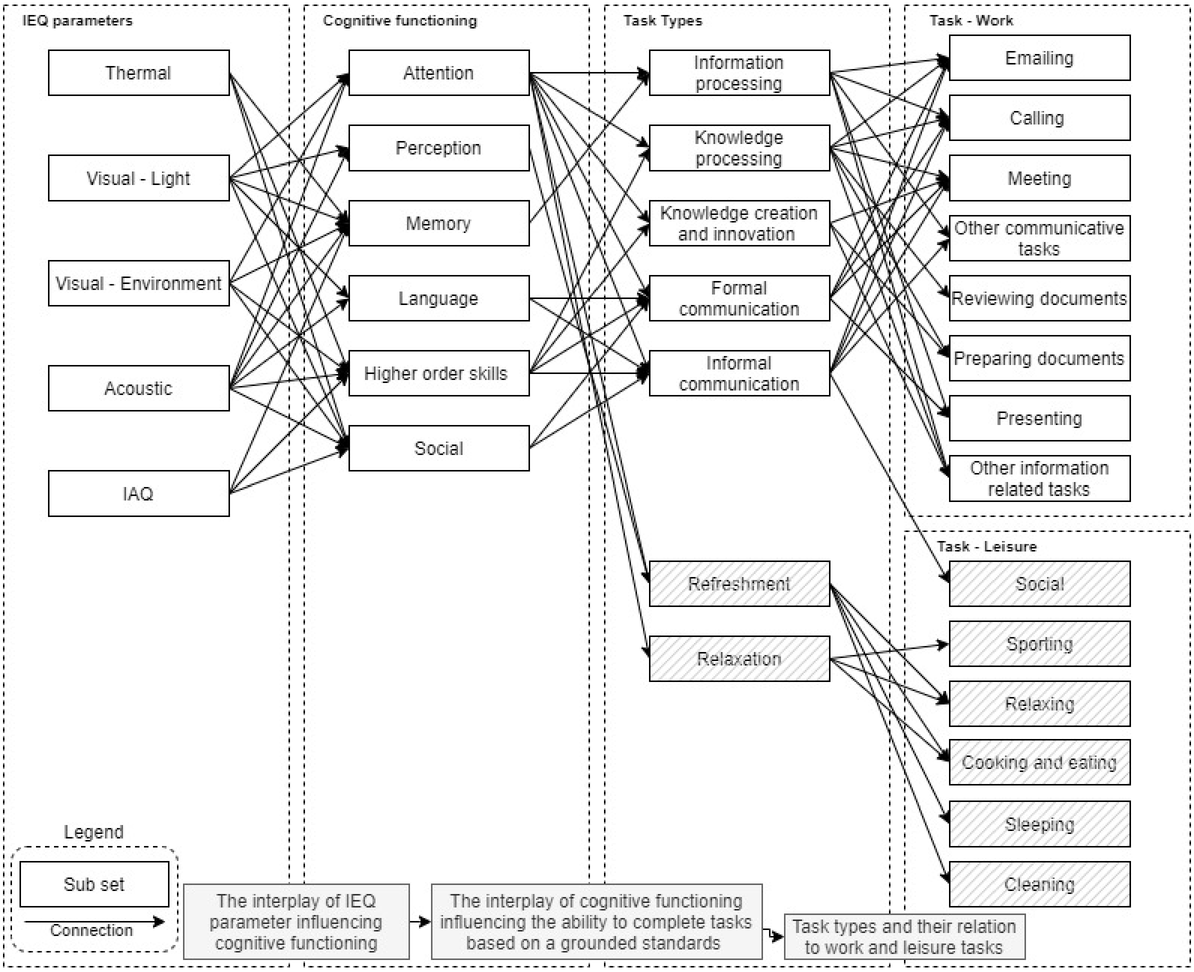


*Figure 3 overview of the connection between IEQ parameters, cognitive functioning, task types, and task (adapted from Wu & Chen, 2020; Tokumura et al., 2021; Torresin et al., 2021 and Wang et al., 2021)*

From the perspective of WFH versus WFO, it is important how the tasks from figure 3 correspond with the IEQ, and how they are completed within their respective environment. So is a colder climate tolerated more than a warmer climate for work-related activities, while the opposite is true for relaxation-related activities (Liu et al., 2021). While this is less the case for light intensity that is mainly coupled to the activity level of the task, rather than the location (Shishegar & Boubekri, 2016). Additionally, in a WFH scenario, the occupant has more influence on non-lighting parameters. However, these decisions are based on leisure activities, and changing them is not preferred. Additionally, social events have by nature a higher accepted sound pressure level than concentration activities. However, this is only the case if all participate in the social tasks, otherwise one can experience noise discomfort (e.g. social tasks such as calling are inherently fine from a WFH perspective. But as the location is not optimized to facilitate these work activities, it could result in a partner experiencing discomfort). While other IEQ parameters might be easier to control such as temperature (both via direct control and adaption), as an occupant in a WFH environment is able to exert more control over its discomforts by directly influencing the cause when able.

## 2.2 Digital Twin technologies and linked data

The increased capacity and quality of data within the built environment creates the possibility for more thorough analysis, and solutions to problems previously either impossible or too resource-intensive to achieve (Pauwels et al., 2017). Using this data, the AEC and the FM sector have an increasing research focus on both the application and development of building real-time Digital Twins (Khajavi et al., 2019; Lu et al., 2019; Parmar et al., 2020). On linked data and semantic web-based Digital Twins less research is available (Boje et al., 2020). However, an effort is being made to integrate these topics in parallel to the Internet of Things (IoT) development. In this case, research into ontologies is especially a key requirement for Digital Twin development (Maryasin, 2019).

Table 10 provides an overview of current literature on digitalizing in the built environment with a focus on the keywords linked data, BIM, and Digital Twin. An overview of their main topics has been presented. It shows that linked data is primarily ontology-focused in its research. Digital Twin related studies are shown to have a primary focus on simulation, standardization, and BIM integration. Most of the studies mention Digital Twins with a 3D visualization as the goal (which ties in with the BIM aspects of the research). BIM as a research topic tries to explore avenues in which new technologies might fit and standardization methods. All three topics often cross-reference each other, showing how much integration there is when exploring these subjects. Another topic that is often covered by the literature is the integration of Internet of Things (IoT) technologies.

The next subchapters will cover these subjects to provide more in-depth insight. A general overview of Digital Twins and user interaction will be provided. Then providing insight into what linked data and what it can do, thereafter placing linked data use in the built environment.

### 2.2.1 Digital Twin design in the AEC domain

While Digital Twins applications span multiple sectors, certain sectors excel at the application and development when compared to others. In the AEC and Facility Management (FM) sectors, the development has only recently been gaining track (Dembski et al., 2020; Lu et al., 2019). The development of use cases and pilot projects has been the leading development strategy, resulting in highly specific uses, with a lack of support for standardization (Lu et al., 2019). Current features are document management, modeling, 3D representation, simulation, data modeling, visualization, model synchronization, and analytics (Harper et al., 2019). The main components of the Digital Twin are its physical components, the virtual models, and the data that connects them (Boje et al., 2020). The flow of data creates a loop in which the physical provides data to the virtual, and where the virtual is able to use this data to influence the physical, creating value during the process. This data cycle is leveraged through simulations, predictions, and optimizations (Boje et al., 2020).

*Table 10 Overview of concepts and variables in current research on linked data, BIM and Digital Twins*

| | Linked data | | | | | | BIM | | | | | Digital Twin | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Year* | 2011 | 2015 | 2016 | 2017 | 2017 | 2021 | 2019 | 2020 | 2020 | 2021 | 2021 | 2018 | 2018 | 2019 | 2019 | 2019 | 2019 | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 | 2021 | 2021 | 2021 | 2021 | 2021 | 2021 | |
| *Author* | Sacco & Passant | Janssen & van den Hoven | Pauwels et al. | Pauwels & Terkaj | Janssen et al. | Sobhkhiz et al. | Tang et al. | Cena et al. | Rhayem et al. | Rasmussen et al. | Babalola et al. | Boschert et al. | Haag & Anderl | Lu et al. | Qi et al. | Maryasin | Khajavi et al. | Laamarti et al. | Boje et al. | Parmar et al. | Zaballos et al. | Chevallier et al. | Zhang et al. | Latifah et al. | Tagliabue et al. | Bosch-Sijtsema et al. | Yitmen et al. | Lin et al. | Conde et al. | **Total** |
| **Use Cases** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Conversion | | | | X | | X | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Policymaking | | | | | X | X | | | | | X | | | | | | | | | | | | | | | | | | | 2 |
| Lifecycle management | | | | | | X | | | | | | X | | X | X | | | | X | | X | | | | X | | X | | | 7 |
| Simulation and learning | | | | | | X | | | | | | X | X | X | X | | X | X | | X | | | X | X | | X | X | X | X | 12 |
| **Focus of study** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Linked open data | X | X | | X | X | X | X | | | X | | | | | | X | | | X | X | | | | | | | | | | 8 |
| Big data | | X | | | | X | | | | | | | | X | | | | | | X | | | | | | | X | | | 4 |
| Behavioral analysis | | X | | | | | | | | | | | | | | | | X | | X | | | | | | | | | | 2 |
| Semantic web | | | X | | | X | X | X | X | X | | | | | | X | | | X | | X | | | | | | | | | 6 |
| AEC Domain | | | X | | | X | X | | | X | X | | X | X | | | | | X | | X | X | X | X | X | X | X | | | 14 |
| IoT | | | | | | X | X | X | X | X | X | | | X | X | | | | X | | X | X | X | X | X | X | X | X | X | 17 |
| Sensors and actuators | | | | | | | | X | | | | | | X | | | X | X | | | X | | | | | X | X | X | X | 8 |
| Machine learning | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | | 1 |
| **Focus of result** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Privacy | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 |
| Ontologies | X | X | X | X | | X | | | | X | | | | | | X | | | X | | | | | | | | | | | 5 |
| IFC | | | | X | | X | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| BIM | | | X | | | X | X | | | X | X | | X | X | X | | X | | X | | | | X | X | X | X | | | X | 13 |
| Standardization | | | X | X | | X | X | | | X | | | | X | | X | | | X | | X | X | | | | X | X | | X | 12 |
| Simulations modeling | | | | | | | | | | | | X | X | X | X | | X | | X | X | X | X | X | X | X | X | X | X | X | 15 |
| Current status of research | | | | | | | X | | X | | | | | X | X | | | | | | | | | | | X | | X | | 6 |
| Validation modeling | | | | | | | | X | | | | | | | X | | | | | | | | | | | | | X | | 3 |
| **3D model-oriented** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Yes | | | | | | | | | | | | X | X | X | | | | | | | X | | X | X | X | X | | | X | 9 |
| No | | | | | | | | | | | | | | | | X | X | X | X | X | | X | | | | | X | X | | 6 |

The current ISO standard for a Digital Twin framework is under publication and review as of 10/2021, with a publication of its current state being present under ISO 23247-1, ISO 23247-2, ISO 23247-3, and ISO 23247-4 (ISO, 2021a; ISO, 2021b; ISO, 2021c; ISO, 2021d). However, other DT-related standardizations are also under development (Laamarti et al., 2020; Shao, 2021). To state the different hierarchical levels of Digital Twins, Lu et al. (2019) stated a structure that can be generalized into Complete DT level, Grouped Object DT levels, Object DT levels, System & Part DT Levels. These levels are needed for the connection and interactions within the DT. The current perspectives of both the standards and the academically structured visions have in common are modeled in figure 4.

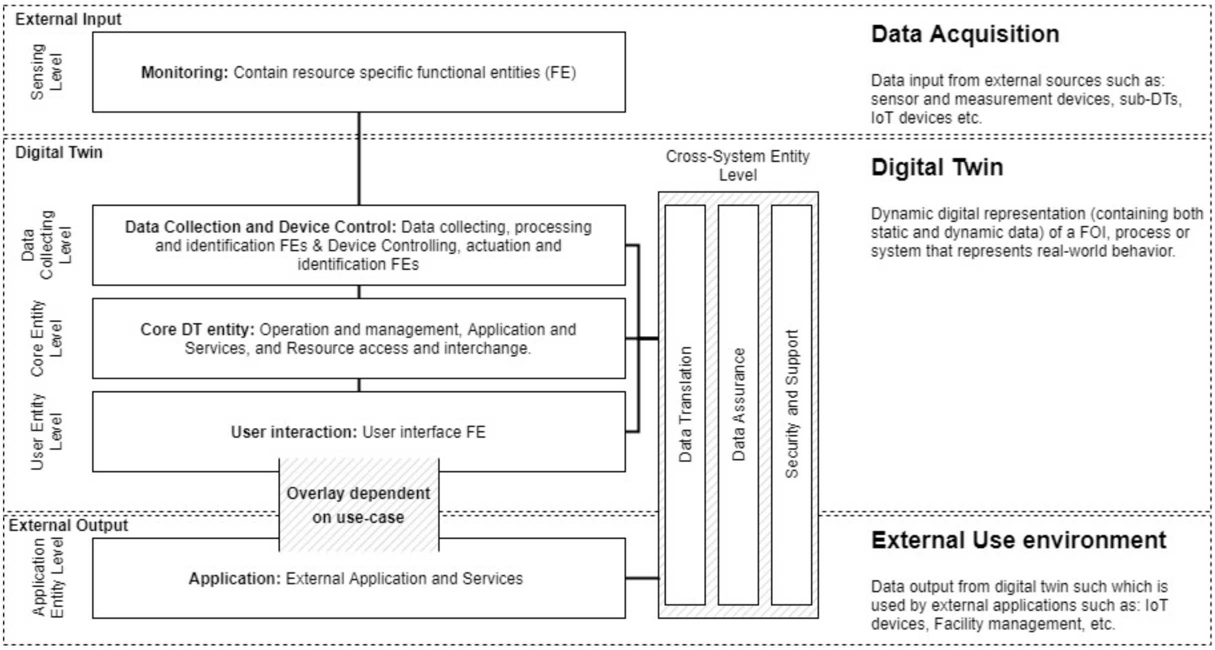

*Figure 4 Schematic representation of the Digital Twin and its connection to external input and output (adapted from Lu et al., 2019; Laamarti et al., 2020 and Shao, 2021)*

This shows that there are three parts needed for the DT framework: an input layer for data acquisition, the DT itself (consisting out of a data collection layer, the core entity layer, and a user entity layer), and the external output layer which uses the Digital Twin for a certain goal. The application layer is an extension of the ISO standard stated by Shao (2021). The Digital Twin itself can be a collection of different entities, hierarchies, and interactions based on the needs of the users and the implication of the use case (Shao, 2021; Lu et al., 2019).

The procedure for applying such a framework has five different stages (Shao, 2021):

1. Selection of standards and technologies for data collection (*What is available/ what is needed*)
2. Selection of standards and technologies for data control (storage and management) and selection of standards and technologies for device control (actuation) (*How should the DT interact with its internal systems*)
3. Selection of standards and technologies for communication between the data collection layer and the core entity (*How should the data be integrated within the DT*)
4. Selection of standards and technologies for the digital representation of the information contained with the DT (*How should the data be made readable within the DT*)
5. Selection of standards and technologies for interaction between the DT and users (*How should the data be provided to the user*).

Between the user and the user interface an external application can provide a selection and interpretation of the data available within the DT to support the user. If this is the case then a sixth stage is required:

6. Selection of standards and technologies for interaction between the DT and the external application layer (*How should the data be provided to the application and how should this application provide the (selected) data to the user*).

Due to the DT being a dynamic representation of a feature of interest (FOI), process, or system that represents real-world behavior (Lu et al., 2019), more flexible applications are required.

### 2.2.2 User interaction

The interaction between users and machines is fundamental to the ability of the machine to interpret the occupant's preferences and comfort. The consensus is that the amount of effort of input should always result in the highest result of output by ratio, where the lower amount of effort trumps a higher amount of effort. The smart housing principle has extensive research about human and machine communications. Especially with regards to IoT devices, which are becoming more common within homes as it is (Prange et al., 2019; Gorecky et al., 2014).

For IEQ performance the emphasis is placed on seamless monitoring via the use of monitoring devices and sensors as part of the input section of the Digital Twin (Parkinson et al., 2018). For the DT framework based on the ISO standard mentioned by Shao (2021), there is a clear distinction between the user interface of the DT and the application layer (which uses the output of the DT). These results are then presented to the users (Lu et al., 2019; Shao, 2021). The application layer should provide its information per its use case, depending on the requirements.

*Table 11 Overview of studies exploring user interaction*

| Communication methods | Result | Source |
|---|---|---|
| Dashboard. Data is represented via a visualization method using tables and graphs. | A dashboard overview of current and historic measurements. Problematic values can be highlighted. | Boerstra et al. (2019) |
| Providing visualization through a software extension tool acting as a gateway server. | Only provides current and historical measurements, no option for communication. Maintains a category system of 4 categories. (Good, moderate, bad, and problematic). | Silva et al. (2019) |
| Combining the information in a 3D reference model, separating the information based on required needs. Additional information can be provided in tables and graphs. | Use-case of combined information in a model integration layer. Visualization of data is primarily promoted. | Lu et al. (2019) |
| Making use of a user entity that interacts with the Digital Twins core entity. | Standards of Digital Twin aspects. Stating ways of integrating an application layer as an extension to a Digital Twin. | Shao (2021) |
| Gateway server to the local environment which publishes a dashboard. Visualized data, including information prompts (alerts) | Visualization of data in a dashboard form. Showing values and indicators of quality. | Parkinson et al. (2018) |
| - | Elemental interface design principles. Six primary elements text, color, graphics, animation, video, and sound. | Kamaruddin & Sulalman (2016) |
| Mirco Ecological Momentary Assessments (Micro-EMA). Only feedback requested no information provided. | Use of data, by tagging information through a positive, neutral, or negative directional response. | Jayathissa et al., 2020 |

Table 13 provides an overview of different communication methods used in current literature from Digital Twin data to IEQ parameters. Most noticeably is that most tend to only visualize data or request survey data to tag information. One of the problems with Post Occupancy Evaluation (POE) for example is the effect of survey fatigue (Jayathissa et al., 2020). So large amounts of surveys requesting ample time of the individual will result in them creating bias, or provided skewed data. Jayathissa et al., therefore suggests the use of directional feedback responses. Simple and short responses over a long survey to allow the occupant to tag current measurement values, participate in current votings, and create a preference model. Lu et al. (2019) goes in the opposite direction and does not request any interaction, but rather provide a visualized Digital Twin. Boerstra et al. (2019), Silva et al. (2019), and Parkinson et al. (2018) do similar visualization from an IEQ measurement point of view. This highlights a gap in current interactive models of IEQ comfort. It should be noted that informing individuals about their current objective IEQ via visualization, can result in bias of individuals accepting the current IEQ or rejecting it based on expectations (Geng et al., 2017). So while visualization is great to provide an understanding, it might also result in individuals showing non-desired behavior. Primarily as individual IEQ expectation is not the same as IEQ comfort. Therefore directed communication might be better suited (positive, neutral, or negative). This directed communication is something an individual understands and is understandable by the system. Especially, since there is the requirement of an individual's capability to make sense of the provided information (Parkinson et al., 2018). The occupant's ability to interpret the information correctly is key in the communication between the system and the Occupant. This interpretation is based on the individual's experience, its current knowledge pool, and the occupant's ability to adopt the available information and thus learn (Parkinson et al., 2018).

### 2.2.3 Semantic web technologies

The semantic web is a network where information is portrayed in directed labeled graphs, containing nodes and links all identified by a Uniform Resource Identifier (URI) which are located by a Uniform Resource Locator (URL). It makes use of RDF-triples (subject (URI), predicate (URI), and object (UIR or literal)), consisting of nodes and relations. An example of what an RDF-triple represents is given in figure 4. Where there is a subject (living room), a predicate (has a), and an object (floor). With the arrow indicating the direction of the relationship. The difference between an URI and a literal is that an URI is unique (and thus relations linking to it are all connected), while a literal is often a simple string value. In the case of the example, a computer can understand that the living room is a space (including all properties that a space might encompass), and any other rooms that are also linked to space can then be traced back to the living room.

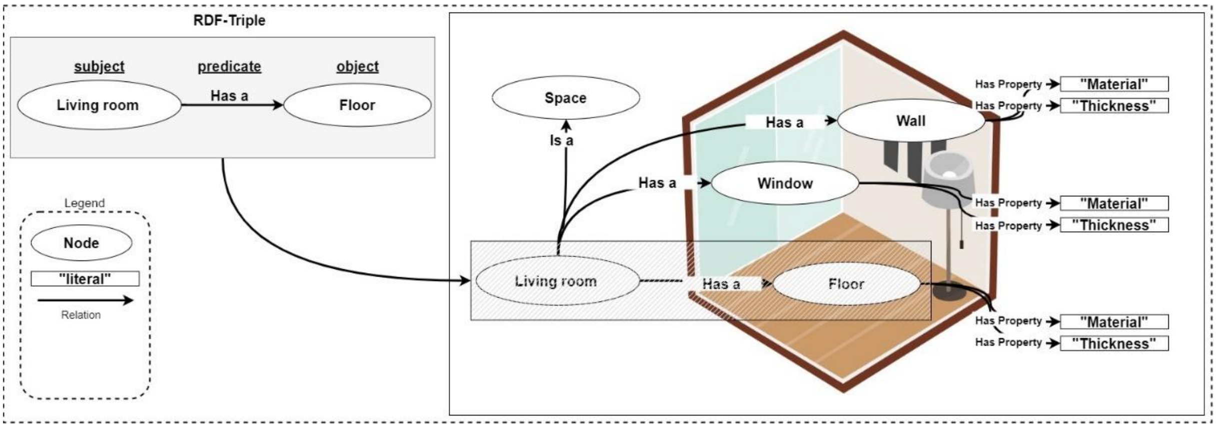


*Figure 5 Example connection of RDF-triples of a living room*

Furthermore, the living room is linked to space, wall, and window. Showing the comparison between a relational database that would specify a row-based relation of three times living room to the specified subparts (floor, window, and wall), wherewith the linked data approach only one living room is linked as it is unique. These types of relations hold extra value due to them being understood by computers as well.

The strength of these URIs is that it allows both humans and machines to (re)use information (Pauwels et al., 2017). Instead of restating the information, a link can be created to the URI, which in turn creates more value for the existing data. The RDF graph uses RDF ontologies to improve its semantic structure, where the most fundamental basic elements are within the RDF schema (RDFS), and the more expressive elements are found within Web Ontology Language (OWL) (Pauwels et al., 2017). To set an open standard for linked data resources within the semantic web the five-star criteria for linked open data has been established (Berners-Lee, 2010) as seen in table 12.

*Table 12 five-start development steps for linked open data (adapted from Berners-Lee, 2010)*

| Stars | Description |
|---|---|
| 1 | Available on the web with an open license (open data). |
| 2 | Available on the web with an open license, and structured and machine-readable data. |
| 3 | Available on the web with an open license, structured and machine-readable data, and without proprietary format |
| 4 | Available on the web with an open license, structured and machine-readable data, without proprietary format, and with W3C open standards (RDF and SPARQL). |
| 5 | Available on the web with an open license, structured and machine-readable data, without proprietary format, with W3C open standards (RDF and SPARQL), and complete linking of available data to other locations on the semantic web when possible. |

### 2.2.4 Semantic web and the built environment

Implementations and use-cases of linked data are still developed, with an expanding knowledge base within the built environment (Pauwels et al., 2017; Sobhkhiz et al., 2021). An emphasis in the literature is placed on the Architecture, Engineering, and Construction (AEC) industry as a whole, while individual developments are less dominant (Sobhkhiz et al., 2021). It is only recently that more practical implementations are executed over theoretical implementations. However, good support structures for data distribution within this new approach are still lacking (Sobhkhiz et al., 2021). Especially since it is still reliant on the converting of already existing reference models instead of a direct RDF representation. The challenge is that it has to be developed within already existing BIM protocols and guidelines (Sobhkhiz et al., 2021).

Currently applied Building information management is done via the use of Industry Foundation Classes (IFC), which is the most generally accepted standard. IFC is defined by the EXPRESS schema. The aim is to preserve data throughout the life-cycle of the asset, through standardization. Additionally to the IFC standard, there are XML and RDF-based instances, with their corresponding schemas (ifcXML with XSD schema, and ifcRDF with ifcOWL ontology). The latter, ifcOWL ontology, has been produced as a domain ontology within the AEC industry (Pauwels et al., 2017; Pauwels & Terkaj, 2016). However, ifcOWL is only one of many building ontologies available (Donkers et al., 2021). Within the built environment two primary ontology approaches can be distinguished, the one-file approach (a generic ontology) and the domain-specific approach (which separates the ontologies based on their domain, e.g. building-specific ontologies) (Pauwels et al., 2017).

### 2.2.4.1 Building semantic web technologies

For building-specific ontologies, the general premise is that there is a need for a core ontology, which should cover the topology of the building. the most commonly used is the Building Topology Ontology (BOT) (promoted by the Linked Building Data Community (LBDC)) (Rasmussen et al., 2017). However, there is still no scientific agreement about a core building topology ontology as of now (Donkers et al., 2021). BOT aims to describe a building via zones (imaginary locations with set boundaries) and elements (physical objects). A real-world object (e.g. a building stated in BOT as a bot:Zone) ought to be divided into zones: a building (bot:Building), on a site (bot:Site), having levels (bot:Storey), and having spaces (bot:Space). These zones then have relations with elements. For example, a space can be next to a bounding element (bot:adjecentElement), a space might contain an element (bot:containsElement), and a space might be intersected by an element (bot:intersectingElement) (Rasmussen et al., 2017). BOT tries to reduce dataflow redundancy. It can be extended with complementary linked building data (LBD) ontologies (Rasmussen et al., 2017; Donkers et al., 2021). Depending on the required level of detail more extensive ontologies can be used to cover elemental levels combined with hierarchical structures (Donkers et al., 2021).

Additionally to the topology, information can be enriched by adding both static- and dynamic properties, which are measurable characteristics of Features Of Interest (FOI) (Donkers et al., 2021). Where static properties are (generally) not prone to change (generic information, geometrics, material, environmental data, etc.), dynamic properties are changing over time (sensor measurements, temporal states, etc.) (Donkers et al., 2021). While there are many ontologies available for similar purposes, complemental use might still result in complications due to them not being designed for the same purpose and thus behaving differently (Donkers et al., 2021).

### 2.2.4.2 Semantic web technologies for IEQ

To account for the specific nature of building performance parameters, Donkers et al. (2021) created a Building Performance Ontology (BOP). Their research is based on extensive literature research where existing ontologies are compared and examined, to develop an ontology aimed at integrating dynamic and static properties with topological building information (Donkers et al., 2021). Other research on IEQ are mentioned by Adeleke & Moodley (2015), and Qiu et al. (2018). Both focus on an as-is situation through observation and measurement. The key difference between BOP and the IEQ specific ontologies is that BOP does not state IEQ quality as a property, but rather places it outside of the ontological framework for IEQ analysis. The reason for this placement is so that a homogenous data environment can be created that aims to support building performance assessments, such as the IEQ (Donkers et al., 2021).

For best use within the building management sector, the hybrid variant (both sematic web and relational database combined) seems to align best with its intended use (Pauwels et al., 2017; Tang et al., 2019). BOP can be integrated with BOT and is domain neutral. However, BOP aims to fit within the building performances domain (during the building management phase), is queryable with SPARQL, and extendable by other ontologies. Besides BOP, no clear universally accepted ontology for connecting dynamic property patterns and static property patterns was found. This lack of accepted standard ontology is due to most of the existing ontologies being for specific use cases which lead to problems in scalability and adaptability which often results in either too broad or too narrow of class definitions (Donkers et al., 2021). Both Tang et al. (2019) and Donkers et al. (2021) advocate for the use of time-series and relational databases combined with the semantic web to reap the benefits of both practices.

### 2.2.4.3 IoT integration and the semantic web

To improve user comfort, an increasing number of stakeholders have taken interest in the integration of objects within the network of information technologies (Dibley, 2012; Rhayem et al., 2020). The inclusion of semantics in everyday "things" (where a "thing" can be anything as long as it retains a unique identifier (UID), and is able to provide and received data without human interaction), allows for the ability to obtain real-time information from information carriers and providers at any given time and place (Rhayem, et al., 2020; Parmar et al., 2020; Pauwels et al., 2017). In the AEC industry, the use and sharing of building semantics have increased in popularity over the years, shifting from only a design and built perspective towards a perspective covering the entirety of the building life-cycle. As a result, letting go of temporary software solutions in favor of preserved semantic information (Pauwels et al., 2017). Tang et al. (2019) described five methods to integrate building information and sensor data (table 11).

*Table 13 Description of the integration methods for building information and sensor data (adapted from Tang et al., 2019)*

| Name | Description |
|---|---|
| BIM tools' API + relational Database | BIM- and sensor data is directly exported to a relational database (through the use of APIs (application programming interface)), where it is stored and updated when new data becomes available making use of time-based intervals. A database schema using UIDs is required to link the data, and SQL queries are used to read the data. |

| | |
|---|---|
| Transformation of BIM data into a relational database using a new data schema | BIM data is transformed into structured data and exported to an open-source BIM-server database. Then sensor data is directly exported to a relational database, where it is stored and updated when new data becomes available making use of time-based intervals. A database schema using UIDs is required to link the data, and SQL queries are used to read the data. |
| Creation of new query language | BIM data is processed using a custom-built BIM tool, which stores it on a BIM-server database. Then sensor data is maintained by the use of a data stream management system. No standardization is used or needed, abolishing SQL altogether in favor of a custom process. |
| Semantic web approach | BIM- and sensor data are stored using a representation of data in RDF on the semantic web. To read the data available, SPARQL (SPARQL Protocol and RDF Query Language) queries are used. |
| Hybrid approach: semantic web + relational database | BIM data is stored using a representation of data in RDF on the semantic web. Then sensor data is directly exported to a relational database. This database is available through the RDF graph. To read the data available SPARQL is used, then SQL queries are needed to retrieve the data from the relational database(s). |

Stating time-series data in this RDF-triple makes the hybrid approach best suited for systems making use of PIT data (e.g. sensors measurements) over the full semantic web. The hybrid approach still allows for data integration, while keeping time-series sensor data in its relational form, and still using standardized methods (SPARQL and SQL) (Patel & Jain, 2019; Tang et al., 2019).

### 2.2.4.4 Relational databases for the hybrid approach

To preferent latencies, and to keep information stored within its native format, relational databases can be combined with linked data models (Pauwel, et al., 2017; Tang et al., 2019; Donkers et al., 2021). It further avoids redundancy in data, emphasizes standardization of collected data (and thus available to different programs), and is efficient in maintenance. This is especially true for dynamic data, such as time-series data, where these benefits are requirements for reliable data usage (Pauwels et al., 2017; Tang et al., 2019). In line with the vision of BOP, there is a clear separation between the static and dynamic properties of the databases. To query the relational database Structured Query Language (SQL) is used. A Database Management System (DBMS) is used to access, manipulate, and represent the data from a database, where relational databases are most commonly used. The relations within the database are set by tables that structure data by combining information in rows. This structure is vastly different from the linked data structure which defines relations via RDF-triples in graph structures. Relational databases can be complex systems without proper database management.

### 2.2.4.5 Privacy of open access relational databases and open linked data

Linked open building data provides the opportunity to use data to better the community and the occupant's indoor environmental quality. However, this is where problems arise from the perspective of open-linked data and privacy. Rashik et al. (2020), state that to generate value, data should be shared openly so that the sheer mass of available data can attract those who want to use it to create new data and enrich the totality of data available for analysis, which is in line with the principles of open data stated in the five-star criteria (Berners-Lee, 2010). However, building data is privacy sensitive. Especially when taking into account that compared to Big and Open Linked Data (BOLD) (which is used primarily by governmental agencies to drive innovation, execute analysis, etc.), this is not data from publicly available data sources (Sacco & Passant (2011); Janssen & van den Hoven, 2015; Janssen et al., 2017). Due to the personal nature of LBD, the collection of dynamic data is especially prone to ill intent or mistrust by the community. To overcome this challenge, access privileges are required via measures such as access control lists (ACL) as stated by the Web Access Control (WAC) vocabulary (Sacco & Passant, 2011). The controlled access, however, restricts the user to either full access or no access at all. As only specific properties and values are privacy-sensitive, a specified access restriction method is required. The scope of this research will not focus on the privacy restriction methods, but will, however, mention the necessity for them, and advocate their importance. Werbrouck et al. (2021), states that an in-between solution could arise from an API function that can interact with data on different levels. Especially, as multiple stakeholders interact with building data over the course of its existence, creating the opportunity to enrich data during every phase of the building lifecycle. More so as there is no requirement to store data on a centralized location, and thus allows for a federated network. In this network, all stakeholders can make use of generally available open data, but also allow access to their own servers creating a net of interoperable data that can be governed independently if required (Werbrouck et al., 2021).

# Chapter 3. Methodology

*This chapter will elaborate on the research methodology applied for the study and system architecture design. First, an overview of the entire methodology and general system design will be provided. Then the integration of IEQ parameters will be elaborated. Followed by the process of preparing the available data will be explained. Followed by an in-depth explanation of how the prompt information is triggered. Leading up to the system architecture and user interface.*

## 3.1 Research methodology

This research is based on the theoretical literature as provided in the previous chapter. This review aims to provide a grounded understanding and foundational knowledge of indoor environmental quality, linked data, and Digital Twins in a working from home environment. The main benefit of this review is to understand an emerging problem, where individuals have to work in an environment never designed for that singular purpose. This, due to the COVID-19, has been increasingly strained. While the subject of WFO and IEQ has been thoroughly researched through the years, there is a noticeable gap within the combination of WFH and IEQ, as this has not been the primary working methods for most companies. Combined with a change in work behavior where individuals show selective tendencies towards tasks and specific environments (such as concentration-dependent solidary tasks at home, and social tasks at the office), results in individuals being prone to poorer IEQ conditions.

To provide a solution in which individuals gain more insight into their IEQ, linked data is proposed. Linked data, as of Pauwels et al. (2017) and Tang et al. (2019), provides a flexible and generic language for easy data representation, while maintaining profoundly usable information crossing multiple domains. The key benefit is that data, from a Digital Twin perspective, can be used to provided information about the physical in a digital environment. Therefore, in turn, can be used to benefit the physical environment, creating a cycle of learning (Boje et al., 2020).

After this literature research, a proof-of-concept case is described. This case makes use of a prototype design highlighting the use and integration of linked data Digital Twin models with a selected use-case of individual IEQ comfort in a WFH environment. For this to be applied a general system architecture is developed, containing the primary flow of information and a detailed description of the human-machine communications required.

When a general system architecture is developed, the IEQ parameters will be selected. This selection will provide an overview of the available options, their connection to the IEQ parameters, and their reasoning for use. To connect the IEQ parameters to certain tasks, a task activity level is coupled so that different threshold values can be used. To provide a deeper understanding of how the linked data will be used within the system itself a more specific understanding and use will be provided of the Digital Twin, this in turn shall be used to reflect on choices to state decisions and assumptions. Then a case will be selected including a description of the to-be-used systems, programs, and other resources. A clear overview of the proof-of-concept case is provided alongside the clear goals of the case itself. After the required preparation a complete overview of the intended system design will be provided, including the data processing and evaluation as part of the uses of the system design.

Then the application and methodology will be applied within the selected case environment making use of two subjects within two distinctly different WFH situations (a hybrid environment located between the living room and kitchen, and a dedicated WFH office made from an unused bedroom). A schematic overview of the methodological approach can be seen in figure 6.

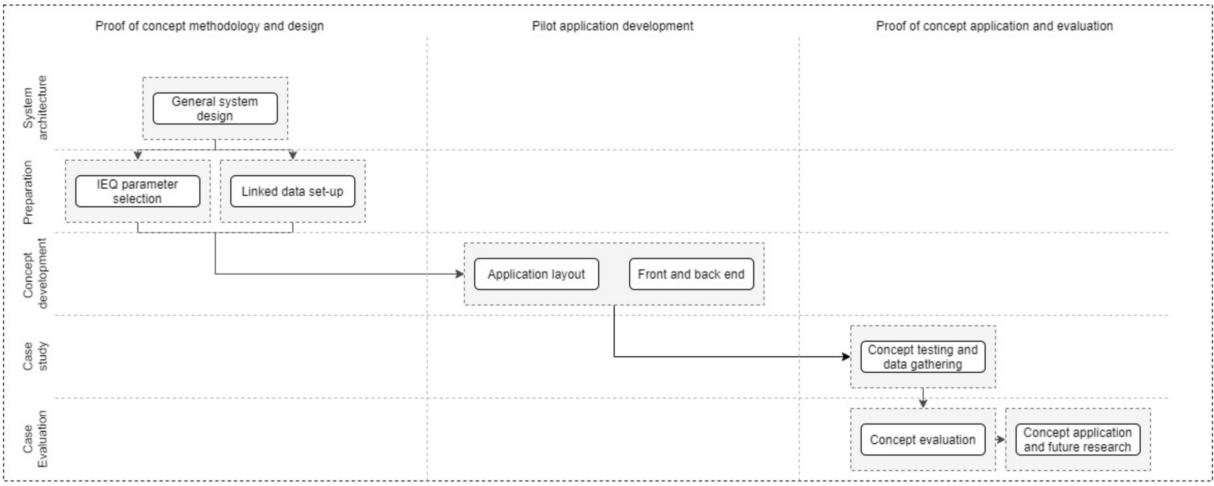


*Figure 6 Methodological overview of the study and proof-of-concept case*

### 3.1.1 General system architecture

To gain the relevant data a general system architecture is designed, as can be seen schematically in figure 7. This model splits the system into two different environments. There is a local case environment that hosts the occupant, user interface, and case locations (living room, and at-home office). Furthermore, there is a processing environment that is located outside of the case environment which hosts the processing environment and the linked data representation of the building. In between these environments, there is the IEQ sensor data which is transferred from the case environment towards the processing environment, and there are different databases that store all data used by the system. The databases in this instance allow for the different parts of the system to interact with each other while allowing them to maintain independence. A more in-depth representation of figure 7 is available in Chapter 3.2, which describes all parts of the system in more detail.

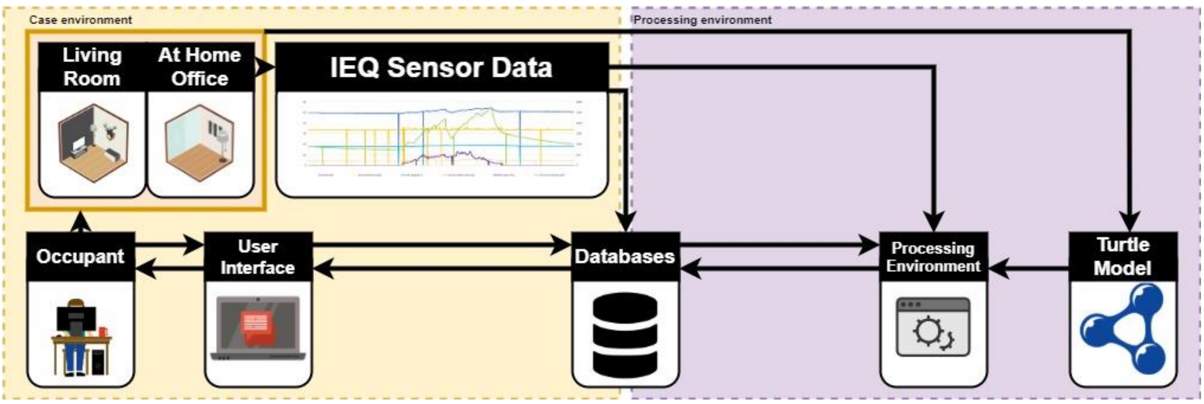


*Figure 7 General overview of the system architecture for the proof-of-concept case*

### 3.1.2 IEQ parameter selection and system integration

According to Tokumura et al. (2021), a split in workdays when working from home and working from office is to be expected. This split is around the two to three day mark depending on the task types to be completed, and the amount of time spend commuting to reap the benefits from the working from office environment. If the tasks can be completed at home, and the additional benefits do not outweigh the time commuting, then the likelihood of WFH increases. This results in an active split between task types completed at home and at work, with an emphasis on the requirement of concentration and the ability to perform these tasks at home.

As for the common workplace within the working from home environment, multiple studies have researched the possibilities for different locations based on survey results. The emphasis was placed on either a dedicated work environment, such as an at-home office or in a more general relaxation environment, such as the kitchen table (Cuerdo-Vilches et al., 2021). Especially dwelling sizes with a smaller usable floor area are prone to lower quality WFH locations, due to them not having access to spare rooms that can be dedicated to a WFH office. As seen in the study from Tokumura et al. (2021) and Torresin et al. (2021), this as well results in a split between different levels of concentration required for certain tasks and the dedicated location of an individual to complete the certain task.

The tasks coming from the literature on work, and other non-work-related tasks are represented alongside their respected activity level required to complete in table 14:

*Table 14 Task description and corresponding activity level*

| Task | Description* | Activity Level** |
|---|---|---|
| ***Work-related*** | | |
| Emailing | Both formal and informal communication related to work through an email service provider. | 2 |
| Calling | Both formal and informal communication related to work through direct contact by use of phone provider or by use of internet calling. | 2 |
| Attending a meeting | Both in-person and via a digital meeting service provider. | 2 |
| Other communicative tasks | All communicative tasks that are not related to emailing, calling, or attending a meeting, but do require a certain amount of effort to be completed. | 2 |
| Reviewing documents | The act of preparing and adjusting documents with an emphasis on creating and problem-solving. | 4 |
| Preparing documents | The act of reviewing and correcting documents with an emphasis on reading and remarking. | 2 |
| Presenting information | The act of presenting or actively hosting a meeting, document, or other information sources. | 3 |
| Other information related tasks | All information related tasks that are not related to reviewing documents, preparing documents, or presenting information, but do require a certain amount of effort to be completed. | 2 |
| ***Non-work-related*** | | |
| Sleeping | The act of sleeping or actively resting for more than 30 minutes | 1 |
| Cleaning | The act of cleaning a definite object, subject, or area | 2 |

| | | |
|---|---|---|
| Cooking and eating | The act of preparing and consuming food within proximity to the WFH environment or general area of relaxation | 3 |
| Social | The act of performing a social activity within proximity to the WFH environment or general area of relaxation | 2 |
| Relaxing | The act of relaxing, by performing an activity that does not require a (highly)active input from the individual | 1 |
| Sporting | The act of performing a sportive activity within proximity to the WFH environment or general area of relaxation | 2 |
| Other leisure activities | All other activities that are non-work-related | 1 |

* As used by this research
** Based on the levels in BS EN 12464-1:2011: Relaxation (1), Active(2), Focused or Concentrated (3), and High Concentration (4)

Therefore, the corresponding activity levels are based on the activity intensity levels stated in the BS EN 12464-1:2011, which are used for lux required per task executed. These were then merged into four categories usable by the other IEQ parameter values to create a distinction between relaxing tasks (which are either non-active to slightly active), active tasks (which are more active than slightly active but do not require continuous focus), focused or concentrated task (which require a continuous focus or concentration to be completed and thus hinder highly from disruption), and high concentration (tasks that require a high level of concentration to avoid mistakes).

The ability to cope with the need for a qualitative WFH environment is therefore based on the individual's ability to directly change its environment so that the IEQ parameters are up to the required standards for the task (this is because different tasks have different needs). From the study by Wang et al. (2021), a comparative relation can be stated between cognitive functioning and IEQ parameters. This trickles down into different IEQ parameters coupled to certain tasks.

Table 15 provides an overview of the used IEQ parameters and their corresponding threshold values. These are based on the literature research of chapter 2. In this table, the IEQ parameters are represented including their measurement group (distinctive separation on which the measurement is relying) and measurement condition (the way the measurement is tested is how it uphold the boundaries set by that group). These are then linked to the corresponding task (Tokurua et al. (2021) and Torresin et al. (2021)).

*Table 15 IEQ parameter method of measurement description*

| IEQ parameter | Measurement group | Measurement condition | Threshold values |
|---|---|---|---|
| **Thermal** | **1)** Work Task | Exceeding MIN/MAX value | 17-23\|18-24 |
| Male \| Female | **2)** Non-work task | Exceeding MIN/MAX value | 18-24\|19-25 |
| | **3)** Non-measurement | Survey input | Too warm / cool |
| **Humidity** | **1)** Overall | Exceeding MIN/MAX value | 20 – 50 RH |
| | **2)** Activity level 1 | Exceeding MIN/MAX value | 20 – 50 RH |
| | **3)** Activity level 2 | Exceeding MIN/MAX value | 30 – 45 RH |
| | **4)** Activity level 3 | Exceeding MIN/MAX value | 30 – 45 RH |
| | **5)** Activity level 4 | Exceeding MIN/MAX value | 35 – 45 RH |
| | **6)** Non-measurement | Survey input | Air too damp / feels stale |
| **IAQ** | **1)** Overall | Exceeding MIN/MAX value | 400 ppm (CO2) |
| | **2)** Overall | Exceeding threshold value | Boolean (general IAQ) |
| | **3)** Non-measurement | Survey input | Unpleasant smell |
| **Visual (light)** | **1)** Activity level 1 | Exceeding MIN/MAX value | < 200 lux |

| | | | |
|---|---|---|---|
| | **2)** Activity level 2 | Exceeding MIN/MAX value | 200 – 500 lux |
| | **3)** Activity level 3 | Exceeding MIN/MAX value | 500 – 750 lux |
| | **4)** Activity level 4 | Exceeding MIN/MAX value | > 750 lux |
| | **5)** Non-measurement | Survey input | Too dark / light |
| **Visual (environment)** | **1)** Non-measurement | Survey input | Room Cleanness<br>Room Layout<br>Room Color<br>Room Texture<br>Room Biophilia<br>Room Privacy<br>Room Outdoor View |
| **Acoustic** | **1)** Overall | Exceeding MAX value | 110 dB |
| | **2)** Work Task | Exceeding MAX value | 45 dB |
| | **3)** Non-work task | Exceeding MAX value | 40 dB |
| | **4)** Non-measurement | Survey input | Noise Outside/Inside |

### 3.1.3 Applying linked data

In line with the hybrid approach of semantic web and relation database combination, this system uses both a relational database (to host the historic PIT data) and a linked data model (to represent the occupied building). This “Turtle” (Terse RDF Triple Language) model hosts a series of RDF-triples which can be queried within the processing environment. Based on these queries certain statements can be made by the system about the rooms that the subjects occupy, which types of IEQ control measures are available, how the measurements are made, and where they are stored.

To get this Turtle file, an IFC model has to be converted. The resulting model will then be manually restructured to be more human-readable. After the restructuring, the file is enriched with information not present in the IFC model, or lost during conversion.

#### 3.1.3.1 Converting IFC model to linked data model

For this research an existing “OpenFamilyHome.ifc” is converted to a Turtle file, which makes use of the Terse RDF Triple Language (Turtle). The base URL used for the “inst” ontology URI is “https://github.com/TheRealHatsikidee/OpenFamilyHome”, additional options selected are: product (True), Separate file (True), Geolocation (True), Props (true), level 1, blank nodes (False), Separate file (True). Important choices are the level, which depicts the level of linkage details. The reason why level 1 is chosen is due to the needed complexity of the proof-of-concept case which does not require a high level. Level 1 generates simple properties which depict certain aspects of the object as a literal instead of a new URI (Such as its root id, name, special attribute, etc.). In the case of other open linked data use cases, a higher level of detail might be required than for this proof-of-concept. Via the IFC-convertor (IFCtoLBD convertor 2.30.1)[1] a Turtle (.ttl) file has been created. This Turtle file after conversion is mainly machine-readable. To make it more human-friendly a manual reformatting of the file has taken place. This reformatting is done based on floor levels and room numbers (ascending). Except for the exterior walls which are modeled to be covering all floor levels, and thus are situated on ground level. Turtle makes use of prefixes to shorten the RDF-Triples. These prefixes link, by using a prefix directive, a prefix label to an URI. The prefix is separated by a colon ”:”.

[1] https://github.com/jyrkioraskari/IFCtoLBD

Additionally, a base URI can be used, which will compliment all relative URIs that are not already complemented by a prefix. In the “OpenFamilyHome.ttl” no additional base URI is used, as the convertor already complements all relations with a prefix, and additional relations not part of the origin IFC file are added also with complementary prefix URIs.

### 3.1.3.2 Enriching the linked data file

To make the Turtle file more usable for this research, the converted file is enriched with additional semantic information. The enrichment is achieved via additional RDF-Triple relations between parts of the linked building data model using the BOP ontology. Since BOP is not an output from the convertor, all BOP relations have to be put in manually. Additionally, the “props” prefix has been used to add additional properties, these properties are now static inputs due to the choice of making simple relations, but could in future research direct to a URI containing non-static information. The following information is appended to the model via those RDF-triples:

- Sensor location information
- Sensor measurement values information
- PIT values storage location
- Static room properties
- Additional relations of URIs

Due to these enrichments, additional information can be queried. For example, the spaces contain information of certain IEQ control measures (such as curtains), have a relation to certain properties (such as the temperature value of the living room), and host certain sensors (such as the temperature sensor located in the living room). If this information was present in the IFC file, and if BOP was a part of the convertor, then the output file might have had these relations already. The reason for adding additional relations which are “simple” (referring to a literal instead of a URI) alongside relations to other URIs is due to the nature of the proof-of-concept case, which does not benefit from additional information other than if these properties are present. If more properties are required a new URI can be created which hosts these properties so that they might be queried instead of the now stated simple information (an example is: a mechanical ventilation unit which has properties like: model, brand, year of purchase, etc.).

As an example figure 8 shows a visual representation of the RDF-triple relations of a selected subset of the converted Turtle-file. This visualization shows the path going from the living room (which is a space) to the temperature sensor (which is a sensor), which holds a property and a property state, which are connected to a database storing the PIT data. All of which can be queried for applications to use the data stored within the Turtle-file as it would be able to with more traditional models. The added benefit of linked data is the ability to create more RDF-triple relations to incorporate other data sources and databases, which makes it more saleable. Additionally linked data is non-discriminatory and allows for different programs, applications, and languages to be used in the same environment. In the case of the example, there is PIT-data, stored in a SQL relational database, which can be queried through the Turtle-file. This connectivity highlights the potential of the linked data approach and shows the application of the hybrid approach as mentioned by Tang et al. (2019).

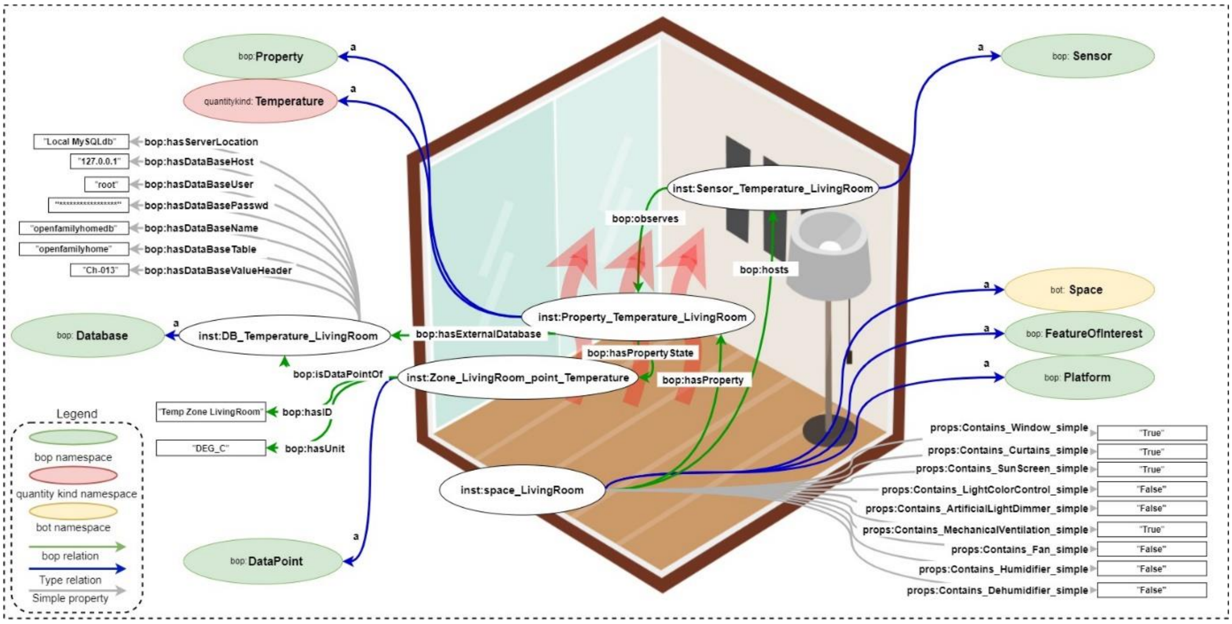

*Figure 8 Visualization of the Turtle representation of the space living room connecting to its corresponding nodes*

### 3.1.4 Data collection

As this research aims to provide insights in the use cases of linked data Digital Twins in a WFH-environments, data is gathered of occupants interacting with a system providing them with insights and information of their IEQ. As this data will be gathered to provide insights in the use case of DTs and not IEQ parameters, the emphasis will be placed on the usability of linked data over the IEQ. This emphasis skews the results of the IEQ parameters somewhat. Additionally, the case study will be held in the Netherlands, which results in a strong representation of Dutch WFH situations, but does not allow the data to be used for other types of housing. For this reason, a review of the gathered data will provide insights into what can be seen within said data, instead of providing statistically proven relations between those actions and the measured IEQ parameters. The data gathered can be categorized into the six categories mentioned in table 16.

*Table 16 Data type categories as obtained in this research*

| Data type category | Description |
|---|---|
| IEQ data | This data is tied to a specific room. It contains measurements of thermal (temperature and humidity), visual (light intensity), IAQ (general IAQ and CO2 levels), and acoustic (sound pressure levels) |
| Individual (dis)comfort responses | PIT tags of positive, neutral, or negative input |
| Individual prompt reactions | PIT reactions to IEQ based survey questions |
| Individual task information | PIT range of tagged information about current task and works status |
| Individual daily influencers | Daily input about influencing factors spanning one day |
| Individual daily preference information | Result of task-related input spanning one day |

This data is then translated by the system to provide the occupant with information prompts. For the system to understand the comfort of an individual a communication structure is needed, this requires three main components which are represented in table 17.

*Table 17 Communication categorization as used in this research*

| Communication category | Description |
|---|---|
| Measurement input | Interaction based on measured results of the occupant's IEQ |
| Random response input | Interaction based on randomly selected survey questions related to the occupant's IEQ |
| Direct input | Interaction based on the direct input of information tagged |

### 3.1.4.1 Measurement input:

Since the measurements are about different IEQ parameters, different threshold values are required. The way these threshold values are interpreted by the system is based on the works of Seppänen & Fisk (2006), Park et al. (2018), Wang et al. (2020), Boegheim et al. (2021), and Wang et al. (2021). Who have their primary focus on IEQ parameters and their impacts on perceived quality, performance, comfort, and health.

The interpretation of the incoming measurements goes in three stages, checking if critical thresholds are exceeded (such as noise exceeding the pain/damaging limit). Then if set boundaries are crossed (based on limits stated in the literature). Lastly, when within the allowed range optimizations might be possible. These types of input are then translated into a prompt, which requires action and response from the occupant. The way these prompts are labeled is “A” and results in A-prompts.

A-prompts are the most common prompts used in this research. The aim is to have them available in either a warning, normal, or optimization form (A-prompts with W and O variants). The hierarchy is W>A>O. All of these measurement prompts are checked similarly against boundaries as stated in the literature or by individual preference, which is changed based on the activity level corresponding with the occupant's current task. Additional influencers such as rest level and sick status can be used to constrain the boundaries (e.g. lowering the range of optimal temperature when someone is feverish). The measurement input can be checked by using the following expression:

$$Y_i = a + \sum(T_n * M_n) - \sum C_n \quad \text{with} \quad C_n = (\beta_n * Z_n) \qquad [2]$$

$Y_i$ = Value individual IEQ parameter
a = Constant
$T_n$ = Transformative measurement weight
$M_n$ = Measurement value
$C_n$ = Constraint measurement
$\beta_n$ = Constraint weight
$Z_n$ = Constraint value

With i being the individual IEQ-parameter and n being the individual measurement corresponding to a point-in-time value.

Then the $Y_i$ of the individual is compared to a minimum and maximum boundary value which acts as the range of which measurement comfort is determent. As long as the value is between these values no measurement prompt is triggered.

### 3.1.4.2 Random response input:

For the system to understand an individual's preferences, general bias has to be prevented. If an individual has time structured prompts requesting their current comfort, that individual might create a biased opinion leading up to the moment of response. To prevent these types of bias random response requests are preferred.

However, to gain additional information outside of the measurement prompts which are linked to literature-based values, more personal input is required. This input will be obtained through direct questions regarding the current IEQ comfort. The nature of these questions are based on the works from Seppänen & Fisk (2006), Park et al. (2018), Wang et al. (2020), Boegheim et al. (2021), and Wang et al. (2021). These types of interaction are labeled "B", and result in B-prompts. Differentiating from the aforementioned A-prompts, additional feedback is required, which happens after a response of the individual.

### 3.1.4.3 Direct input:

To understand direct input, the occupant has to provide information about their current (dis)comfort. This discomfort has to be tagged with information for the system to understand the input. This information, in directional tags, can either be a positive tag, a negative tag, or a neutral tag (similar to the 7 point scale used for the PMV, which uses a similar system, but has a different scale within the tags themselves). Alongside a directive tag also time has to be appended for the system to link the incoming data to IEQ measurements, and thus overrule the current measurement input with a personalized feeling of comfort.

These tags are then used by the system to direct the personal model to align with the individual's preferences. These types of interactions are labeled as "C", and result in C-prompts.

### 3.1.5 Data processing

The prompts are connected to tasks to use the measurement data and the input provided in the UI. This is how the NULLModel (the base model of IEQ parameter boundaries, based on the literature) is adjusted by the daily input which results in the updated NULLModel, which is named the DAILYModel. The benefit of a DAILYModel over direct input and overrule is that this creates more robust historical data which contains not only measurement information, but also personal preference. When working with a more automated system this could provide a more gradual changing model which does not use only the last input available (e.g. the temperature right before going to bed), but rather uses input that is linked to certain tasks. This principle of adjusting boundaries based on tasks is a combined approach of the research done by Wang et al. (2020), Wang et al. (2021), Gou & Chen (2020), Cuerdo-Vilches et al. (2021), Tokurua et al. (2021), and Torresin et al. (2021). These all have a combination of either WFH and IEQ, IEQ and Tasks, Tasks and cognitive functioning, and cognitive functioning and IEQ, or any more complex combination thereof.

The NULLModel is the standard model used in general cases based on the standards stated in the literature and the corresponding values required to perform certain tasks. The daily adjustments are meant to simulate a learning algorithm able to work alongside the subject preferences. The current application of the DAILYModel has its primary aim to gradually stimulate change and connect this change to tasks intensity values, which is visualized as followed:

$$Y_{it} = A_n + G_i * \left(\frac{\sum(M_n + (M_n + B_n) * P_{na} + (M_n + B_n) * P_{nb} + (M_n + B_n) * P_{nc})}{N} - A_n\right) \quad [3]$$

$Y_{it}$ = Value individual IEQ parameter per task intensity level
$A_n$ = Current Model Value
$M_n$ = Measurement value
$B_n$ = Prompt feedback correction
$P_{nx}$ = Prompt type correction
N = Total number of individual registered measurements
$G_i$ = Individual IEQ parameter growth rate

With i being the individual IEQ-parameter, n being the individual measurement with a time key, x being the prompt type, and t being the task intensity level.

Where the prompt type correction can have a positive or negative direction based on the feedback provided and works by setting a weight to the prompts with A-prompts having a weight of 1, B-prompts having a weight of 2, and C-prompts having a weight of 3. These weights are represented by Pnx having a Boolean value of 1 or 0 corresponding with the weights of the prompts. (A-prompts only have a value 1 at Pna, while C-prompts have a value 1 at Pna, Pnb, and Pnc). A growth rate is used to prevent bias within the system where if one day is skewed, the influences the model less heavily which allows this change to happen over time. After the $Y_{it}$ value is calculated for all the boundary values the DAILYModel is updated and used as input for the next day.

Important assumptions with this model are that the individual performs the task asked by the prompts, and provides feedback on the result. In an automated system, the emphasis would be placed on the feedback rather than the prompt itself due to the system being able to adjust where needed.

Additionally, tags are provided attached to the data (such as status of being sick, etc.) so that in future research this can be part of a DAILYModel. Now the model's focus is entirely on tasks performed in a WFH setting, but statuses of individuals that can explain skewed data would enrich the learning potential of the algorithm. Mainly, it would allow for prompts specific to those statuses alongside their current tasks. This combination could benefit linked data usage. Additionally, more developed systems can also use other linked data information. For this proof-of-concept case, the emphasis is placed on the IEQ-parameters in a WFH environment, but the potential to expand is applicable.

### 3.1.6 Data reliability and validity

The data gathered in the proof-of-concept is not going to be used for statistical analysis. Simply due to the data not matching the standards for the number of respondents and the number of measurements required for the proofing of statistical relations. It does, however, obtain data to visualize the connections between the measured data and the expected response of a proof-of-concept.

For the validity of the measurement devices, the devices used to measure the IEQ parameters are calibrated by an expert at one of the research facilities of the TU/e. The system then was checked for the instruments to work properly. The research instruments are seen as consistent during measurement. To maintain this consistency within the system, the data is both stored in a local relational database and a cloud-native database. The measurement output is compared within the system every minute and thus updated every minute to correspond with the most recent measurements. To ensure all data is in line with the response within the UI a failsafe has been implemented in the form of the clout-native database. This database has separate clusters to maintain clarity in the data transfer and to prevent data mergers due to overlap of matching IDs.

For the system to be used correctly a supportive letter was written explaining the nature of the research and the different aspects of the user interface with which the subjects would be working. This letter can be found in appendix 1 and was integrated into the file structure which the subjects received as a “Read me” file. During the measurement period, there was close contact with the subjects to solve problems originating in their native system or within the scripts running locally. These were fixed during the measurement period and will be made visible in the data.

The UI was integrated into a local laptop system available to the subject within arm’s reach during the entire period of measuring. This system worked independently from the system they had to use to perform their tasks in a WFH environment. To maintain a generalized approach, all prompts presented to the subjects are without bias or implication directing to preferred answers. The questions are further not tied to any of the work activities of the subjects but are generally based on the tasks presented by Torresin et al. (2021).

## 3.2 System architecture

To understand the application a step-by-step explanation of the different processes, as well as, the reasoning of why certain choices were made will be provided in this chapter. To give an overview, the following programming languages were used during this study: Python (version 3.10), HTML, CSS, TypeScript (version 4.4.3), and JSON. Additionally, the following software was used: Angular (version 12.0 & 13.0), Microsoft Visual Code (version 1.63), Darca (Version 3.1), and Eltek GPRS Server (version 1.0.1.18). Figure 9 shows a generalized perspective showcasing the front- and back-end interactions respectively, a complete overview of the system architecture and the flow of information is shown in figure 10.

Within figure 10, there are 4 main locations, which can be categorized as either front end, back end, or case environment. The cloud environment is only used as a central communication location where different scripts can update their current status in order to trigger reactions from other scripts. The case environment is dependent on the case specifics used in the proof-of-concept case.

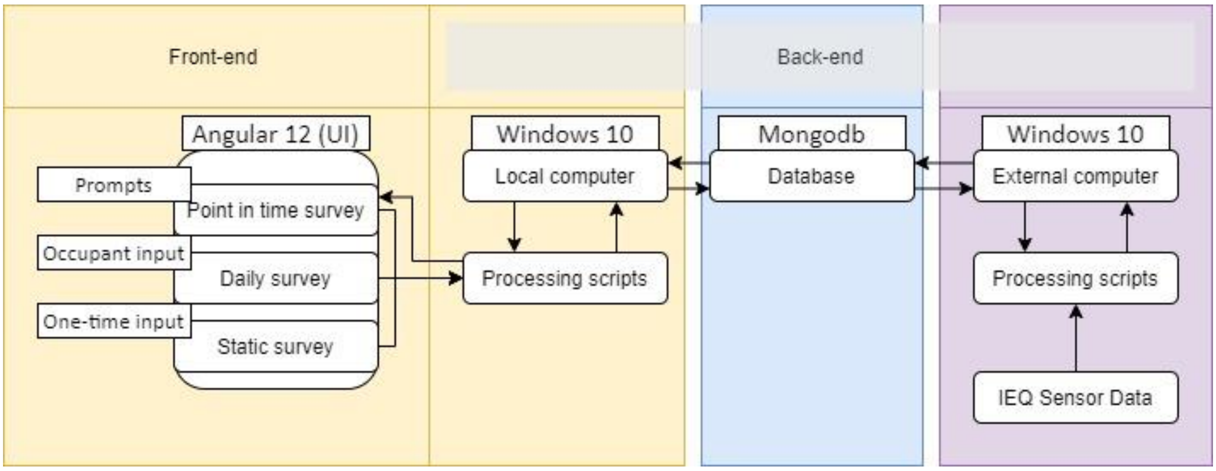


*Figure 9 Front-end and back-end communication flow*

### 3.2.1 Front-end

To communicate with the occupant of the room within the test location a user interface is needed. This user interface aims to communicate prompts with and receive input from the occupant. The input must be received as close as possible to the corresponding time key to match the IEQ perception to the IEQ measurements at the time the prompt was initiated. Furthermore, not every input is directly registered (e.g. if a subject changes its mind about, or presses the wrong button, etc.), as a safety measure a confirmation is also required.

The angular environment works with a layered four language architecture system. The main draw to angular over other comparative web application frameworks is its scalability. For this research angular was chosen due to that reason. However, the level of scalability was not required, and less complex application frameworks might be advisable for future research.

#### 3.2.1.1 User interface

The first element of the case study is the user interface which the subjects used to interact with the system. Within this user interface the individual is able to add information using the add button, respond to prompts by toggling their response combined with confirm, are able to toggle both static and current information about their IEQ comfort and personal labels. Figure 11 shows the landing page of the web application. The application is designed as a “one-pager”, where all information is visible and interactable from the landing page.

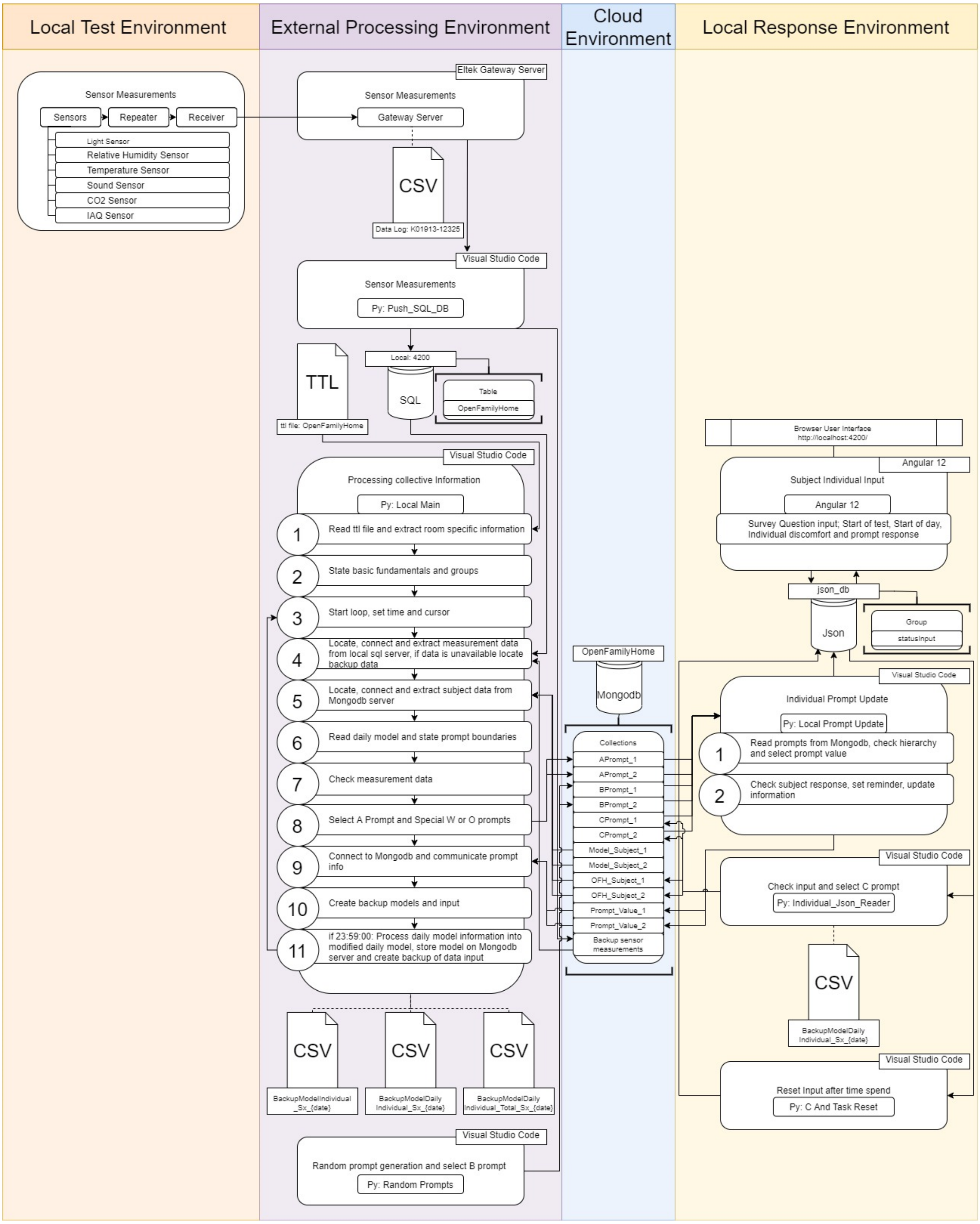


*Figure 10 Complete overview of system architecture*

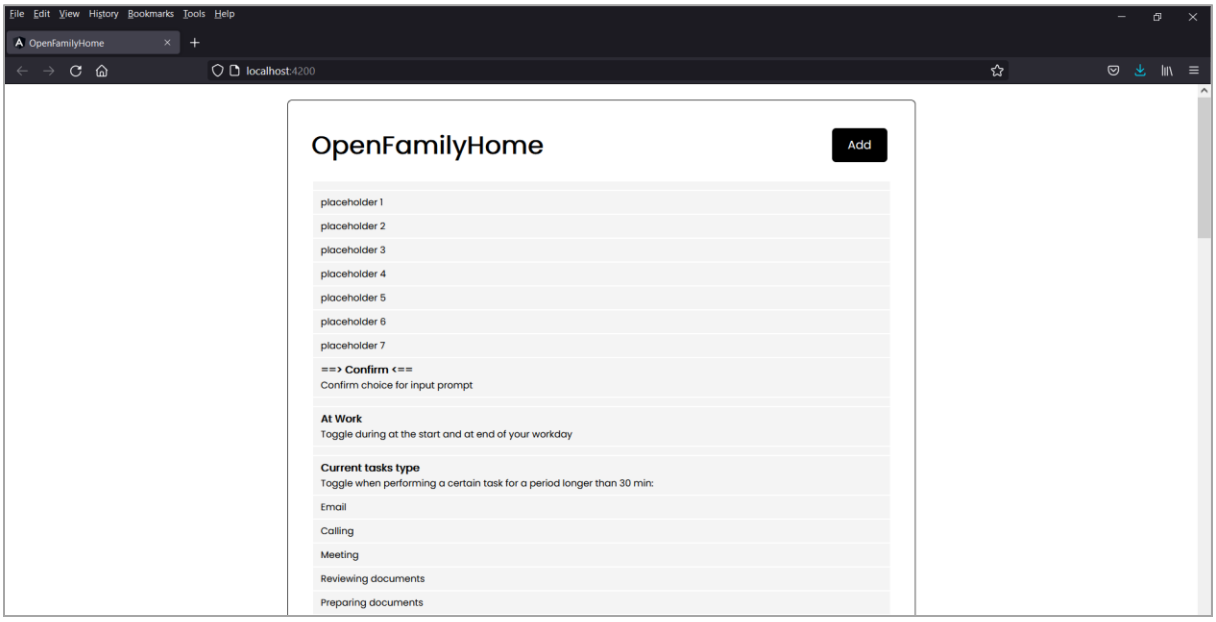


*Figure 11 Landing page of the application as seen by the subjects*

Figure 12 provides the looks of a prompt. In this case, “Glare_S1” which is a C-prompt, a direct response on the toggling of “Current Discomfort: Direct Glare”. If the subject decides to respond they toggle the correct line and toggle confirm. The responsible back end will update the current status within 60 seconds. Since this is the only page which the subject is required to use a logical structure is applied in which first the prompts are presented. Then the current information such as at work, current task, and current discomfort is shown. Thereafter all daily survey information is stated, and lastly, the static information is stated. Any toggles change the active color from grey to blue as seen in figure 13. This color change allows the subject to identify any given input at any given time.


*Figure 12 Prompt as seen by the subjects*


*Figure 13 Prompt response as seen by the subjects*

For the user interface both subjects were given a laptop (windows 10) with access to the internet. These laptops were positioned near their WFH location and only used for interaction with the UI. Both laptops belonged to the subjects, on which the required software is installed. Alongside this software, additional packages were stored on the local drive.

### 3.2.1.2 Angular environment behind the UI

Angular works by integrating components and services into its framework. The components are always subdivided into four layers. There is a CSS, an HTML, and two TypeScript layers. The CSS determines the style of the individual component and the HTML determines the general structure and layout. The first of the two TypeScript files is the spec-file which is mainly used for testing (this is not used in this research due to the web application being kept locally, and not be published). The last of the two TypeScripts is a TypeScript class combined with angular directories, and will henceforth be mentioned as the TypeScript-file. This file is the main component alongside the HTML layer and allows for data linkage between different parts of the application (or parts that are linked to it) and the HTML script.

This linkage allows for TypeScript binding to the HTML to set classes with defined properties. This binding allows for class properties to be passed in the HTML as variables (e.g. a button which is togglable and initiates a change such as color, referral, etc.). Additionally, functions can be defined in the typescript to initiate events based on interaction with the HTML layer. For this research, the main use of angular is for the combination between setting events and string interpolation (which allows for the incorporation of dynamic string values), which are needed for the prompts. This combination is then combined with a JSON database server (Jsondb) which runs locally. The values within the Jsondb are then linked through the layers to be visual in the UI. To allow the subject to give the input a dynamic directive is needed, which allows the user to toggle Boolean values.

Within the Angular TypeScript-file the AppModule collection is imported and bootstrapped (which allows access to different standard modules, such as the HTTP-module, etc.), this allows within the app for the “app.module.ts” to state declarations, imports, providers, and bootstraps. The declarations state the different components, the imports state the different modules used. For this app, only the root app component (AppComponent) is bootstrapped, and no providers are stated.

Similar to the app.module.ts, within specified components this same logic maintains where components are imported. Then declarations are made containing items, including the HTML tags which are used to embed the component using string interpolation (this also allows for JavaScript expressions and inline directives). Then classes are stated, including the component properties which are embedded within that class. Events are incorporated in the class, the functions of which (depending on reusability) are either within the component itself or are incorporated via an EventEmitter which is declared as an output with an event statement within the class.

An example of this can be seen in Listing 1, which is used to incorporate the “add” button into the application. The button itself is embedded in the HTML layer of the header component which makes use of the emit event stated, as can be seen in listing 2 (their connection visualized in red). This general ruling of embedding classes with properties, which are then stated in the HTML layer to call upon the stated properties, is the primary method of incorporating modules, statements, and information in the web application framework. This framework is based on the stated declarations made, including that which is imported from other components or the root app component. Both the declaration and the classes are needed together within the TypeScript layer to work properly within the HTML Layer via the use of tags.

```
import { Component, OnInit, Input, Output, EventEmitter } from '@angular/core';

@Component({
 selector: 'app-button',
 templateUrl: './button.component.html',
 styleUrls: ['./button.component.css']})

export class ButtonComponent implements OnInit {
 @Input() text?: string;
 @Input() color?: string;
 @Output() btnClick = new EventEmitter()

constructor() {}
ngOnInit(): void {}
onClick() {this.btnClick.emit();}}
```
*Listing 1 TypeScript example of string interpolation*

```
<header><h1>{{title}}</h1>
<app-button
*ngIf ="hasRoute('/')"
color= "{{ showAddStatus ? 'grey' : 'black'}}"
text="{{ showAddStatus ? 'Close' : 'Add'}}"
(btnClick)="toggleAddStatus()">
</app-button></header>
```
*Listing 2 HTML example of string interpolation*

### 3.2.1.3 Survey input integration

The occupant can make use of the angular environment as a web application, which functions of the Ai of this research. Within the angular environment three types of surveys are present, which are:

- **PIT survey input** (which are prompts, current tasks, current discomfort, etc.)
- **Daily survey input** (such as clothes, quality of sleep, etc.)
- **Static survey input** (such as the occupant's sex and age)

A complete overview of all survey structures can be found in appendix 2.

*PIT survey input*

The application in the UI provides the occupants with 9 dedicated prompt slots. These slots are used for the prompt, its response options, and the confirmation toggle. The information of the prompts is updated via the JSON database, which is connected to the angular environment.

When new input is available the web browser can be refreshed to see the new input. This browser refreshing requirement is a result of running a non-published application, which strains the occupants in terms of the effort required to provide a response.

Besides the prompt-dedicated slots, additional PIT data can be presented in the form of data tags that can be toggled. These data tags provide additional information surrounding the individual's IEQ comfort. These encompass the individual's work status, the currently active tasks, and IEQ discomforts within the case environment. The tags can be appended to the measurement data in the back end through the use of a time key corresponding with the moment of input.

*Daily survey input*

The applications have other slots dedicated to daily changing information. This information encompasses the individual's clothes, sleep quality, and sick status. These are all influencers of personal IEQ comfort and might skew input for IEQ preferences. For this reason, these tags are included, which add additional insight into the available data.

During the course of this proof-of-concept case, health data is requested. This health data goes under strict protocols and safety requirements to be used. In this study, this data is used to adjust the range of an individual’s threshold values for the triggering of prompts. Health data can provide insights into skewed results and should be within a dedicated system as multiple sources indicate their relation to IEQ comfort and preference (Geng et al., 2017). For this reason, this has been encoded in the system, and thus allows for survey input to be tagged with current health status. While providing additional insights, this is not further used within the results of the data gathered. As this is not the focus of this research. But to emphasize its importance, it has been incorporated in both the front and back end of the proof-of-concept case.

*Static survey input*

The static survey input is all leftover information still required by the system, but which is not likely to change. These are age (year of birth) and sex (male or female). As of this proof-of-concept case, no additional static information is requested. However, additional static information and comments can be added during the data gathering phase of the research. For this specific reason, the add status button is created so that a subject is able to provide additional insights which might be missing in the initial UI.

### 3.2.2 Back-end

The back end of the application is responsible for processing all input, storing all data, and generating results from the combination of all interactions. The back end of the application is spread over four different areas, these are:

- **Local test environment** (the physical environment occupied by the subject)
- **Local response environment** (the computer-based environment situated in the local test environment which hosts the UI and all scripts and programs required to maintain that UI)
- **Cloud-based database structures** (the independent cloud-based database structure which hosts all communications between scripts, backups of data, and the most recent DAILYModel)
- **External processing environment (**the computer-based environment hosting the primary scripts in order to process the incoming inputs and provide output)

These are separated into the communication structure and processing structure. Responsible for setting up the communication with the subjects and the processing of input respectively.

### 3.2.2.1 Communication structure

*Local test environment*

The local test environment host all sensors connected to the rooms used in the proof-of-concept case. The data is transferred to the processing environment where it is processed and stored. Additional information on the local test environment as used in the proof-of-concept case is presented in Chapter 4. This chapter goes into more depth in the case specifics, alongside the setup of the IEQ sensors, and the descriptive information of the used sensors.

For these case-specific sensors to work additional software is required. The Darca software is needed to connect the sensors to channels via a locally placed receiver. This receiver is then connected to the Eltek gateway software installed on a secure computer situated on the TU/e campus (the external processing environment). This computer (containing windows 10), will receive the information transmitted by the receiver and append this information to a local CSV file which occurs in intervals of 60 seconds starting at every full minute.

*Local response environment*

The local response environment hosts the UI, and all required scripts to maintain the connection and update the available visible information. The scripts themselves are specifically used in relation to the JSON database used by angular. Their primary purpose is to select prompts in order to communicate (based on a set hierarchy of C>B>A) and to communicate all input information to the processing environment.

*Cloud-based database structure*

The cloud-based database structure makes use of the service of MongoDB (version 5.0.6), with a database provided by Azure (the Netherlands, region west-Europe). The general cluster structure is an M0 Sandbox (General). For this research, a subscription-free service is used.

The primary purpose of the cloud database is to provide a communication method between scrips located at different computers. The scripts running are able to provide statements and post these within a dedicated cluster. Other scripts can recognize the information and act accordingly. When information is recognized by the dedicated script, a delete request is sent to remove the post before the next loop cycle requests the information again. Resulting in a cluster structure with only present information, which is not meant for historical data and is therefore stored locally if possible.

### 3.2.2.2 Processing structure

*External processing environment*

The external processing environment maintains the dedicated static IP required for the sensor data to be stored, hosts the linked data model, hosts the SQL relation database, and multiple processing scripts used to make sense of the survey input and provide output (such as prompts and the DAILYModel).

Within this environment, three important processes happen which are fundamental for a working system. These processes can be divided into the following parts:

- Linked data and relational database queries
- Input and output coding
- Daily model coding

Additional to these parts additional backups of all information are stored. This information is used to set preference values in the form of the DAILYModel, as well as, to trigger prompts.

### 3.2.2.3 Linked data and relational database queries

The power from a linked data model comes from the ability to create new RDF-triple relations and to query them regarding their native format. As the model is used as a directional map towards information, as with the hybrid approach, all information is queried individually based on the needs. Any transformations are required to happen within the designated scripts. Listing 3 provides an example of how the linked data is being queried using SPARQL in a python environment. This example query is used to find the measurement PIT data which is stored locally in a relational database. This relational database is queried using SQL, as is represented in listing 4, which provides an example of the sensor data and searched value.

SPARQL works by stating any prefixes (when used) and then using SELECT to state the output which is requested. Then statements are made which are required to be true for the data to be queried. All results are presented in a column and row structure with the results being all that meet those set statements. As the results are stated in a line-for-line structure and thus depend on the statements to hold, no cascading search requests are possible outside of workarounds. This limitation is due to the query results not stating variables, and thus already selected data isn't appended to that variable. The safest way to use SPARQL is by setting SELECT statements, and refining them until the required data is found. In the example, this has happened so that all information present in the database node is used as a python variable. The query results as requested in the Python environment will be (127.0.0.1 root OFH_1507834 openfamilyhomedb Ch-019 openfamilyhome), corresponding with the python variables.

```
SearchRoom = 'LivingRoom'
SearchValue = 'CO2'

Room = '"%s"' % SearchRoom
Database = 'DB_%s_%s' % (SearchValue, SearchRoom)
Zone = 'Zone_%s_point_%s' % (SearchRoom, SearchValue)
ZoneID = '"%s Zone %s"' % (SearchValue, SearchRoom)
Sensormeasurment = '%s' % SearchValue

gr = rdflib.Graph()
gr.parse(r'D:\Graduation_Project_1507834\Python\OpenFamilyHome.ttl')

qres = gr.query('''

PREFIX bot: <https://w3id.org/bot#>
PREFIX BOP: <https://w3id.org/BOP#>
PREFIX inst: <https://github.com/TheRealHatsikidee/OpenFamilyHome#>
PREFIX props: <http://lbd.arch.rwth-aachen.de/props#>

SELECT ?site ?building ?storey ?space ?sensor ?property ?'''+Database+'''
 ?'''+Zone+''' ?DBname ?DBhost ?DBuser ?DBpass ?DBVHeader ?Unit ?Table
Where {

        ?site bot:hasBuilding ?building .
        ?building bot:hasStorey ?storey .
        ?storey bot:hasSpace ?space .
        ?space props:longNameIfcSpatialElement_attribute_simple '''+Room+''' .
        ?space BOP:hosts ?Sensor .
        ?sensor a BOP:Sensor .
        ?sensor BOP:observes ?property .
        ?property a quantitykind:'''+Sensormeasurment+''' .

        ?sensor BOP:hasExternalDatabase ?'''+Database+''' .
        ?'''+Database+''' a BOP:Database .
        ?'''+Database+''' BOP:hasDataBaseHost ?DBhost .
        ?'''+Database+''' BOP:hasDataBaseUser ?DBuser .
        ?'''+Database+''' BOP:hasDataBasePasswd ?DBpass .
        ?'''+Database+''' BOP:hasDataBaseName ?DBname .
        ?'''+Database+''' BOP:hasDataBaseValueHeader ?DBVHeader .
        ?'''+Database+''' BOP:hasDataBaseTable ?Table .
        ?'''+Database+''' BOP:hasDataPoint ?'''+Zone+''' .
        ?'''+Zone+'''  BOP:isDataPointOf ?'''+Database+'''.
        ?'''+Zone+'''  BOP:hasUnit ?Unit.
        ?'''+Zone+'''  BOP:hasID '''+ZoneID+'''}''')

for Database in qres:
        host = Database.DBhost
        user = Database.DBuser
        password = Database.DBpass
        name = Database.DBname
        header = Database.DBVHeader
        table = Database.Table
```

*Listing 3 SPARQL query in Python of living room CO2 sensor data from the Turtle file*

For the SQL query again a SELECT statement is made, however instead of creating statements which require to be true. SQL requires the location of the data to be specified, as well as, as any search requirements. In the example of the SQL query in the Python environment, the information is queried using a MySQL cursor which is due to the use of the MySQL database, as the local relational database. The SQL query in the example is SELECT CH-011 (which is the channel of the corresponding sensor) and the corresponding table which stores the information WHERE ID = time key. The result of the query at time 12/01/2022 17:34:00 is 24.2, which is the light intensity in Lux. In this example is the output from the SPARQL query used as input for MySQL connector, which connects the script to the SQL database.

```
        db = mysql.connector.connect(host='%s' % host, user='%s' % user, passwd='%s' %
        password, db='%s' % name)

        SearchRoom001 = 'LivingRoom'
        SearchValueHeader001 = 'Ch-001'
        SearchMUnitTransformer001 = (1)

        SensorCH001 = "SELECT `{}` FROM {} WHERE ID = %s".format(SearchValueHeader001,
        table)
        mycursor001 = db.cursor()
        mycursor001.execute(SensorCH001, ID)

        myresult001 = mycursor001.fetchone()
        if myresult001 != None:
                for Sensor001 in myresult001:
                        if Sensor001 == 'No Data':
                                mSensor001 = Sensor001
                else:
                        mSensor001 = float(Sensor001)*SearchMUnitTransformer001
```

*Listing 4 SQL query in Python of living room light intensity sensor data from the MySQL database*

Additional to the already existing RDF-triples, new relations can be created to enrich the available data. These RDF-triple relations are then query-able similarly to the SPARQL query example in listing 3. Any relational database information such as new sensor data is query-able similarly to the SQL query of listing 4.

*Input and output coding*

All incoming input is transformed into Python variables to be used by the scripts. As many different native formats are used (linked data, relational databases, MongoDB posts, etc.) much of the data has to be transformed or redefined to be used properly. Python variables are used in order to make the data format readable by the designated Python script.

A detailed description of all interactions of the Python scripts is available in Appendix 3. The way output is generated is through the use of the threshold values based on literature and the individual's preference. The method of which is described in Chapter 3.1.4.1.

The coding of these inputs is in an if-then format, which is visible in listing 5. In this example, a temperature value coming from the SQL query is checked against the parameter threshold values. Dependent on the individual input, the DAYLIModel, and the current task/at work status different threshold values are used. In the case that a threshold is exceeded, a prompt corresponding with that IEQ parameter will be presented to the subjects in the UI.

```
Temp_Influence_Value_S1 = 0
        if CurrentStressStatus_S1 == 'True':
                Temp_Influence_Value_S1 += float(0.5)
        if CurrentRestStatus_S1 == 'True':
                Temp_Influence_Value_S1 += float(0.2)
        if Sick_S1 == 'True':
                Temp_Influence_Value_S1 += float(0.3)
        if Fever_S1 == 'True':
                Temp_Influence_Value_S1 += float(0.7)
        if Female_S1 == 'True':
```

```
                if MenstruationCycleEffects_S1 == 'True':
                        Temp_Influence_Value_S1 += float(0.3)

        if mSensor013 != 'No Data':
                if AtWorkStatus_S1 == 'True':
                        if mSensor013 > (Temp_Max_S1 - Temp_Influence_Value_S1):
                                Room_TooWarm_A_S1 = 'True'
                elif mSensor013 < (Temp_Min_S1 + Temp_Influence_Value_S1):
                        Room_TooCold_A_S1 = 'True'
                if AtWorkStatus_S1 != 'True':
                        if mSensor013 > (Temp_Max_NonWork_S1 - Temp_Influence_Value_S1):
                                Room_TooWarm_A_S1 = 'True'
                elif mSensor013 < (Temp_Min_NonWork_S1 + Temp_Influence_Value_S1):
                        Room_TooCold_A_S1 = 'True'

    Temp_Influence_Value_S1 -= Temp_Influence_Value_S1
```

*Listing 5 Example in Python of temperature parameter thresholds as used in the proof-of-concept case*

All incoming input is labeled with a time key, a corresponding IEQ parameter, a corresponding prompt response (A, B, C, or NULL), and a response direction (+,-,=, or NULL). Based on this information all input is appended to a list, which is used as input for the DAILYModel.

*Daily model coding*

The DAILYModel uses the input from stated lists to adjust preferences on a daily basis. Depending on the input additional weights can be added to the responses and corresponding measurement values, using the method explained in Chapter 3.1.5. In this example the list containing the measurement values of light intensity in lux tagged with high concertation tasks are used as input for the DAILYModel. If none is available the model value of the previous day is maintained, otherwise it is adjusted according to the designated growth rate. This method is applied in the proof-of-concept case as seen in listing 6.

```
if len(LuxInt_High_Concentration_S1_MeasurementValue) != 0:
                LuxInt_High_Concentration_S1_MeasurementValue_Average =
                sum(LuxInt_High_Concentration_S1_MeasurementValue)/
                len(LuxInt_High_Concentration_S1_MeasurementValue)
        if len(LuxInt_High_Concentration_S1_MeasurementValue) == 0:
                LuxInt_High_Concentration_S1_MeasurementValue_Average =
                Value_LuxInt_High_Concentration_S1

        LuxInt_High_Concentration_S1 = Value_LuxInt_High_Concentration_S1 +
        ((Value_LuxInt_High_Concentration_S1 -
        LuxInt_High_Concentration_S1_MeasurementValue_Average) / GrowFraction)
```

*Listing 6 Example in Python of the DAILYModel value generation of light intensity*

# Chapter 4. OpenFamilyHome case study

*This chapter will elaborate on the use-case setup, used materials, and results. The results section will go into depth in the IEQ parameter data and evaluate the application as a whole. It will first describe the collected data and highlight interesting results. Then the next paragraph will provide an overview of the different sections of data and the corresponding interaction of the application.*

## 4.1 General description and setup

This location is presented voluntarily by the test subjects. As is in line with the TU/e code of scientific integrity additional documents regarding the test subjects are signed, of which copies are found in appendix 4.

For this case study, a semidetached house situated in the Netherlands has been used. The period of data gathering has been in January 2022, $13^{th}$ till $20^{th}$. The study consists of two subjects and two rooms within a working from the situation. The first subject is tied to the living room/kitchen area (living room), the second subject is tied to the at-home office (bedroom).

The evaluation of these cases aims to provide insights into the following topics:

- To establish the use-case of linked data-based Digital Twin models from a WFH perspective.
- To evaluate the ability to communicate information of the IEQ sensor measurements within the corresponding rooms with the occupants via the use of linked data.
- To visualize the interaction between the individuals and the user interface through prompts responses and the daily model.

*Room description*

Two rooms are used, the living room and a bedroom dedicated as working from home office. The living room is a hybrid room connecting the Livingroom/kitchen area to the kitchen. It has a connection to the outside environment with a large surface area, allowing for light to pass through (South oriented). The bedroom has one window oriented at the south and one at the west. Both rooms have access to mechanical ventilation. The living room has a large kitchen table used for the WFH location, while the bedroom has access to a desk. Both rooms were not designed with a WFH situation in mind and are upholding the standards corresponding with their original purpose. The building itself is around 5 years old, and thus up to the current standards as of 2022.

### 4.1.1 IEQ sensor selection

As the defining EIQ parameters thermal, humidity, IAQ, acoustic, visual light, visual environment are selected. Of these IEQ parameters only thermal (temperature in °C), humidity (Relative Humidity in RH), IAQ (both as a general quality in Boolean, and CO2 levels in ppm), Acoustic (Sound pressure levels in dB), and visual (light surface intensity in lux) are chosen as measurement parameters ranges. The visual environment is left out of the sensor measurement section of the research but is covered by the survey section of the research due to it being tremendously hard to measure environmental visual quality as it is highly personal. Especially in a WFH environment, where a subject has high agency in its surrounding environment and thus more easily accepts deficiencies (Wang et al., 2021; Cuerdo-Vilches et al., 2021). The sensors selected are represented in table 18.

*Table 18 Sensor specifications for measuring the IEQ parameters*

| IEQ Parameter | Range | Measurement Resolution* | Instrument |
|---|---|---|---|
| Thermal | -20-80 | Temperature in 0.1°C | Eltek RHT10D |
| Humidity | 0-100 | Relative Humidity in 0.1 RH | Eltek RHT10D |
| IAQ | 0-5000<br>0-10 | CO2 levels in 0.001 V (translated to 0.5 ppm)<br>IAQ Quality in 0.001 V ** | Eltek GW47<br>Eltek GD47AC |
| Acoustic | 30-130 | Sound pressure levels in 0.001 V (translated to 0.01 dB + 30) | PCE Instruments PCE-353N Decibel meter 30-130 dB 31.5Hz-8kHz |
| Visual | 0-4000 | light surface intensity in 0.1 lux | Eltek LS50 Light puck |

* As PIT values, three measurements per minute, with output once per minute.
** two sensors are used in this study that transmits their values in different resolutions scales. The output is in V, the value which it represents is with transmitter (A) 0-10 V, and transmitter (B) 0-1 V. This is automatically translated in their Booleans threshold value.

The reason for selecting these particular sensors is that they were already available for the research and are easily accessible during the tests. Due to them being individual sensors more precise handling is possible when compared to other combined solutions. However, they are not easy in placement and might result in hindrance by the test subjects when the available space is not sufficient enough. In the case of smaller WFH spaces (mainly the desk environment), other solutions might be better such as the Elsys ERS combined sensor solutions.

The sensors act as transmitters, which are either directly sent to, or via a repeater sent to the Gen II SRV250 receiver logger. The receiver will then, via a SIM card, transmit the combined and collected data, via the GPRS cloud (General Packet Radio Services), to a connected Eltek Gateway server running via a fixed IP router. This Eltek Gateway server publishes this data in CSV format (comma-separated value) locally.

Figure 14 shows a schematic overview of the setup of one of the rooms in the case study. The receiver in this case hosts both rooms and combines the information based on the incoming channels. A general overview of the case site has been provided in figure 15. During set-up, it was made sure that all sensors are within the 4m range (especially needed for sound). Temperature, $CO_2$, IAQ, and sound are measured at ground level (near the wall), due to the close proximity to the subject (within 1,5m overall), and because only a general indication is required. The light intensity is measured at desk level at the location of the subject.

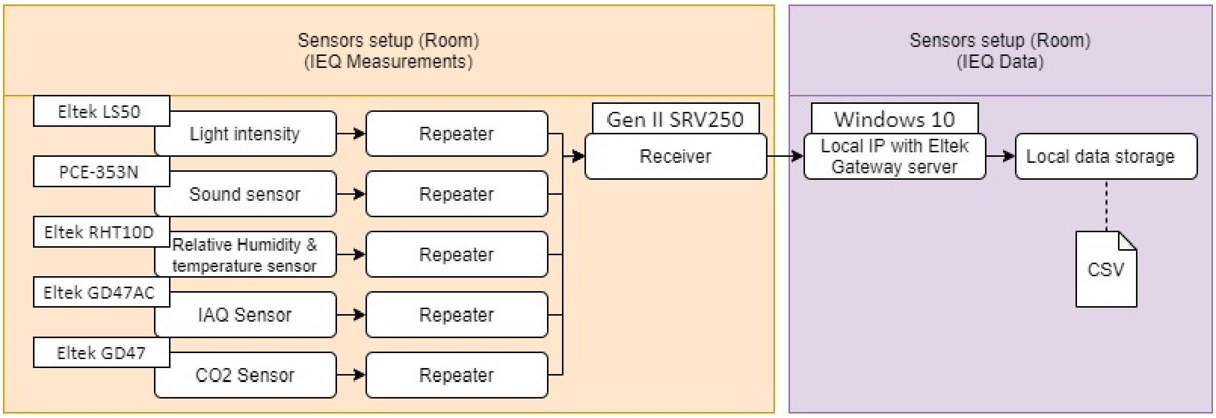


*Figure 14 Schematic overview of sensor setup*

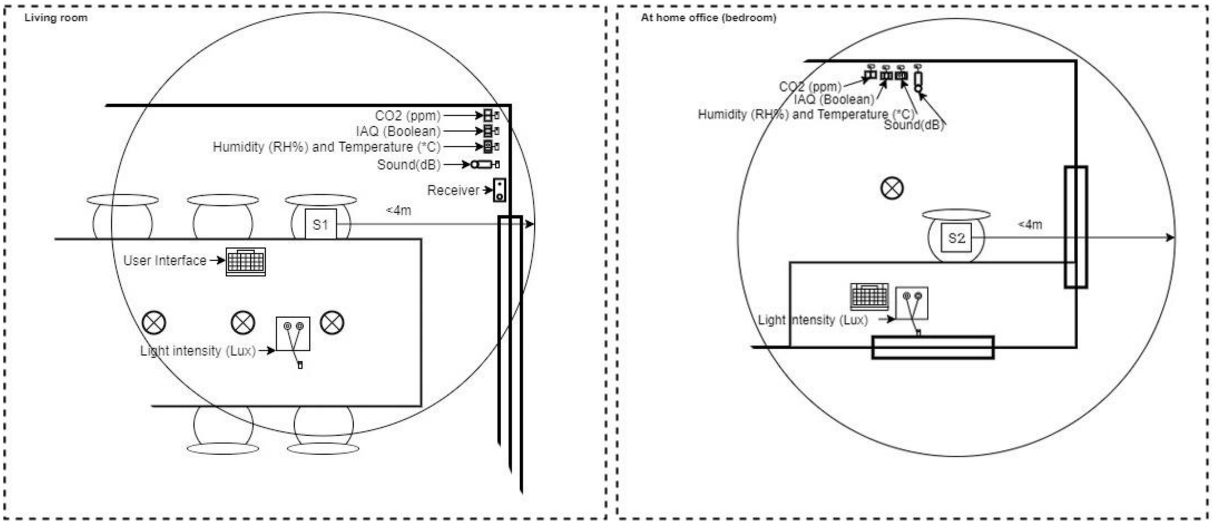


*Figure 15 Visualization of sensor setup in the living room and at the home office as used in the proof-of-concept case*

## 4.2 Case results

The system as a whole (room measurements, Digital Twin, and user interface) worked as intended. Using the adapted model figure 16, as adapted from chapter 2.2.1, figure 4, the system spans the external input (sensing level), Digital Twin (data collecting level, core entity level, and user entity level), and external output (application entity level) respectively. Where the sensors are providing the external input. This input is collected and stored in a SQL relational database locally on a secure computer. Within this system, the SQL database is the primary result from the linked data Digital Twin (which spans the data collecting layer and the core entity layer), alongside static information stored in RDF-triples. This format of Digital Twin could be interacted with via SPARQL, which is the user interface layer of the Digital Twin (in the case of this proof-of-concept case that user interface for other applications is the python environment).

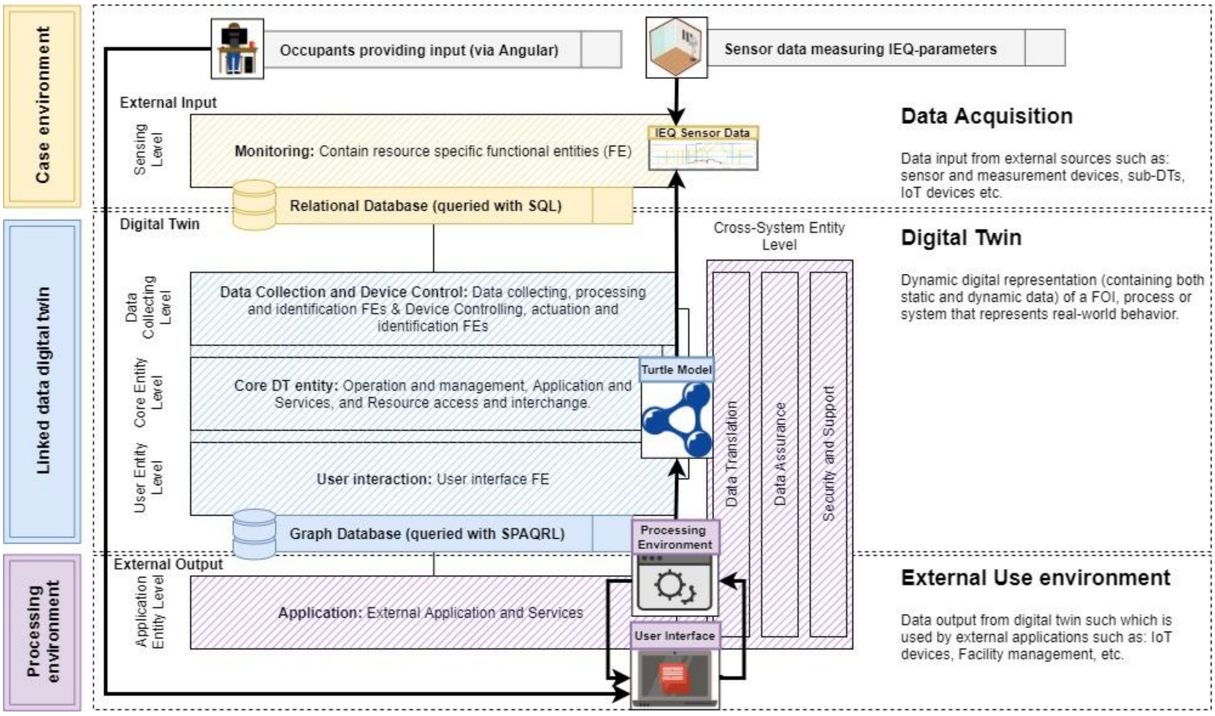


*Figure 16 Schematic representation of the Digital Twin as used in the proof-of-concept case (adapted from Lu et al., 2019; Laamarti et al., 2020 and Shao, 2021)*

The application entity layer is the use-case of this research and spans the data received from the SPARQL query and uses it to create added value from the data and uses the principles of the cross-system entity level (such as data transformation, since all input is transformed into python variables)). The information from the SPARQL query results in the SQL query, and the reading of the input values in the UI via the MongoDB cloud-based database collections. This separates the evaluation into two distinctive sections: the evaluation of linked data-based Digital Twins, and the application in the form of the use-case.

### 4.2.1 Description of use-case results

During a period of 5 workdays from the second week of January 2022 till halfway through the third week, data has been gathered about the IEQ parameter values, the individual's comfort, and tasks performed in a working from home environment. A total of two participants provided input via the user interface by responding to the different types of surveys. The subjects of the study were on voluntary bases and were situated into two different WFH environments. The first subject was situated in the living room (the area between the living room and kitchen) at the kitchen table. The second subject was situated at a stay at home office (which was a bedroom converted to facilitate the needs of a WFH environment). The participants were notified about the user interface, and an explanation was given about the workflow required. Increased emphasis was placed on the requirement of the subjects to select current tasks, in order for the DAILYModel to understand the values of comfort and task activity levels during the day.

An overview of how the data is used by the system is given in figure 17. Appendix 5 and 6 provides, for subject 1 and 2 respectively, the descriptive frequencies of the most important variables.

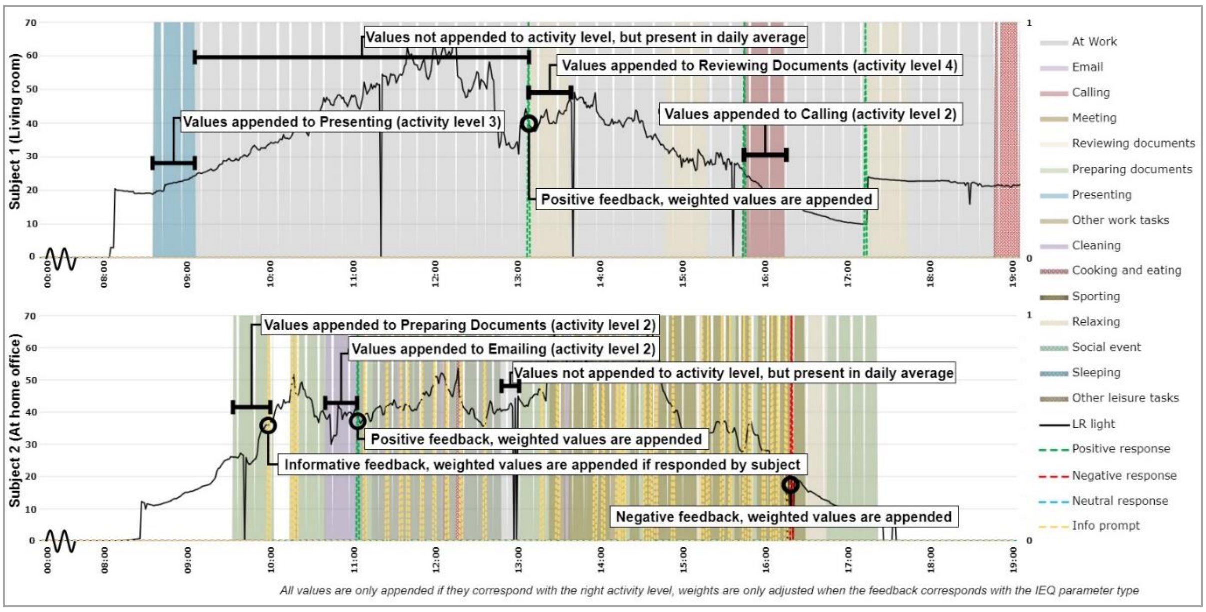


*Figure 17 Graphic overview of how data is interpreted by the system*

To clean the data from the collected CSV files first all independent files are collected. Secondly, all data was restructured to maintain a row to row relation to their corresponding timestamp. Thirdly, all restructured data files were combined into one combined file. Fourthly, all responses are enriched with their corresponding direction, labels, and response type. Lastly, all missing data has been dealt with via taking the sum of both the predecessor and after values and taking their combined average.

The total number of data points measured during the case run is 11519 for subject 1, and 7198 for subject 2. This discrepancy is due to the system running during the weekend (day 4 and 5 of the total 9 starting from 1) for subject 1, while subject 2 has no data during that period. The amount of inputs of subject 2 to subject 1 is 3287 to 554, which is about 6 times as much. Table 19 provides an overview of the task distribution including the task activity level per subject. This results in subject 1 having 4,81 % of all IEQ measurements being appended to their DAILYModels, and the rest only being visible in their daily average. Subject 2 has 45,67% of all its data points being appended to their DAILYModels, resulting in a more informed model, better showing the individual's preferences.

*Table 19 Overview of the number of data points tagged with tasks*

| **Subject** | **Task activity level (*Tasks*)** | **Total** | **%** |
|---|---|---|---|
| 1 | 1 (*Relaxing (27)*) | 27 | 5 |
| | 2 (*Email (82), Calling (27), Meeting (55), Preparing documents (192)*) | 356 | 64 |
| | 3 (*Presenting (28), Cooking and eating (60)*) | 88 | 16 |
| | 4 (*Reviewing documents (83)*) | 83 | 15 |
| 2 | 1 (None) | 0 | 0 |
| | 2 (*Email (110), Meeting (2671), Preparing documents (470)*) | 3175 | 97 |
| | 3 (*Cooking and eating (3)*) | 3 | <1 |
| | 4 (*Reviewing documents (109)*) | 109 | 3 |

The descriptive averages of the individual rooms on a workday basis are presented in table 20. The responses of the IEQ parameters in a WFH environment are represented in tables 21 and

22. Of these responses only 8,25% was a response that was made about an IEQ parameter that was within its boundary. Showing that most interaction with the subjects was about IEQ parameters that did not conform to the norms stated by the literature. Overall this shows that individuals are complaining about IEQ parameter values when they are within boundary and when they are outside their stated boundaries.

Distinctive differences can be seen between subjects 1 and 2 according to table 20. Subject 1, situated in the living room, has by far the best performing IEQ parameters with the noticeable exception of light intensity. The IAQ within the living room performs on average according to the stated thresholds, which is not the case with the bedroom. The average humidity of the living room is almost up to the stated standard of a maximum of 45% when performing work-related tasks. Again this was not the case for the bedroom, which can be too damp on average. Even succeeding the 50 RH threshold stated by the literature for both leisure and work-related tasks in general. The average temperature of both rooms was lower than when accounting for a WFO environment. However, only a total of 5% of all responses on the IEQ parameters was too warm or too cold (1% and 4% respectively), as seen in table 21. On average the light intensity of both rooms was not up to the required standard. However, according to the required intensity of the tasks combined with the IEQ parameter (figure 18 and 19) shows that the leisure tasks seem to be meeting their requirement. For the bedroom, the light intensity is far more up to the required levels, but still far beyond what is deemed desirable, and is far lower than the WFO requirements from the literature. Additionally, the average sound pressure levels, and the Out of Boundary (OoB) levels are comparable to that of a WFO environment.

*Table 20 Overview of IEQ parameter averages per room per workday*

| **Day** | **Average light intensity (lux)** | | **Average IAQ** | | **Average CO2 level (ppm)** | | **Average Relative humidity (%)** | | **Average temperature (°C)** | | **Average sound level pressure (dB)** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Subject* | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| 1 | 43,6 | 381,6 | 4,6 | 5,0 | 928 | 1936 | 46,3 | 52,2 | 19,28 | 18,7 | 34,2 | 34,2 |
| 2 | 33,4 | 499,7 | 4,5 | 5,4 | 1012 | 1656 | 46,7 | 51,9 | 19,28 | 18,6 | 34,7 | 34,5 |
| 3 | 26,4 | 290,5 | 4,0 | 5,2 | 683 | 2169 | 47,1 | 56,8 | 19,03 | 18,8 | 33,6 | 34,1 |
| 4 | 20,3 | 267,9 | 4,2 | 5,1 | 966 | 1830 | 49,9 | 56,9 | 19,50 | 18,9 | 34,5 | 33,9 |
| 5 | 18,3 | 148,1 | 3,9 | 5,3 | 804 | 1856 | 46,8 | 55,7 | 19,10 | 18,9 | 34,1 | 33,9 |

*Table 21 Response distribution out of boundary per IEQ group*

| IEQ response (response type) | % of total responses |
|---|---|
| IAQ (too low) | 22% |
| Thermal (too cold) | 4% |
| Thermal (too dry) | <1% |
| Thermal (too humid) | 25% |
| Thermal (too warm) | 1% |
| Visual (too dark) | 20% |
| Visual (too light) | 20% |
| Within boundary responses | 8,25% |

Furthermore, table 22 shows the within boundary responses on IEQ. This table shows that Acoustic and IAQ when within their boundary, suggest a positive response. While thermal, when within its boundary, still results in a neutral or negative response. Visual seems to be on the positive side. However, when this is compared to table 21, it shows that 87% of all discomfort responses are about visual (40%), IAQ (22%), and humidity (25%). Comparatively, temperature is only 5%, and acoustic is not represented.

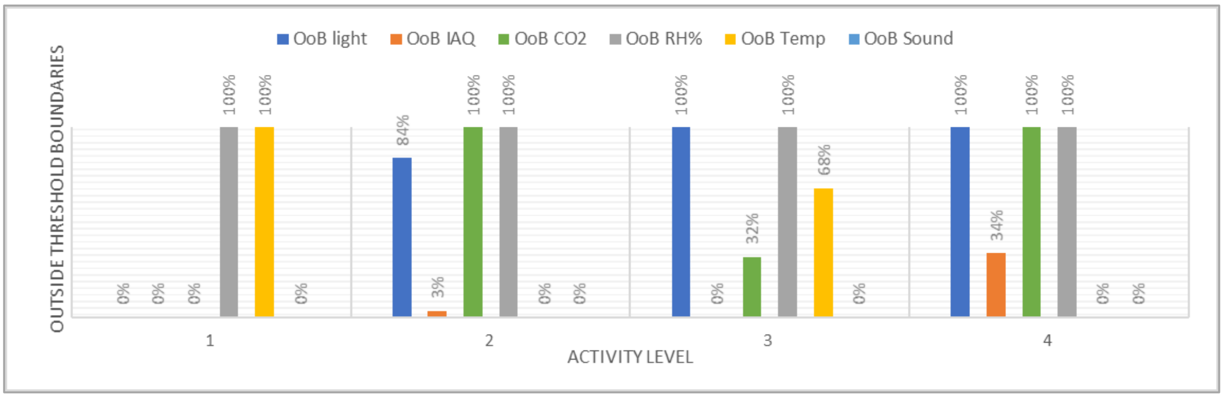


*Figure 18 Out of boundary (OoB) values per activity level for subject 1*

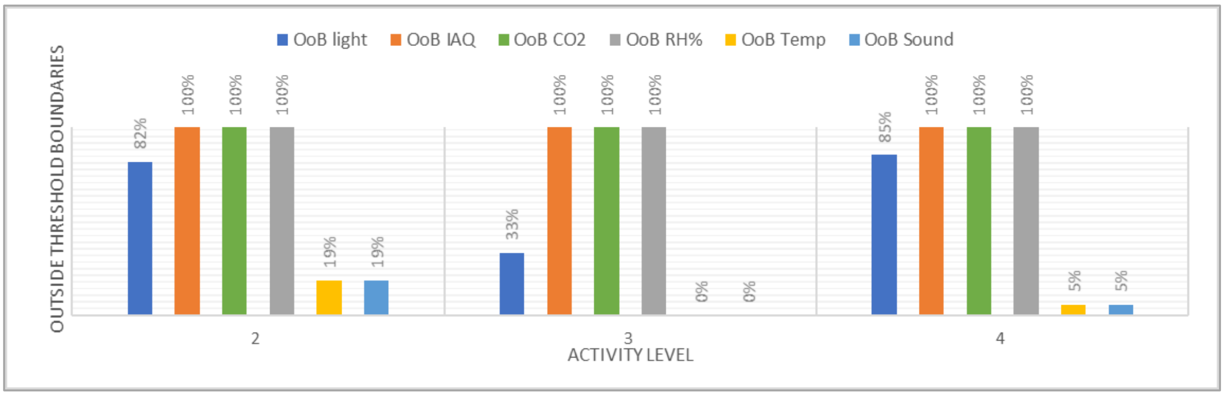


*Figure 19 Out of boundary (OoB) values per activity level for subject 2*

*Table 22 Response distribution within boundary per IEQ group*

| Within boundary IEQ response | | | |
|---|---|---|---|
| **IEQ group** | **Positive** | **Neutral** | **Negative** |
| Acoustic | 100% | 0% | 0% |
| IAQ | 100% | 0% | 0% |
| Thermal | 0% | 50% | 50% |
| Visual | 67% | 33% | 0% |

Additional insights in the results of the individuals are given in figure 20 which shows the prompt types, corresponding IEQ parameter, and representation in the percentage of the IEQ parameter within the prompt type group. The figure shows that there is a difference between the individual parameters in relation to the types of prompts (and thus shows how well represented they are within the different groups). So is thermal (represented through temperature) only represented 5% and 7% of the measurement prompts and random response prompts respectively. The direct input of the individuals show that 43% of all prompts are related to temperature. This distinction is inverted with respect to thermal (represented through humidity), which shows a 27% and 31% of the measurement input and random response input respectively while being absent from direct input. With respect to acoustic no OoB values are measured. However, there are still prompts originating from the direct input. This shows the contrast between figure 20 and table 22, where table 22 shows that 100% of all responses are positive with respect to acoustic. However, table 22 does not account for the direct input and only counts the responses on the prompts. Figure 20 further shows that both IAQ and light are represented highly in all three prompt types.

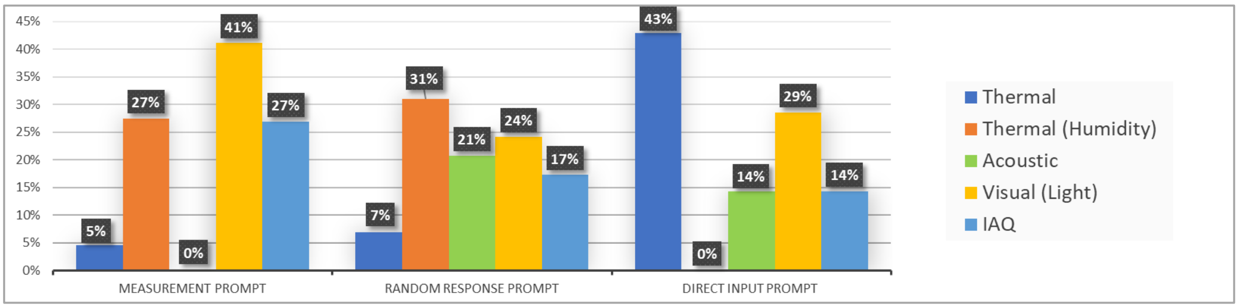


*Figure 20 Overview of IEQ parameters to prompts*

When accounting for the OoB levels of the IEQ parameters per task type and activity level (figure 18,19,21, and 22), it is noticeable that the bedroom (the smallest of the two options) performs worse than the living room. When the bedroom is dedicated to a WFH environment, while the living room is not. The tradeoff of light intensity versus IAQ and humidity suggests representing the location and size of the rooms to be important factors. Figure 21 and 22 further underpin the statements about figure 18 and 19. It is noticeable that temperature and sound are far less OoB compared to the other IEQ parameters. Due to the short amount of time covering both locations, no significant results can be pinned to the IEQ. However, this difference between rooms, between activity levels, and between tasks shows proof-of-concept as the difference is noticeable and measurable.

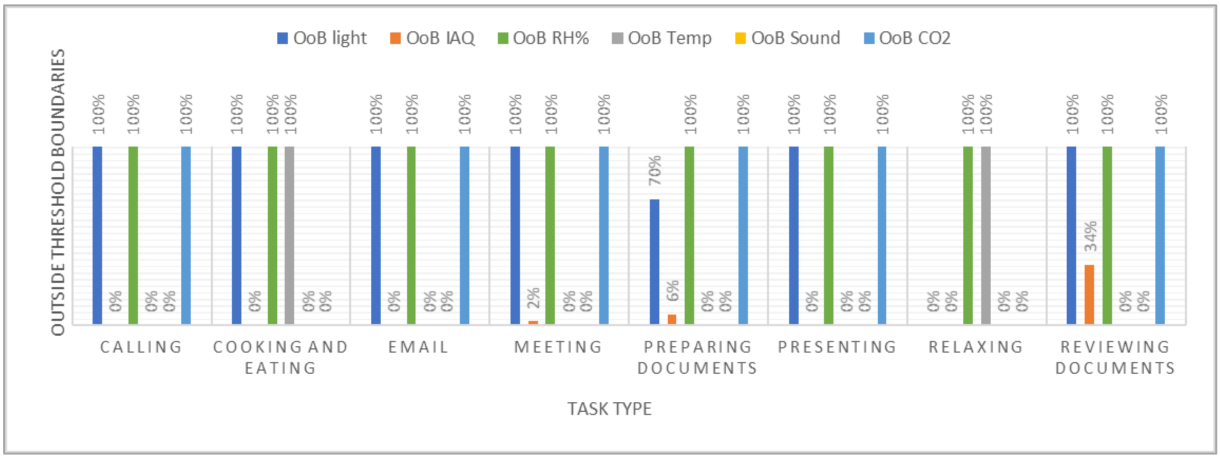


*Figure 21 Out of boundary (OoB) values per task type for subject 1*

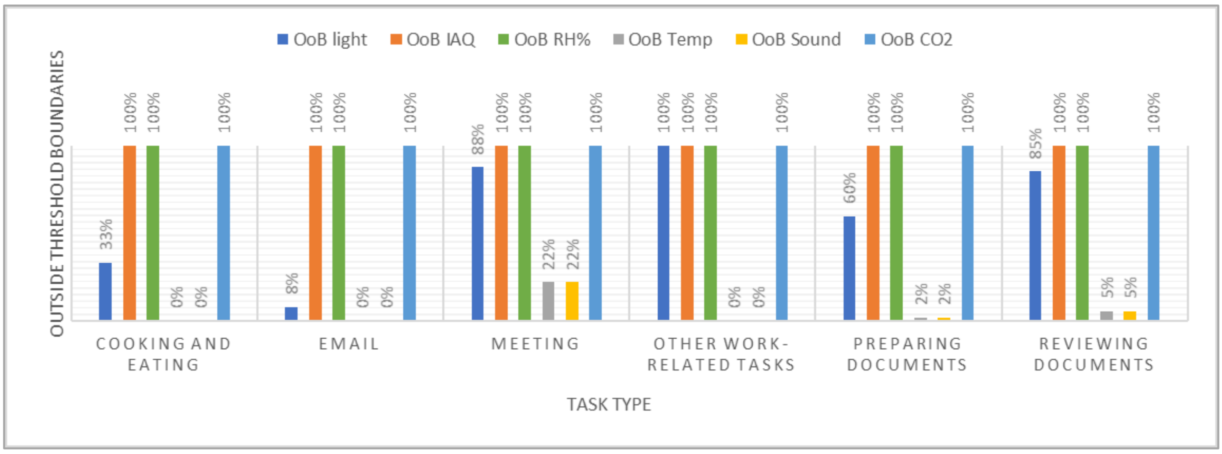


*Figure 22 Out of boundary (OoB) values per task type for subject 2*

## 4.2.2 Evaluation of the prototype

The first part of the evaluation will focus on the system's ability to respond to input. Figure 23 shows the sequence of a prompt trigger. First, a shift in tasks is noticed (1) (going from a meeting to reviewing documents), this triggers a response to check the current IEQ values (2) (in the figure to the corresponding threshold values of the activity level). Then the prompt is provided to the subject (3). The response time of the system is about 1 minute, due to the limitations of processing power and a continuous check and update required. It is noticeable that the light intensity is outside of the threshold values, but no direct negative feedback is provided from the occupant other than at the shift from one task to another. This lack of negative feedback might be connected to the task at hand, the shift, and thus the becoming aware of the subject, or due to the activity level that does not match the task proper (of which a meeting and preparing documents are now the same).

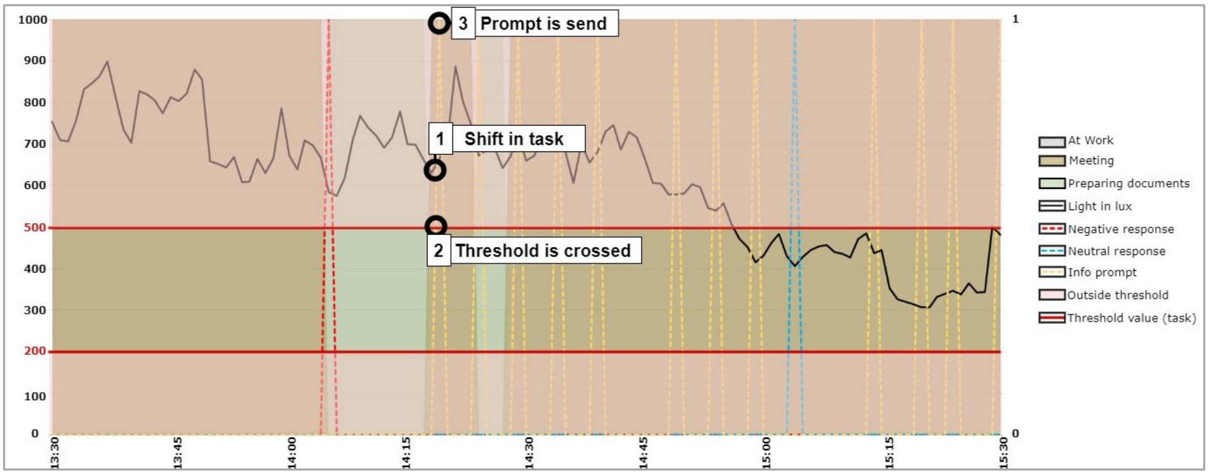


*Figure 23 Example of the prompt trigger after threshold condition (measurement input)*

Additionally to the prompt trigger with a task that has a similar activity level, figure 24 shows the trigger of a prompt when the task is of another activity level. This prompt was responded to with a neutral disposition of the subject. This response is noticeable since the light intensity in lux is far too low for the activity level. However, this activity is only of short duration. This might indicate why the demanded level is not required. Another reason might be due to the individual's adaption to its WFH-environment, which indicates a lower quality of indoor environmental parameters is accepted over similar tasks in a WFO situation. The IEQ parameters that show similar behavior to visual (light) are IAQ (general, which is almost 50% of the time over the threshold value), IAQ (CO2, which is on average over three times the accepted limit for good air quality), and temperature (which is lower than in a WFO environment, however, the amount of feedback on being too cold is incredibly low).

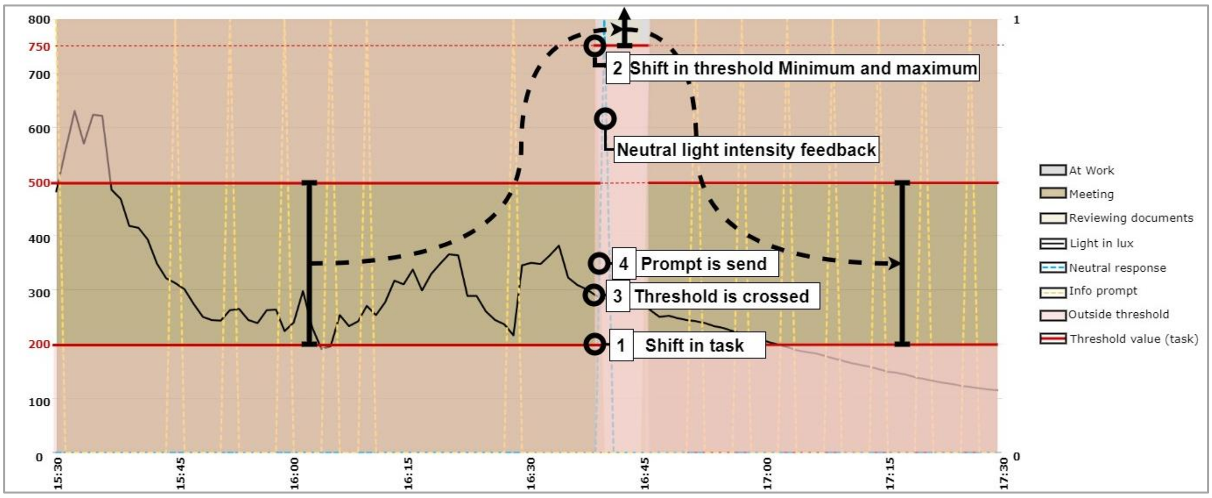


*Figure 24 Example of the prompt trigger after switching tasks with different boundaries*

Furthermore, additional information can be derived from the data, which the system is unable to understand as-is. Figure 25 shows an example, where the CO2 in ppm drops after the subject indicates to make and eat as a task. The CO2 drops significantly, which indicates a sudden flow of air such as with opening a window or a door. Then the CO2 level slowly decreases probably due to the subject leaving the room. The last of the tasks are ended (due to the failsafe embedded in the system after thirty minutes of no new input), which holds up to the moment the CO2 levels start to increase again, and new tasks are toggles (indicating a return of the subject). Most of the prompts during this period are about the CO2 levels being too high. Most others are prompts requesting the subject to indicate whether the subject is prone to certain indicates of bad air quality (such as dry eyes, dry throat, etc.). The system does not compare rooms to understand changes in data. However, if the same period of figure 25 is compared to that of subject 1, it is shown that shortly after the decrease in CO2 levels in the room of subject 2, the CO2 levels of subject 1 start to rise indicating an additional individual in the same space. This is indicated in figure 26. Furthermore what can be seen is that the CO2 levels of subject 1 (while still way above the threshold values) are on average lower than that of subject 2, this is probably due to the size of the space which allows for more of a buffer. As can be seen in figure 26, the peak value of that period is lower than that of subject 2. However, the decrease in CO2 in ppm per minute is lower, indicating the capacity of larger space to maintain critical levels over smaller space with similar intervention methods (the space of subject 2 would benefit more per ratio to an intervention method like opening a window than if a similar-sized window would be opened by subject 1). These types of information are not present in the current iteration of the system, but could highly benefit from additional information via the linked data based Digital Twin (such as meteorological data, to determine if the mechanical ventilation would be more impactful than opening windows (accounting for their size from the building model, the outside parameters coming from meteorological sources, outside air quality, outside noise, etc.), or if opening both is a necessary solution).

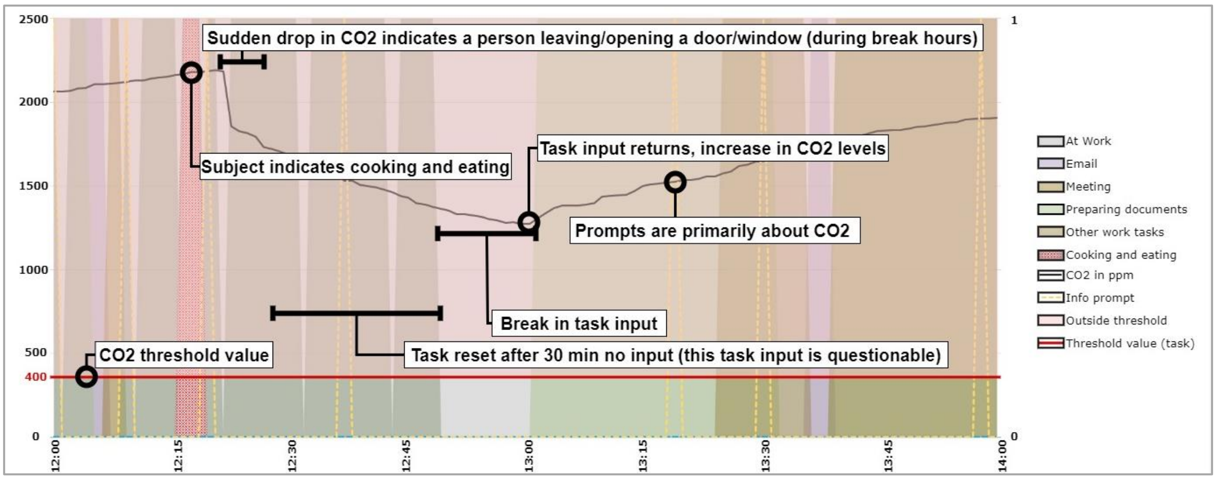


*Figure 25 Example of limitations in the current iteration of the system*

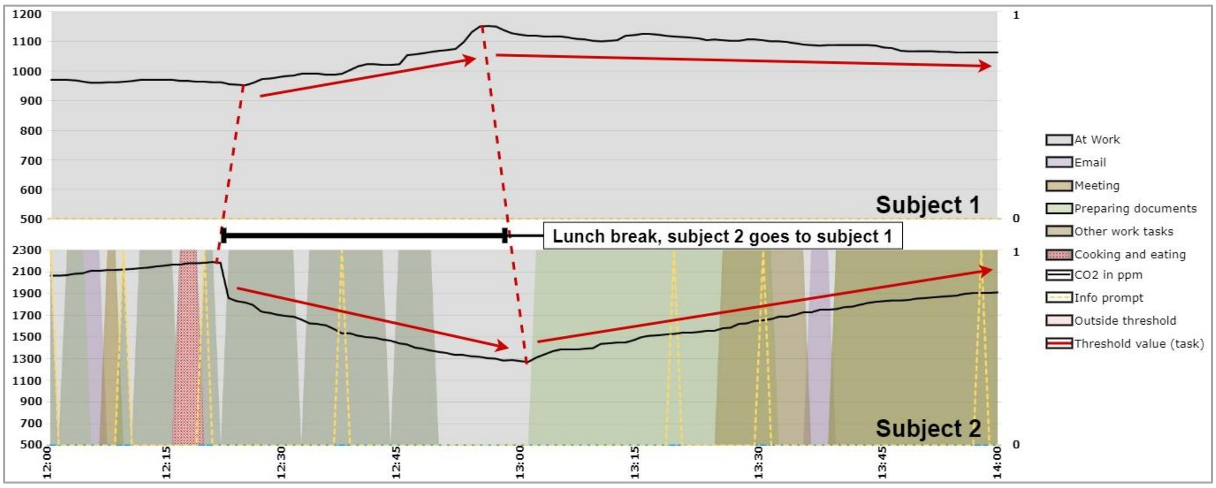


*Figure 26 Example of cross-room comparison*

The interaction between the individual and the system is visible in figure 27, which shows a negative prompt response about the IAQ that results in an increased IAQ level after a significant amount of time without change. The reasoning for this time without change provides two potential reasons. First, the individual did not perceive the low IAQ consciously until the prompt was given (since the system allows for the option to provide direct feedback about discomforts, and no discomfort was mentioned). Or secondly, the individual did not provide its discomfort up till the point it became too much and a negative response was given (might be due to a gradual build-up, to the individual being preoccupied with more important matters, etc.). Given that the system takes one minute to post the prompt, one minute to receive the prompt. Then action has to be taken, which has to change the condition up to the point that the sensor can measure the difference. Combined this would explain the delay after the initial response. An additional benefit comes from automated systems that can decrease the time between measurement and action. Furthermore, automated systems can take action on their own and thus intervene earlier in the process. This automation is, however, not always available in a WFH situation which results in a trade-off between costs of systems, and the IEQ. Noticeable no negative feedback was given for quite some time, indicating that in a WFH situation a higher tolerance of a poor IEQ could be the case. This increased tolerance is likely due to the individual's ability to adapt, and a higher acceptance due to the inability of the individual to control the IEQ parameters as precisely as in a WFO environment. These are in line with the definitions of IEQ comfort of Frontczak & Wargocki (2011), Andargie et al. (2019), and the findings of Krekel et al. (2019), and Gou & Chen (2020).

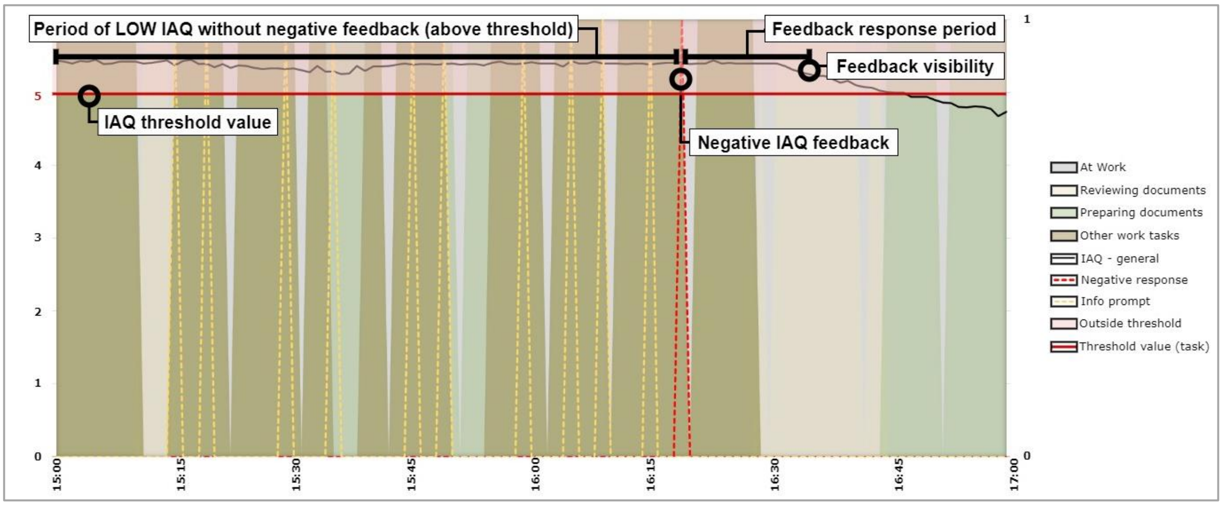


*Figure 27 Example of negative feedback (direct input) and the corresponding result after implementation of the solution*

Alongside the IEQ parameters of IAQ, also light intensity can be shown to conform to a certain period of acceptance. The periods are manageable, and thus no negative responses are provided, or any discomfort regarding light intensity as can be seen in figure 27. It is seen that this is the case for most tasks, with the noticeable exception of reviewing and preparing documents which both might be coupled to the wrong activity level. Due to a lack of data, this cannot be significantly proven, but it is shown most prominently when compared to the data. Future research is needed to understand the activity levels compared to their respective tasks when working from home. Additionally, the amount of time spend in discomfort from a WFH situation is interesting to research further, as higher levels of acceptance are expected.

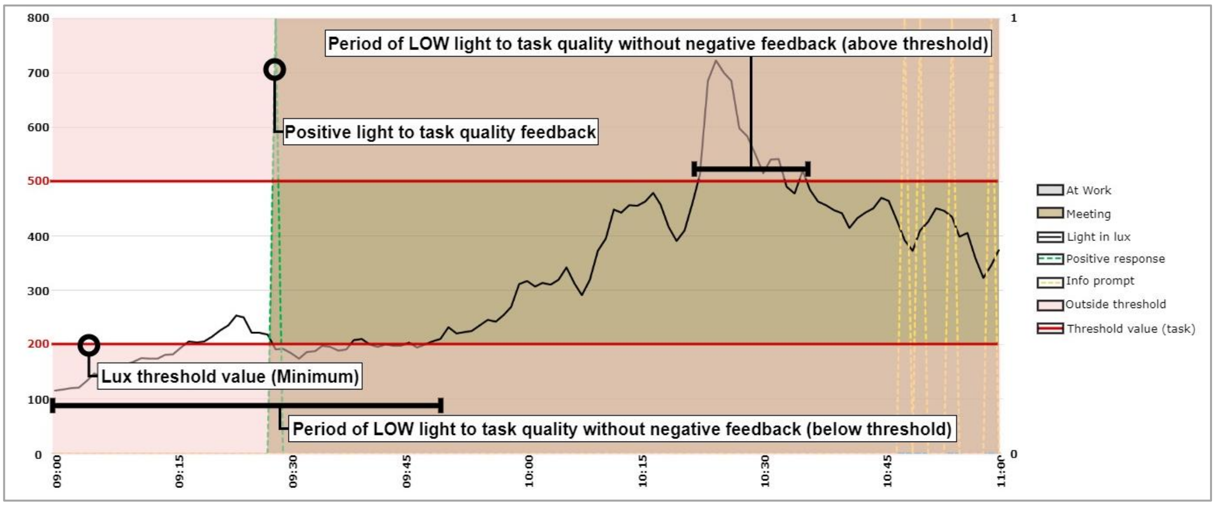


*Figure 28 Example of acceptance of values outside of the threshold for short moments*

The data itself lines up with the expectations on the days both the system and the input provided went as planned. Figure 28 shows the IEQ-parameter noise measured during a meeting, compared to outside of the meeting. The general noise levels are far within boundaries and compare well to the standards set for WFO. The amount of time measured was too short to indicate other problems regarding to sound, such as construction work, traffic, etc. The benefit of the subjects is their location (sub-urban in a village), which compared to large cities provided less noise pollution overall. This lower amount of noise pollution could result in some locations being better suited for WFH than others (this can be the case for air quality as well).

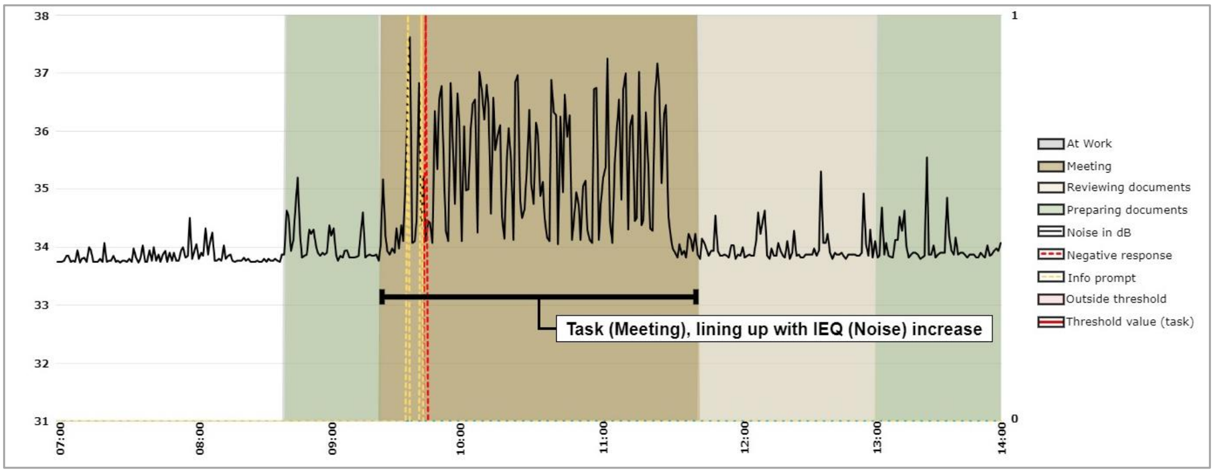


*Figure 29 Example of correct task and measurement input overlay*

All this is reflected in the final DAILYModels. The model of subject 2 is further developed in a period of 5 days than the model of subject 1 after 7 days (accounting for the weekend that was left unchecked) which corresponds with the amount of input given (thus allowing for faster adjustments). A complete overview of the DAILYModel is seen in figure 30 for subject 1 and figure 31 for subject 2. It is noticeable that the DAILYModel is deviating from expected values. Especially humidity shows a deviation from its expected direction. This deviation seems to be the case due to the values also incorporating average values of non-negative prompts, thus providing positive feedback which allows for the model to adjust. This positive feedback does, however, not account for the inability of the individuals to correctly adjust the variables. As no dehumidifier is present, all are dependent on ventilation. If inside the house the humidity levels are similar and outside the house, humidity is higher, no good solution can be given. This should then not be incorporated in the DAILYModel, as this value is skewed. Additional information via the linked data Digital Twin might help provide better solutions (e.g. meteorological data about humidity in the area), as well as, automatization options that help regulate the levels. Depending on the availability more data can be provided to give more meaning to the data available and thus allows the system for better decision making. It can be that, alongside a gat in information, also the checking method might be less suited for some IEQ parameters than for others (especially those that are in more flux, or those harder to manage without automatization options).

In the period of measurement subject 1 shows a gradual decrease in temperature (which corresponds with the input), and a definite change in the noise threshold values (due to an extremely quiet environment within 4 meters of the subject). Subject 2 shows a similar decrease in temperature. However, the results for both humidity and noise are more skewed due to the location of the room, the overall size, and the availability of IEQ control measures (which subject 1 has more access to due to the connection of the space to the kitchen, the living room, and hallway. While the space of subject 2 only connects to the hallway).

A better way compared to the DAILYModel, would be to only append feedback data (instead of all data during the task) combined with pattern recognition algorithms able to make better sense of the triggers leading up to the feedback. Additional research could provide more accurate results, and thus better help the individuals working from a WFH situation. To give more meaning to the data, additional tags are required (e.g. the hour of the day, the season, etc.), which help place the measurement values in their right groups for individual personal preference. This kind of follow-up research could not only benefit a WFH situation but also a WFO situation, as the method is similar when making use of linked data to connect different sources of information.

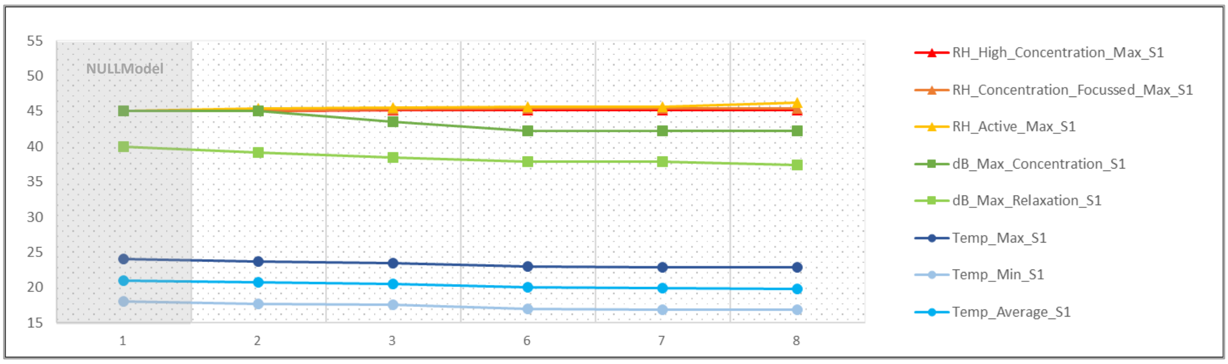


*Figure 30 DAILYModel development of subject 1*

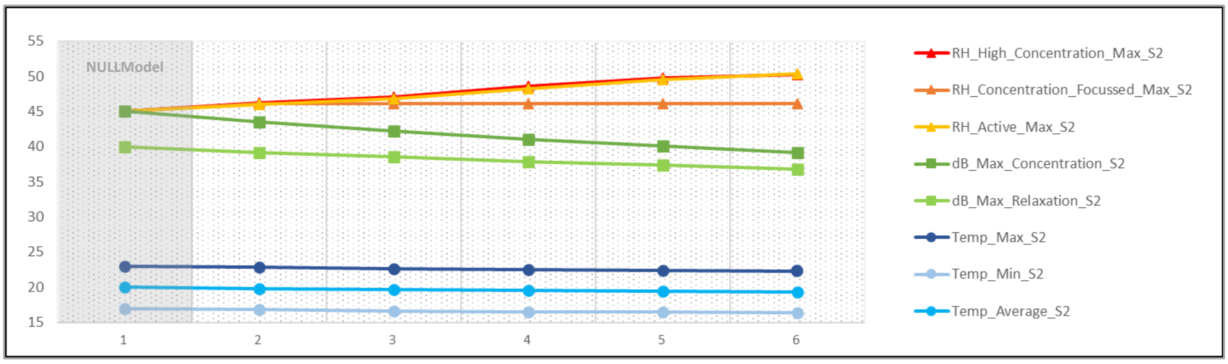


*Figure 31 DAILYModel development of subject 2*

# Chapter 5. Discussion

*This research aims to find a methodologic solution to better the IEQ of individuals working from home. By proof-of-concept, this solution has been provided in the form of a linked data-based Digital Twin, with a use-case-specific application. Although this research is valuable, limitations apply which are mentioned in this paragraph.*

At the start of this study, there was a large number of studies making use of different IEQ parameters in order to determine the overall IEQ in a WFO environment. Only recently there has been an increased emphasis on WFH as well. As many studies provide insights into the parameter values in order to achieve comfort, none of them focused on specific tasks as a way to select parameter ranges. This study tried to achieve the ability to differentiate between tasks through the use of an activity level, which would be coupled to certain IEQ parameter ranges. Based on the results of the previous chapter it can be seen that different IEQ parameter ranges (based on the activity levels, current task, and personal preference per individual) show significant differences in results. These differences are more present within the individual tasks and between the personal preferences compared to the activity levels. This difference is likely due to the current iteration of the activity levels as only a few work-related activities are above level 2, and those can be considered concentration-related tasks, which in turn indicates that both levels 3 and 4 can be combined. This combination would create a different way of scaling, where instead of having levels 1 to 4, there would be scaling from low concentration (i.e. level 1), concentration (i.e. all level 2 tasks), to high concentration (i.e. level 3 and 4). In the literature, a similar comparison is made by wang et al. (2020) and wang et al. (2021) who connects the individual comfort based on the IEQ to cognitive functions. It is, however, hard to discern which cognitive functions, tasks, and IEQ parameter ranges are to be combined. This study tried to do this, but additional research is required alongside more substantial data. Importantly, a key difference between this study and the reviewed literature is the distinction between tasks as a way to predict comfort, rather than to be a result of a good IEQ (as is the case with task completion rate, productivity, etc.) as mentioned by Geng et al. (2017), Kang et al. (2017), Altomonte et al. (2019), Xiao et al. (2021), Cuerdo-Vilches et al. (2021), and Wang et al. (2021).

Furthermore, Antoniadou et al. (2017) and Gou and Chen (2020) both state the importance of the influence of the type of work that is done, something that is lacking from this current study as-is. The reason for the exclusion of the type of work was due to the integration of tasks that could loosely be related to it. However, as the results are so different between the individuals, and due to the performed tasks (especially the amount of data tagged per task), suggests that there should be an inclusion of work type alongside task type. As certain work profiles (a combination of different tasks in sequence) could be distinguished in the results (e.g. a combination of preparing documents, presenting information, reviewing documents, which can be seen regularly with subject 2, but never with subject 1).

Additionally, the statement of tasks per cognitive functioning made in this research is based on the inclusion of leisure tasks. While subject 1 provides some leisure tasks, subject 2 did not provide any significant amounts. Overall most leisure tasks can be trivialized to their inherent function and still maintain the same purpose (so relate back to their task group rather than individual tasks), which would make the leisure tasks: relaxation, refreshment, informal communication. For leisure tasks, the individual will simply adjust the current IEQ parameters to their liking due to the high agency of control, which is in line with the statements made by Bae et al. (2017), Andargie et al. (2019), Altomonte et al. (2019), and Gou and Chen (2020), whom all focus on the importance of the ability to control certain parameters. As the point of view of this research is from a work perspective, this states the lower requirement to incorporate all leisure tasks. For work-related tasks, both emailing and calling fulfill the same basic requirements and can therefore be combined. All these changes result in figure 32, which is the adjusted overview of IEQ parameters to tasks.

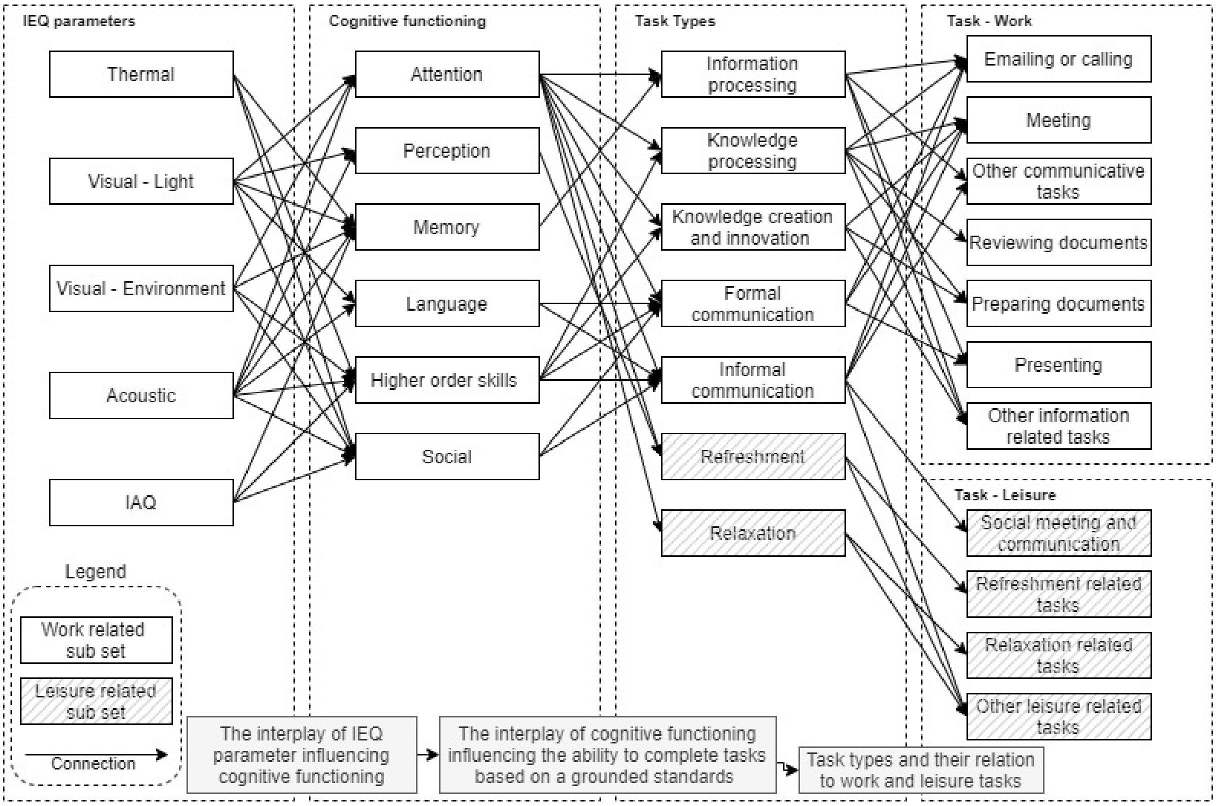


*Figure 32 Adjusted overview of the connection between IEQ parameters, cognitive functioning, task types, and task*

For the work-related tasks, no current literature states their place in a WFH and/or WFO environment. Research done during the Covid-19 crisis indicates that task complexity and required concertation can influence the location where the tasks are completed (Wu & Chen, 2020; Tokumura et al., 2021; Torresin et al., 2021; Wang et al., 2021). However, no significant result is presented. Based on the results of this research, the activity level 3 and 4 work tasks (presenting information and reviewing documents respectively), are shown to be dominant when combined with preparing documents (thus information-related tasks). As all three require a certain level of concertation, and importantly the absence of distraction, it would be logical to place these activities in a stationary location without too much interference (which would result in a preference for the at-home location or the at-office location when facilities are required that are not available in an at-home situation). Flexible tasks with an activity level of 2 can be located at both the at-home location and the at-office location if required and would be based on personal preference (e.g. calling, attending a meeting online, emailing). Communicative tasks which require an offline environment are best suited in an at-office environment. Overall the distinction is made between the required concentration, the efficiency, and the ability to complete the task from within an online environment.

From the perspective of discomfort, it is shown that discomfort is not experienced as soon as a shift in tasks happens as it is shown that an extended period can be spent out of boundary without negative feedback. This finding further highlights the complexity and suggests the need for pattern recognition over clearly stated boundaries, as certain states of discomfort are tagged while similar states are rejected.

The literature review provided that many studies try to account for preference via a PMV and similar methods. The focus of these methods is to gain the highest amount of collective comfort. These methods are not well suited for a WFH environment as the individual preference is far more dominant. Jayathissa et al. (2020) introduced the directive vote (positive, neutral, or negative), which has been used in this study and is shown to work well with individual preference. However, the results (DAILYModel) were skewed, which hints at the current system stating tolerance over preference (as certain IEQ parameter values are tolerated even though they are out of boundary according to the literature). This originates from the lack of automation options (thus the subject is required to maintain the environment themselves), which is a limitation of WFH.

Furthermore, the results show that individuals complain about their IEQ when it is within and outside of the set boundaries. These types of complaints highlight the complexity of the interdependencies of IEQ parameters and additional influencers even more, as the comfort of one parameter is still jeopardized by the discomfort of other parameters and are in line with the statements made by Antoniadou et al. (2017), Torresin et al. (2021), and Wang et al. (2021). Overall, this hints at a different method of approaching individual comfort. In the current iteration of the system individual comfort is stated through the DAILYModel, which does not account for longer periods (but rather a singular time value at the time of input) or patterns within the data.

For the linked data-based Digital Twin section of the study, the representation of tasks with the cognitive functioning and IEQ comfort has not been present in current literature. Most of the applications of the Digital Twin paradigm in the built environment are an extension of or deviation from BIM, this results in many 3D representations and software modules to facilitate the IEQ within the virtual environment. This study specifically uses linked data to facilitate the IEQ parameter values. This use of linked data results in two primary deviations from the literature as mentioned by Lu et al. (2019), Qi et al. (2019), Bosch-Sijtsema et al. (2021), and Lin et al. (2021). The first is the way a Digital Twin is visualized, and the second is how the Digital Twin is used. The Digital Twin within this study is visualized only in its linked data format, which provides the benefit of flexibility and applicability to many different situations (as the information stored in the RDF-triples links to the correct information silos when available). Because of this reason, both validation modeling and simulation (which are primary uses of Digital Twins) can only happen outside of the Digital Twin. So the only visualization in the case of this study is the turtle file, and any additional visualizations require external programs. This way of representing data has its benefits as a generalized solution can be created using this format without the requirement of extensive modeling knowledge (which is often the case for Digital Twins, such as those mentioned by Lu et al. (2019) and Parmar et al. (2020). Additionally, how the Digital Twin is used also deviates from the literature. In this study, the Digital Twin is used as a map with the RDF-triple relations providing the ability to gain the required data. The benefit of this method is that when only certain data is required not everything has to be loaded, in terms of privacy API structures can be implemented to protect sensitive information, and due to the linked data structure does not require all information to be in one place (as the information can be scattered over many different servers). A noticeable downside is the requirement of external programs and the lack of quality convertors (and thus requiring much manual labor). Overall, the paradigm stated by Boje et al. (2020) is still applicable for this iteration of a Digital Twin structure, with the functional Digital Twin being the combination between the linked data model and the extended application.

Additionally, the functionality and applicability of linked data-based Digital Twins are underpinned by the proof-of-concept case and make it so that it can be further developed for other sections of the built environment. The application of linked data in particular should be the primary way of storing building information as they better compare to reference models, which is in line with the statements of Pauwels et al. (2016) and Pauwels & Terkaj (2017). The linked data-based Digital Twin, further improves the quality of the available data as the linked data part allows for linking to the right information, and the Digital Twin part allows for enrichment of the data. Additionally, if this data is stored within a linked data format as part of the Digital twin (either as true RDF-triple relations or the hybrid approach stated by Tang et al. (2019)) it allows for cross applicational data use. The linked data-based Digital Twin is usable in any stage of the building lifecycle but strongly benefits from implementation in earlier stages. Additional uses for linked data-based digital twins which are in line with this research are for example circularity use cases (material passports, locations of materials, the current condition of materials, etc.), IoT technology implementation use cases (cross-linkage of smart features, cross-linking of smart appliances, available data silos, etc.), and similar use case where data is preferably stored in a native format but still requires a combined model structure.

The chosen approach as stated by Tang et al. (2019), which uses the combination between semantic web technologies and relational databases, works as a workable template for linked data-based Digital Twins. The current iteration of the system stays true to this approach and worked as intended. Any problems originating in the proof-of-concept case are from the external application, not the linked data and relational database approach.

The system itself could have been designed with a more generalizable method, as currently it is only intended for WFH environments. As of now, the system strains the user tremendously. The integration of IoT technologies already present at home, or at work makes the solution more accessible. Additionally, applying near location sensor data instead of room data (similar to the method of Jayathissa et al. (2020)) to an individual solves the problem and allows the system to be incorporated in a hybrid WFH and WFO workweek.

Another problem in making this system more generalizable is the lack of quality conversion tools for current IFC models to a linked data format. Much of the data inherent to the IFC model is lost during the conversion, this is made more problematic due to the absence of quality data standards that are required for proper conversion. Additionally, the current application is made for a full WFH environment and requires adjustment for a hybrid WFH and WFO scenario.

## 5.1 Research limitations

Multiple limitations have been experienced during this research. These limitations can affect the accuracy of the results. While some have been mentioned with the corresponding evaluation and discussion a complete overview will be provided.

First, the knowledge and experience in scripting are limited. The application is made with limited software knowledge. All skills required have been developed during the course of this research, the result is an application that is far from optimal. Many latencies can be found within the data where the merge of data skips a beat. This inconsistency is not a problem when accounting for a one-minute time loop, but could pose problems when more test subjects are used.

Second, the scripts were highly fragile. Data from subject 2 has been recorded quite precisely, but for subject 1 this was less the case. As multiple scripts were running and communicating at the same time, not all input was correctly monitored, resulting in a difference in data quality between subjects 1 and 2. While this is not highly influential, it still requires mentioning as the results of subject 2 are more valuable.

Third, the period of five days is too short for statistical analysis. This lack of statistical underpinning results in all IEQ data observations being anecdotal. While there is enough IEQ data to establish relations, this was not the aim of the research, and more valuable research reading on this subject has already been done. The tagged IEQ data with user feedback is far more valuable, but due to the short amount of time available, is not up to the required standards for statistical analysis. So all data has been analyzed based on this premise.

Fourth, all measurements are made under the influence of the Covid-19 crisis during the winter. The measurements are made from a forced WFH perspective as all individuals were required to work at home as much as possible. This forced perspective influences the perceived comfort, as this might not have been their preferred working method, and is not incorporated in the model or the research. One expects that an individual will choose the most preferred working location when given a choice, and thus have a higher acceptance of the IEQ due to individual agency. This option of choice was not the case, and thus a higher level of discomfort can be expected. Additionally, all measurements were made during the same period and thus prone to the environmental quality of that specific week, which is influenced by outside factors. This is no problem for the proof-of-concept case but requires additional measurements spread out over different periods to provide a better quality of results.

Fifth, the OpenFamilyHome use case is a relatively modern housing and thus is up to the current required standard for housing. This might not be the case for other use cases, which might in turn have quite different results with respect to IEQ. When taking accounting for the linked data-based Digital Twin approach this doesn't matter, as this approach makes use of the available sensors (either places or already there), and thus does not require high-quality housing to work as long as there is an internet concoction.

Sixth, both subjects worked in isolation during a large number of their work hours. Any hindrance that might occur when placed in the same room was now not researched. This remains a research gap, as no information about the IEQ comfort of the WFH environment of individuals sharing the same space or room has been gathered. Additionally, this is also the case for other influencers such as children, which were not present during this study.

Lastly, the knowledge of the IEQ parameters interacting with each other is still too sparse to completely separate the individual comforts and state meaningful conclusions with respect to the IEQ comfort as a whole. Both personal parameters and the interaction between all influencers is too complex to completely and accurately model. Understanding what combination of events results in a discomfort response would be highly valuable and strongly increase the ability of this methodology to help individuals working from home.

# Chapter 6. Conclusion

This research aims to explore the possibility of using linked data-based Digital Twins (DT) to provide a proof-of-concept for a methodology aimed at improving the indoor environmental quality (IEQ) of individuals working from home (WFH). This IEQ is based on visual quality, temperature and humidity, noise, and indoor air quality (IAQ), with an emphasis on occupant comfort and personal preference. Since the IEQ of a WFH environment is currently designed to facilitate leisure tasks, this now pressures the at-home environment to conform to both the needs of leisure and work tasks. This was never the aim of the at-home environment and thus poses challenges aligned with the required shift of working from office (WFO) to WFH. This is reflected in the primary research question of: "***How can a linked data-based Digital Twin model be used to improve the Indoor Environmental Quality (IEQ), based on air-, temperature-, noise- and light parameters, of an at-home situated hybrid working- and living environment of the occupant(s), while also accounting for occupant(s) feedback?***". To provide an answer to the primary research question eight additional sub-questions have been answered and will fuel the scientific relevance, societal relevance, and future recommendations.

Individuals in a WFH environment are prone to an IEQ which was aimed at leisure rather than working. To relate this to individuals' comfort the following sub-questions were answered: "***How are the IEQ paraments derived and made measurable according to the literature, for both dedicated work environments and hybrid environments?***", and "***How is the occupant's experience of the IEQ parameters derived and made measurable according to the literature, for both dedicated work environments and hybrid environments?***". Signifying the IEQ and its effect respectively. A significant relation of IEQ parameters to occupant comfort has been established, exploring different avenues (i.e. cognitive functioning, productivity, wellbeing, task completion, and personal influencers). These influence four IEQ comfort groups (i.e. thermal, visual, acoustic, and IAQ), which are measured each on different accepted standards, and optimal parameter value ranges based on literature. Occupant comfort is related to the relation between IEQ parameters and personal factors (i.e. physical and mental health, adaption rate, socio-demographic factors, feeling of control, and expectation of environment).

Based on the literature the IEQ parameters most commonly used, and their corresponding effects have been found. To effectualize these interactions the following sub-question has been answered: "***What are the effects of the IEQ parameters on occupant comfort, and what is the effectual difference between a dedicated work environment and a hybrid environment?***". The primary translation from a WFO to a WFH environment is the ability to perform and complete designated tasks. These tasks are then weighted based on an activity level corresponding with IEQ parameter ranges. A system based on this principle can account for the IEQ needs corresponding with respective tasks, to provide a method of interaction to improve the IEQ of the room.

As a method of improving the IEQ, linked data DTs are proposed (Tang et al., 2019; Jacoby and Usländer., 2020; Zaballos et al., 2020), resulting in the fourth, fifth, and sixth sub-questions: "***How and what should the user communicate with the Digital Twin and vice versa?***", "***What would be a suitable interface for user interaction and how can this dashboard provide suggestions based on the measurements?***", and "***For the Digital Twin and the selected use***

***case, what system architecture is needed and how would this be implemented?***". To communicate the IEQ with the occupant, a prompting system has been chosen. These are characterized as measurement-, randomly generated-, and direct input prompts). Additionally, the occupants can tag current discomfort, current task, work status, and sickness status. As an interface, a web-based UI (user interface) has been developed, which can communicate all input to a central processing environment. As the chosen system architecture a front end (in Angular)and a back end (in Python) has been developed based on the hybrid approach of Tang et al. (2019), using a linked data DT to locate point in time (PIT) measurement data and static building information.

The literature provides the fundamentals for a methodological approach that has been employed within a proof-of-concept case environment. To do so two individuals are used to gather data about their IEQ WFH-environment during a five day timespan. Their IEQ is measured based on noise, humidity, CO2, IAQ, temperature, and light intensity. This is compared to threshold values accompanied with the current task of the individual. Based on these values a response is given, requesting action of, or providing information to the occupant. While accounting for influencing factors (e.g. being sick) and direct input (e.g. discomfort). The data gathered has been used to answer the following sub-question: "***How is the model able to communicate the measurement information and suggestions with the user, in order to improve the IEQ of the occupant?***". This shows that the developed methodology is indeed able to interpret the data and use it to provide suggestive information to the occupant. The PIT-measurement data lines up with the corresponding prompt provided to the individual. Similarly, it is shown that direct input also results in the corresponding prompt. Random prompts were provided when they were selected on an average hourly base. In cases where the information was tagged with either a positive response or a negative response, the effects were visual within the data showing the possibilities of such a system. This feeds in the last sub-question: ***"What are the benefits of linked data-based Digital Twins within a WFH situation, and how is this approach made scalable?"***. According to the literature, the DT paradigm focuses on the interplay between the physical and the virtual, connected through data (Boje et al., 2020). Most of the literature represents this in either a dedicated software solution form, or a theoretical methodology meant to achieve different solutions ranging from construction to facility management. The linked data approach, in the hybrid form as mentioned by Tang et al. (2019), is neither a fully dedicated software solution nor a theoretical methodology as it functions more like a guiding structure to located parts (e.g database locations, sensors, etc.). Additional software solutions can make use of this guiding structure to retrieve the required information. The proof-of-concept case used this approach in a WFH environment. Through linked data, an overarching DTs structure can be created, which then links to the right parts. This solution is applicable on many different use-cases, as scalable by design. When the right ontologies are used and data is kept in the format best suited for its application, then linked data can be the link between applications and the available data. This makes for a flexible solution, which WFH requires.

Based on these answers to the sub-questions an answer to the main research question can be formulated. "***How can a linked data-based Digital Twin model be used to improve the Indoor Environmental Quality (IEQ), based on air-, temperature-, noise- and light parameters, of an at-home situated hybrid working- and living environment of the occupant(s), while also accounting for occupant(s) feedback?***". Linked data-based DTs allow for scalable solutions for

IEQ parameters. By interacting with, and receiving input by, occupants via an application leveraging the capabilities of the DT, the IEQ of the individual can be improved. By accounting for individual preference, over time, a unique model of reference can be created to set threshold values for the individual. Due to the modular nature of linked data, a similar system could cover more influencing factors, to better the IEQ. Linked data DTs provide a high appliable solution to the complex problem created by the shift from WFO to WFH.

### 6.1.1 Scientific relevance

As an addition to the scientific community, this research provides insight into how linked data-based Digital Twin can be used, and how additional value can be generated. This research provides a guide on how to create an application fit for the research, and how linked data-based Digital Twins can interact with extending applications. Additionally, it provides insight into how such a system can communicate with an individual. Very important is using the correct ontologies, obtaining the right data, and creating value by combining data from different sources. Additionally, it highlights a gap in knowledge of individual IEQ parameters and task completion, as the complexity has been established, as well as, its interconnectivity. Relative to other research a new approach has been used for the WFH situation, by using multiple approaches established in the literature and translating this to a working system able to generate usable output.

### 6.1.2 Societal relevance

For societal relevance, this research provides a solution to the shift of individuals to a hybrid workweek of WFH and WFO. The method used in the research is scalable by nature, is easy to use, easy to generalize, and provides an affordable solution for both employers and employees. While this research focuses on using sensors placed at the location, additional substitutes are available to decrease the costs and increase the applicability.

As stated by Tokurua et al. (2021) and Torresin et al. (2021) the hybrid workweek will stay, subjecting individuals to the IEQ of their home. This was never meant to facilitate these activities. As IoT technologies are adopted more, and homes become smarter, the availability of information increases. To leverage these techniques and future techniques linked data-based Digital Twins allow for growth adjacent to the need. This research highlights these possibilities and stimulates the integration of different data sources, as well as, extended applications. This can be adopted by companies to support their employees and stimulate a healthy work environment from home.

### 6.1.3 Recommendations for future research

Future research topics should focus on the development of linked data ontologies and ways of creating linked data models. As of now, most solutions are too restrictive and labor-intensive for the general public to be adopted. A more generalized method in creating these models allows for more development on the extending applications. The Digital Twin is a central point of development and should be explored further. Further developing these implementations and increasing the available knowledge allows for faster growth and easier adoption of similar solutions. Additional research should focus on the integration of multiple data sources and systems, and their interaction through the Digital Twin. Especially at home IoT devices. Due to the modular nature of linked data, more complexity can be built in the Digital Twin. Another interesting topic is machine learning, as the combination of PIT-measurement data and PIT-information tags allows for systems to understand patterns leading up to a certain response. This is where machine learning would be beneficial, as it can learn complex patterns between different data sources which might not stand out using more conventional analysis techniques. However, more understanding is needed about IEQ parameter interaction to fully benefit from these techniques. Additionally, SHACL can be used and researched to create more standardized data forms and requirements to enhance the potential and usability of the data. More research about the usability and requirements of SHACL and the interaction with IEQ data is needed. The growing adoption of SHACL promises to be of great influence for future research about linked data-based Digital Twins. Additionally, laws and regulations, alongside standardizations are still in development. Potential research in how linked data-based Digital Twins would interact with topics such as privacy and security are highly interesting, as well as, how the system architecture of generalized models should be comprised. Figure 33 provides a schematic overview of potential expansion (such as health data sources, geolocation, meteorological, etc.), but also additional applications (such as other forms of user interfaces, other applications, other systems, etc.).

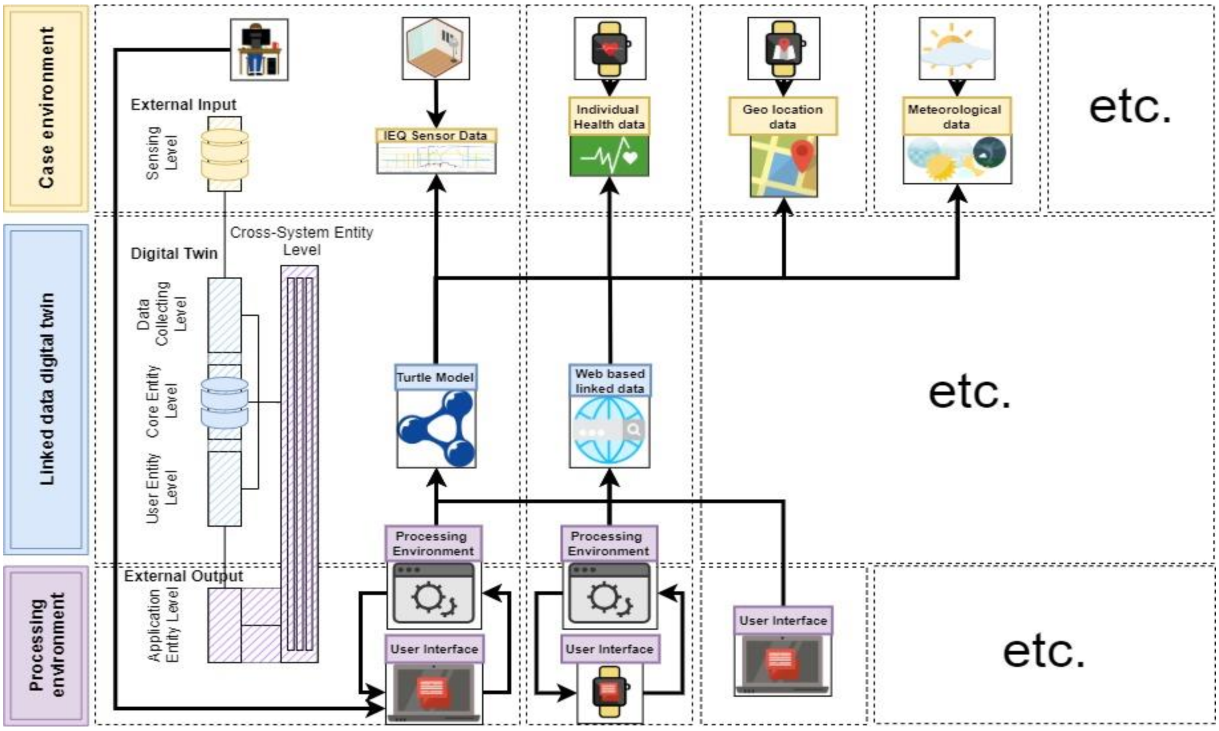

*Figure 33 Example of potential expansion and future research using this study*

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# Chapter 7. Appendices

## Appendix 1. Letter of participation and explanation research

Beste Deelnemer,
U heeft zojuist de volgende onderdelen ontvangen voor mijn afstudeer onderzoek gedurende de week van **dinsdag 11/01/2022 t/m dinsdag 18/01/2022**:

- Een lichtintensiteit-sensor (voor indirect en direct licht)
- Een IAQ-sensor (voor de algemene kwaliteit van lucht in het binnenklimaat)
- Een temperatuur- en luchtvochtigheidsensor
- Een geluidsensor
- Een CO2-sensor
- Een aantal repeaters (gebaseerd op type sensoren)
- Een gezamenlijke receiver
- Een map bevattende de benodigde scripts en software voor het onderzoek
- Een consent formulier

In de map is een "Read Me"-file toegevoegd die instructies geeft over de set-up van het onderzoek.
Gedurende de periode zullen de sensoren data vergaren over het binnenklimaat van uw thuiswerkomgeving. De data zal op een computer worden verwerkt gepositioneerd op de Technische Universiteit Eindhoven (TU/e). Om deze data in te kunnen zien dient u contact op te nemen met de afstudeerder, die dan deze data aan de rechtmatige eigenaar beschikbaar stelt (**u bent gemachtigd uw data ten aller tijden in te zien en op te vragen**).
Naast deze meetdata zal er via de Angular-omgeving een survey beschikbaar zijn om een reactie te geven op verschillende informatie prompts, directe feedback te kunnen verlenen en overige informatie te verschaffen. Deze app zal draaien op een individuele laptop gezamenlijk met een json-database. De locatie is te bereiken via uw internet brouwser op: http://localhost:4200/. Verder zullen er verschillende Python-scripts draaien die uw reacties op de survey verwerken en communiceren met het script op de TU/e computer.
Het wordt van u verwacht dat u de volgende onderdelen aangeeft in de survey omgeving:

**Wanneer van toepassing:**

- Indien aanwezig, geef zo veel mogelijk reactie op eventueel aanwezige prompts en bevestig deze **("Confirm")**[2]
- Indien u werkzaamheden verricht m.b.t. tot uw werk **("At Work")**
- Indien u een bepaalde taak uitvoert, al dan niet los van u werk **("Current Task Type")**[3]
  *(Hiervoor kunt u de taak aanklikken die het dichts bij uw huidige activiteit komt)*
- Uw huidige ervaren gezondheidsstatus **("Health Status")**
- Ervaren disrupties in uw huidige werkomgeving **("Current Discomfort")**[4] **& ("Disruptions within the work environmet")**[5]

**Dagelijks tijdens start werkzaamheden:**

- De kwaliteit van slaap ervaren gedurende de voorgaande nacht **("Sleep Quality")**
- Uw huidige kleding keuze **("Clothing Layers (Sets)")**
  *(Hiervoor kunt u de kleding set aanklikken die het dichts bij uw huidige set komt)*
- Eventuele speciale kledingstukken (toevoegen indien van toepassing)

**Eenmalig:**

- Uw sekse **("Sex")**
- Uw leeftijd **("Age")** *(optioneel voor dit onderzoek)*

**Extra informatie:**

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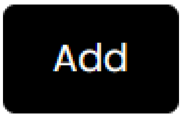
[2] Het bevestigen is een vereiste om de door u ingevulde data te verwerken. Alle input die niet bevestigd wordt zal geen invloed hebben op uw persoonlijke model.

[3] Deze taken zullen na 30 minuten verdwijnen, alleen meeting die toebedeeld kunnen worden aan een taak hebben direct invloed op uw persoonlijke model. Het is daarom van belang dit zo vaak als mogelijk up-to-date te houden. U heeft de mogelijkheid uw huidige taak te verlengen met 30 minuten door **"Expand Time Current Task"** te selecteren.

[4] Deze input zal 30 minuten aanhouden waarna deze automatisch zal komen te vervallen. De input zal dan zijn verwerkt en eventuele informatie prompts zullen worden aangeleverd.

[5] De visuele omgevings-disrupties ("Disruptions within the work environment") staan apart van de huidige ervaren oncomfortabel heden ("Current Discomfort"). Deze input is naar verwachting maar eenmalig vereist i.v.m. de duur van de testperiode.

- U kunt extra commentaar toevoegen indien noodzakelijk. *Dit is voornamelijk bedoeld voor bijzondere gevallen of onmisbare informatie.*

| | |
|---|---|
| Druk op “Add” | Vul “status” in (Naam commentaar)<br>Vul “description” in (Informatie commentaar)<br>Druk op “Save Status”<br>*(Status Value is niet van toepassing)* |
|   |   |

- De sensoren worden bij u thuis geplaats en verwijderd op afspraak met de afstudeerder. Hiervoor wordt een datum en een tijd afgesproken. Het is niet de bedoeling de sensoren te verplaatsen wanneer deze geplaatst zijn.

**[Belangrijk!]: Bedek de sensoren nooit!**

Hartelijk dankt voor uw deelname aan het onderzoek. De resultaten van het onderzoek worden met u gedeeld na afloop van het afstudeer traject. Alle data wordt dan geretourneerd naar de rechtmatige eigenaar, alle overige data zal worden verwijderd ter bescherming van de deelnemers. Hiervoor verwijs ik u door naar de consent verklaring.

Voor eventuele vragen kunt u contact opnemen met de afstudeerder. Bijgevoegd is een verklaring van consent die ondertekend dient te worden voor de start van het onderzoek. Mochten hier verder vragen over zijn dan kunt u contact opnemen met de afstudeerder. Dit onderzoek wordt uitgevoerd middels de richtlijnen van de TU/e m.b.t. wetenschappelijke betrouwbaarheid en ethiek. Voor meer informatie bezoek: https://www.tue.nl/universiteit/over-de-universiteit/integriteit/wetenschappelijke-integriteit/

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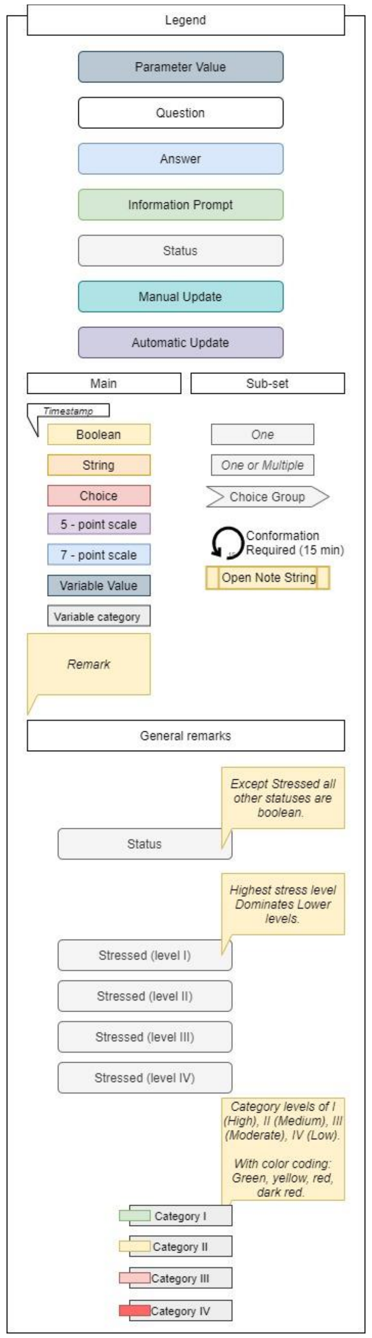
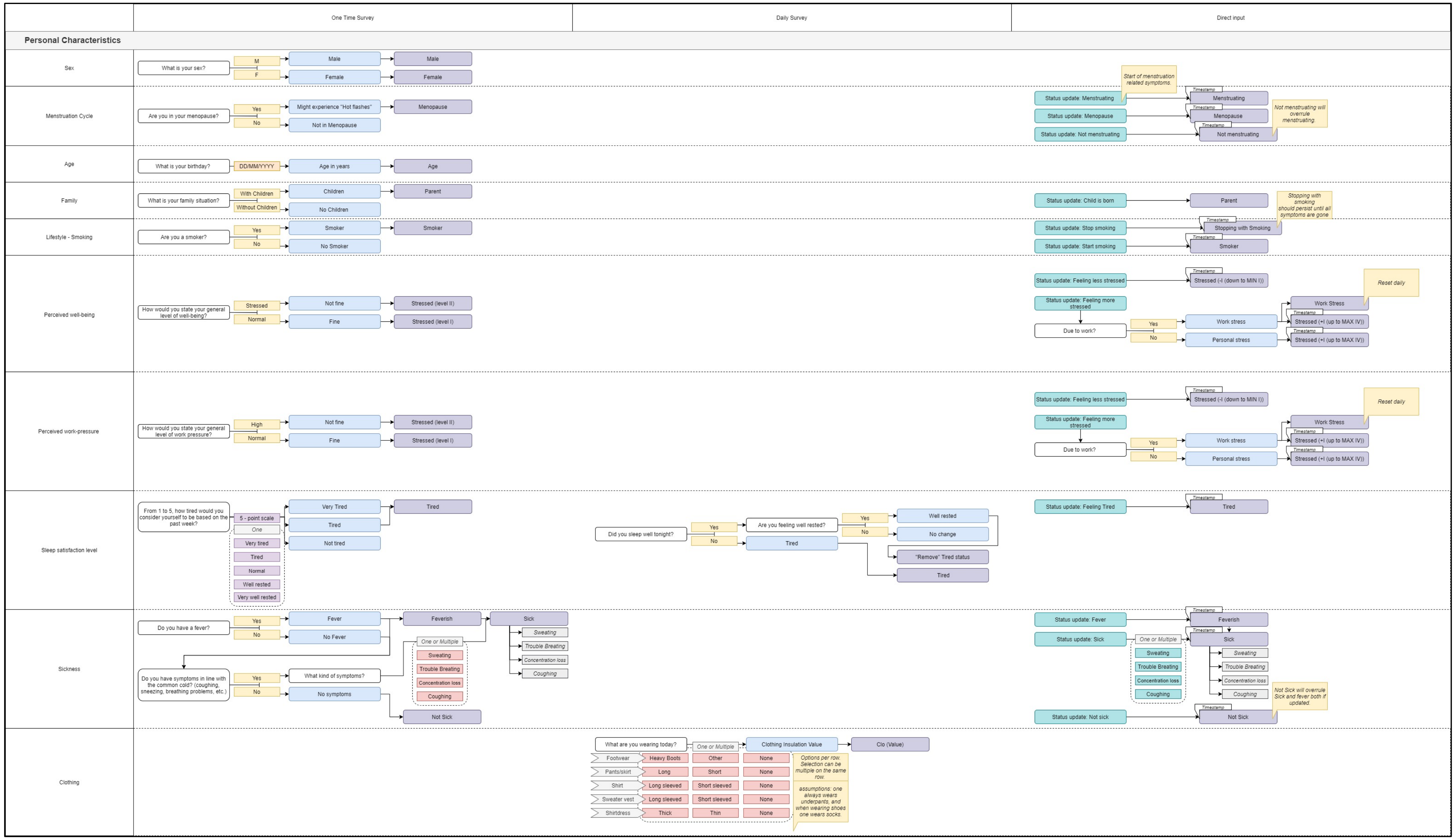
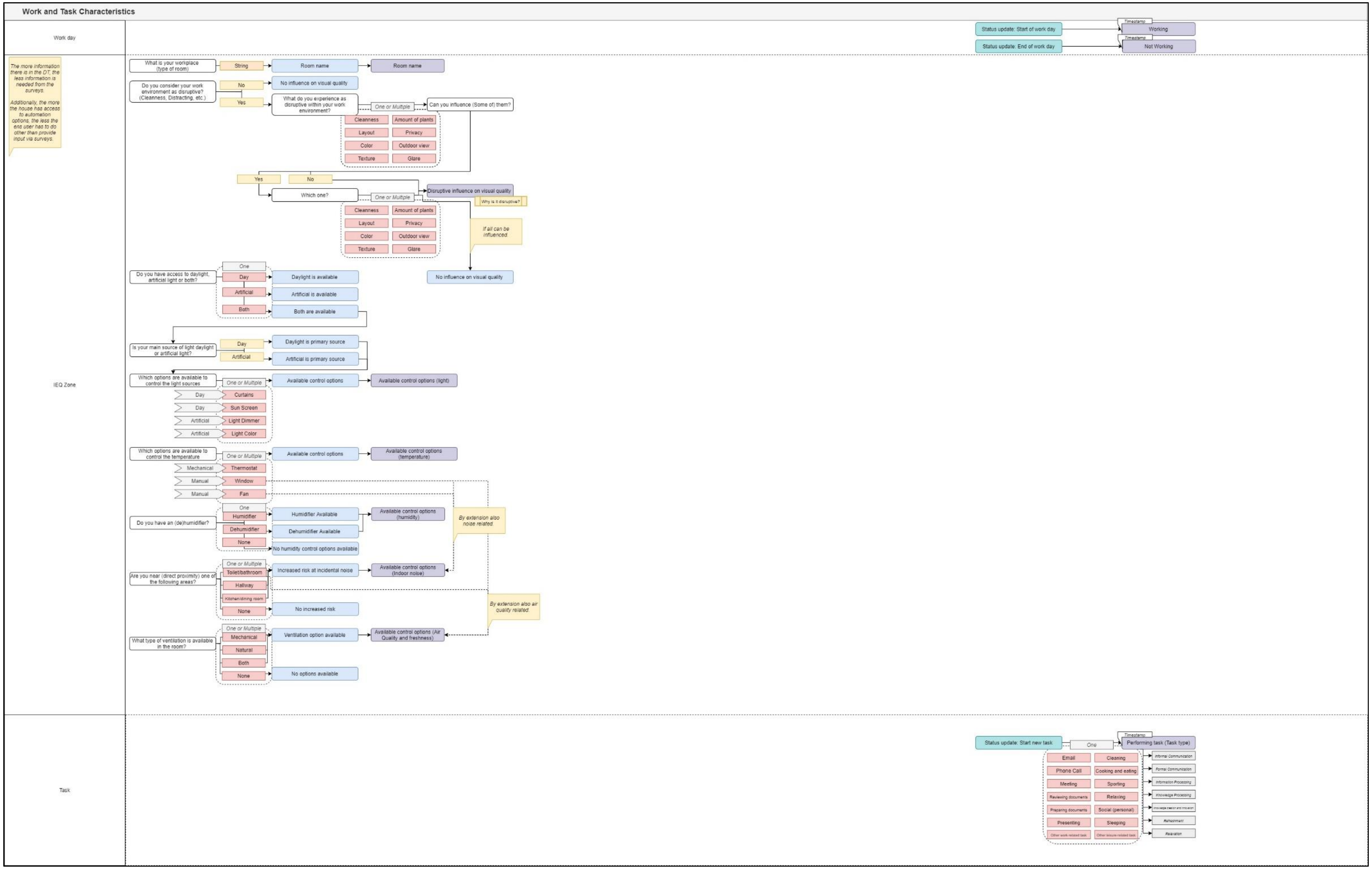
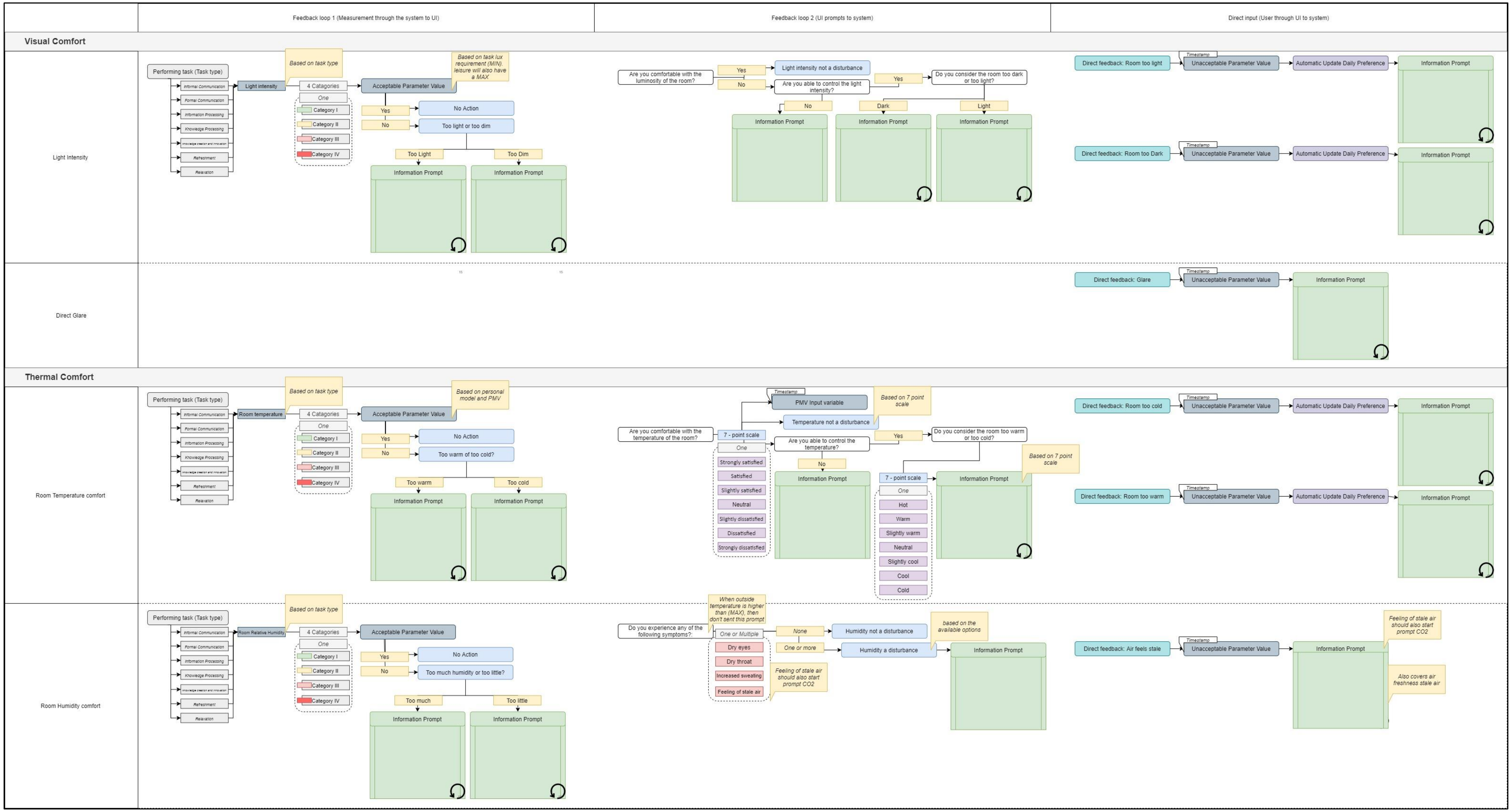
# Appendix 2. Survey structure

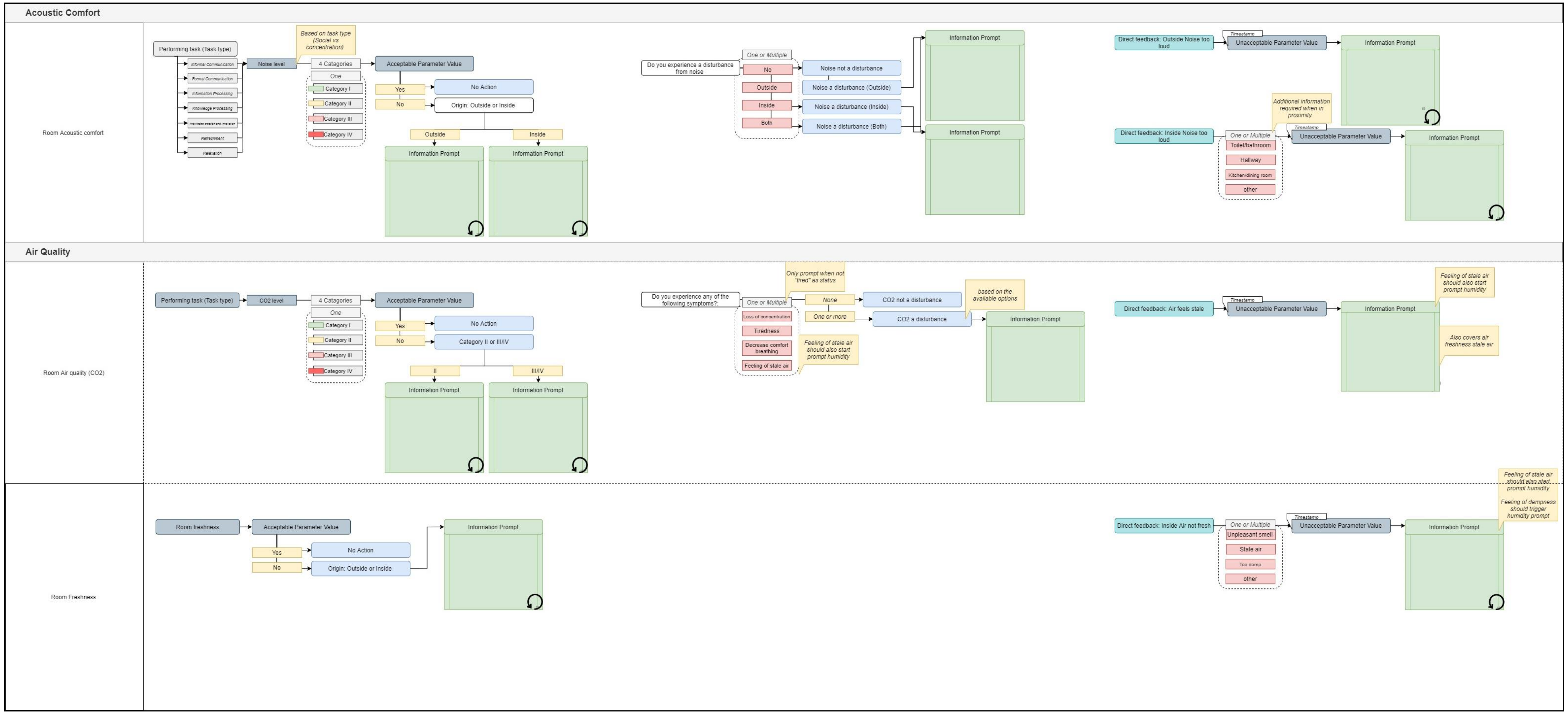



Work and Task Characteristics
Work day
Status update: Start of work day
Status update: End of work day
Timestamp
Working
Not Working
IEQ Zone
The more information there is in the DT, the less information is needed from the surveys.
Additionally, the more the house has access to automation options, the less the ens user has to do other than provide input via surveys.
What is your workplace (type of room)
String
Room name
Room name
Do you consider your work environment as disruptive? (Cleanness, Distracting, etc.)
No
No influence on visual quality
Yes
What do you experience as disruptive within your work environment?
One or Multiple
Can you influence (Some of) them?
Cleanness
Amount of plants
Layout
Privacy
Color
Outdoor view
Texture
Glare
Yes
No
Which one?
One or Multiple
Disruptive influence on visual quality
Why is it disruptive?
Cleanness
Amount of plants
Layout
Privacy
Color
Outdoor view
Texture
Glare
If all can be influenced.
No influence on visual quality
Do you have access to daylight, artificial light or both?
One
Day
Artificial
Both
Daylight is available
Artificial is available
Both are available
Is your main source of light daylight or artificial light?
Day
Artificial
Daylight is primary source
Artificial is primary source
Which options are available to control the light sources
One or Multiple
Available control options
Available control options (light)
Day
Curtains
Day
Sun Screen
Artificial
Light Dimmer
Artificial
Light Color
Which options are available to control the temperature
One or Multiple
Available control options
Available control options (temperature)
Mechanical
Thermostat
Manual
Window
Manual
Fan
Do you have an (de)humidifier?
One
Humidifier
Dehumidifier
None
Humidifier Available
Dehumidifier Available
No humidity control options available
Available control options (humidity)
By extension also noise related.
Are you near (direct proximity) one of the following areas?
One or Multiple
Toilet/bathroom
Hallway
Kitchen/dining room
None
Increased risk at incidental noise
Available control options (Indoor noise)
No increased risk
By extension also air quality related.
What type of ventilation is available in the room?
One or Multiple
Mechanical
Natural
Both
None
Ventilation option available
Available control options (Air Quality and freshness)
No options available
Task
Status update: Start new task
One
Timestamp
Performing task (Task type)
Email
Cleaning
Phone Call
Cooking and eating
Meeting
Sporting
Reviewing documents
Relaxing
Preparing documents
Social (personal)
Presenting
Sleeping
Other work-related task
Other leisure-related task
Informal Communication
Formal Communication
Information Processing
Knowledge Processing
Refreshment
Relaxation



Feedback loop 1 (Measurement through the system to UI)
Feedback loop 2 (UI prompts to system)
Direct input (User through UI to system)
Visual Comfort
Light Intensity
Performing task (Task type)
Based on task type
Light intensity
4 Catagories
One
Category I
Category II
Category III
Category IV
Acceptable Parameter Value
Based on task lux requirement (MIN) leisure will also have a MAX
Yes
No
No Action
Too light or too dim
Too Light
Too Dim
Information Prompt
Are you comfortable with the luminosity of the room?
Light intensity not a disturbance
Are you able to control the light intensity?
Do you consider the room too dark or too light?
Dark
Light
Direct feedback: Room too light
Direct feedback: Room too Dark
Timestamp
Unacceptable Parameter Value
Automatic Update Daily Preference
Direct Glare
Direct feedback: Glare
Thermal Comfort
Room Temperature comfort
Room temperature
Based on personal model and PMV
Too warm of too cold?
Too warm
Too cold
PMV input variable
Based on 7 point scale
Temperature not a disturbance
Are you comfortable with the temperature of the room?
7 - point scale
Strongly satisfied
Satisfied
Slightly satisfied
Neutral
Slightly dissatisfied
Dissatisfied
Strongly dissatisfied
Are you able to control the temperature?
Do you consider the room too warm or too cold?
Hot
Warm
Slightly warm
Slightly cool
Cool
Cold
Direct feedback: Room too cold
Direct feedback: Room too warm
Room Humidity comfort
Room Relative Humidity
Too much humidity or too little?
Too much
Too little
When outside temperature is higher than (MAX), then don't sent this prompt
Do you experience any of the following symptoms?:
One or Multiple
Dry eyes
Dry throat
Increased sweating
Feeling of stale air
None
One or more
Humidity not a disturbance
Humidity a disturbance
based on the available options
Feeling of stale air should also start prompt CO2
Direct feedback: Air feels stale
Also covers air freshness stale air


Acoustic Comfort
Room Acoustic comfort
Performing task (Task type)
Noise level
Based on task type (Social vs concentration)
4 Catagories
One
Category I
Category II
Category III
Category IV
Acceptable Parameter Value
Yes
No
No Action
Origin: Outside or Inside
Outside
Inside
Information Prompt
Do you experience a disturbance from noise
One or Multiple
No
Outside
Inside
Both
Noise not a disturbance
Noise a disturbance (Outside)
Noise a disturbance (Inside)
Noise a disturbance (Both)
Direct feedback: Outside Noise too loud
Timestamp
Unacceptable Parameter Value
Additional information required when in proximity
Direct feedback: Inside Noise too loud
Toilet/bathroom
Hallway
Kitchen/dining room
other
Air Quality
Room Air quality (CO2)
CO2 level
Category II or III/IV
II
III/IV
Do you experience any of the following symptoms?
Only prompt when not "tired" as status
Loss of concentration
Tiredness
Decrease comfort breathing
Feeling of stale air
None
One or more
CO2 not a disturbance
CO2 a disturbance
based on the available options
Feeling of stale air should also start prompt humidity
Direct feedback: Air feels stale
Also covers air freshness stale air
Room Freshness
Room freshness
Direct feedback: Inside Air not fresh
Unpleasant smell
Stale air
Too damp
Feeling of dampness should trigger humidity prompt

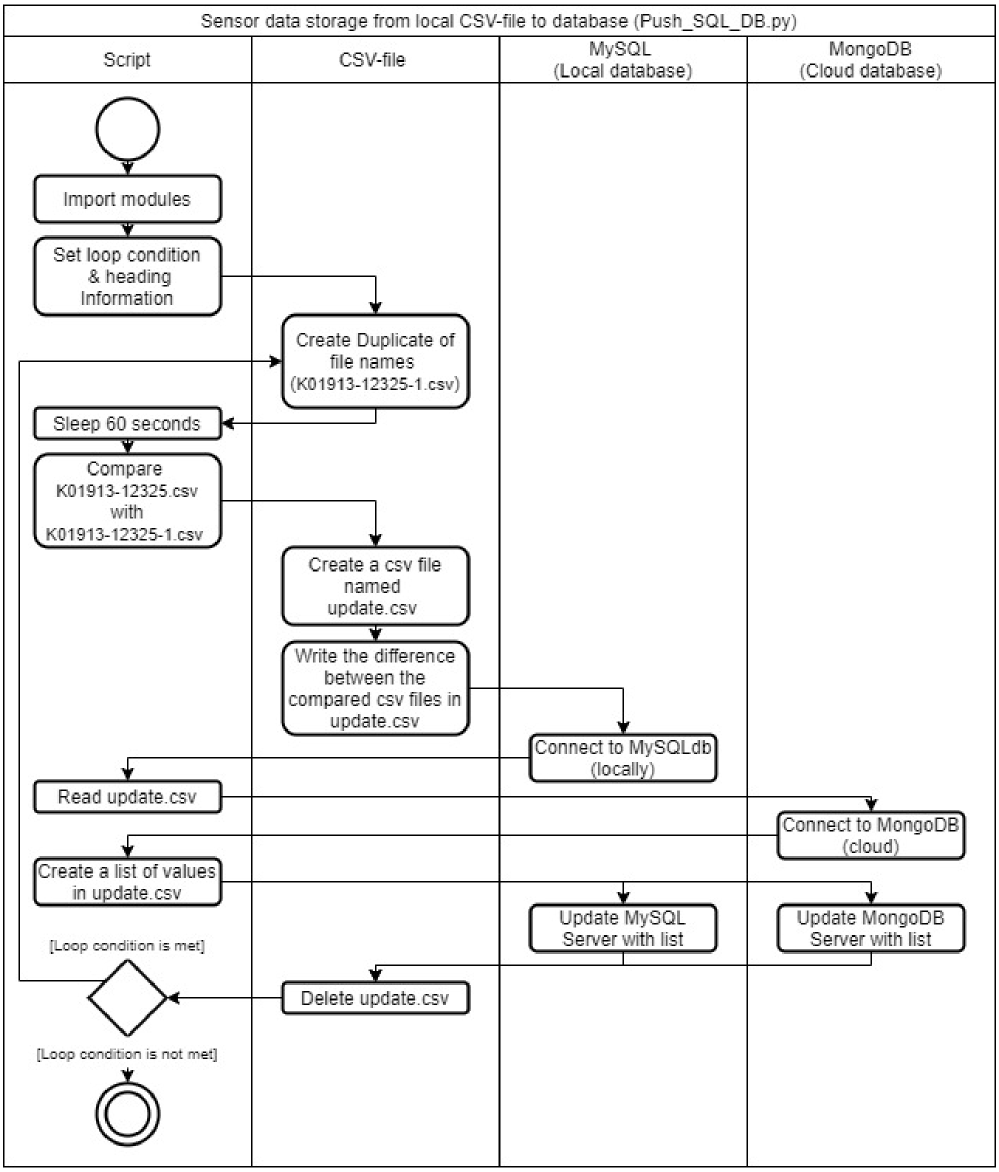
# Appendix 3. UML diagrams

*This appendix covers all UML diagrams of the scripts used in this study. Recreating these structures is enough to build a similar application.*

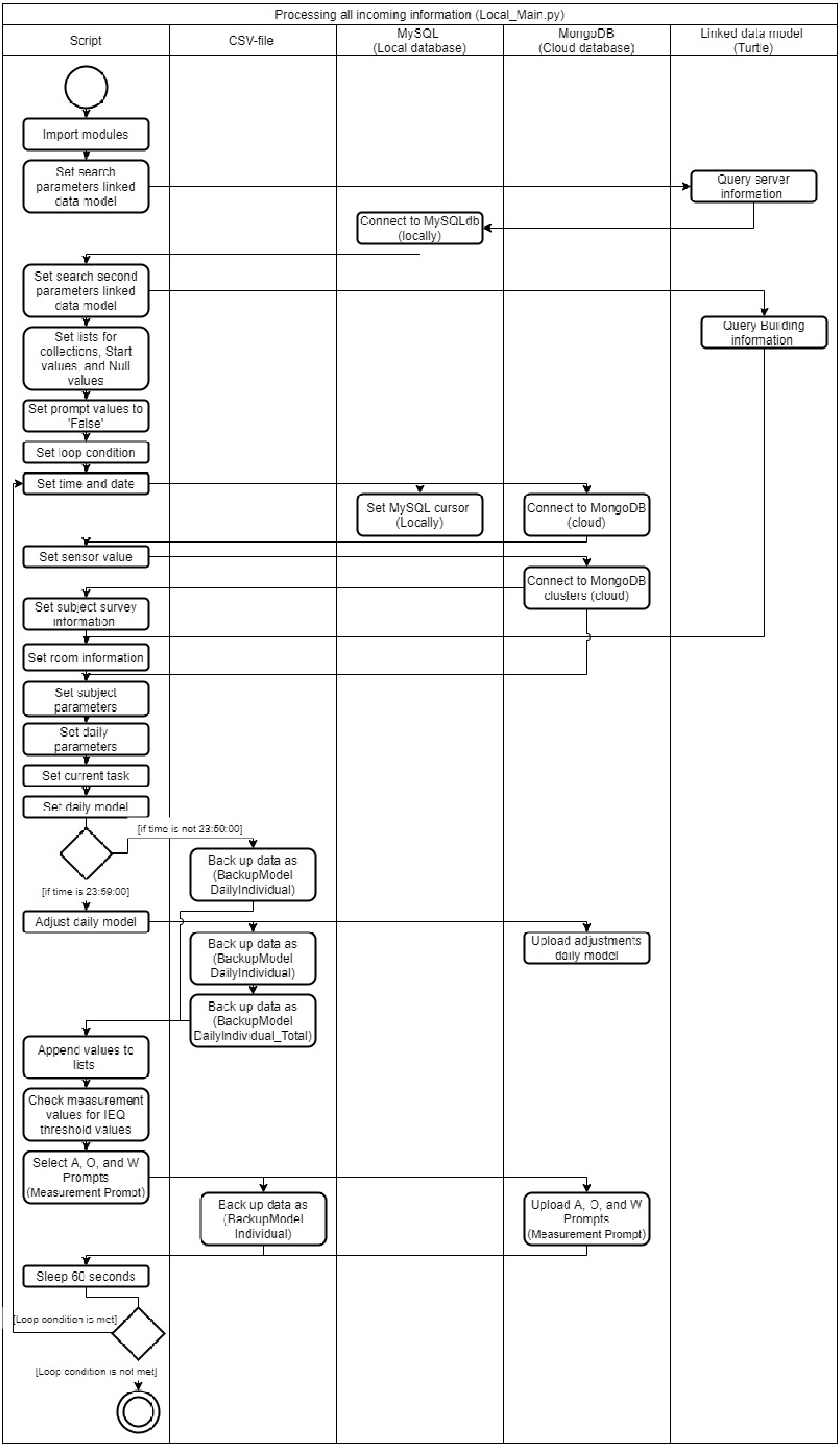
The scripts cover:

- Push SQL database (is used to get the measurements stored in the MySQL database)
- Local Main (is used to process all incoming input and maintain the daily model and the measurement prompts)
- C and task reset (is used to reset direct input from the occupant)
- Individual JSON Reader (is used to read the JSON database and retrieve information for backup)
- Local Prompt updater (is used to read and update the JSON database of the user interface so new prompts are seen and prompt response is processed )

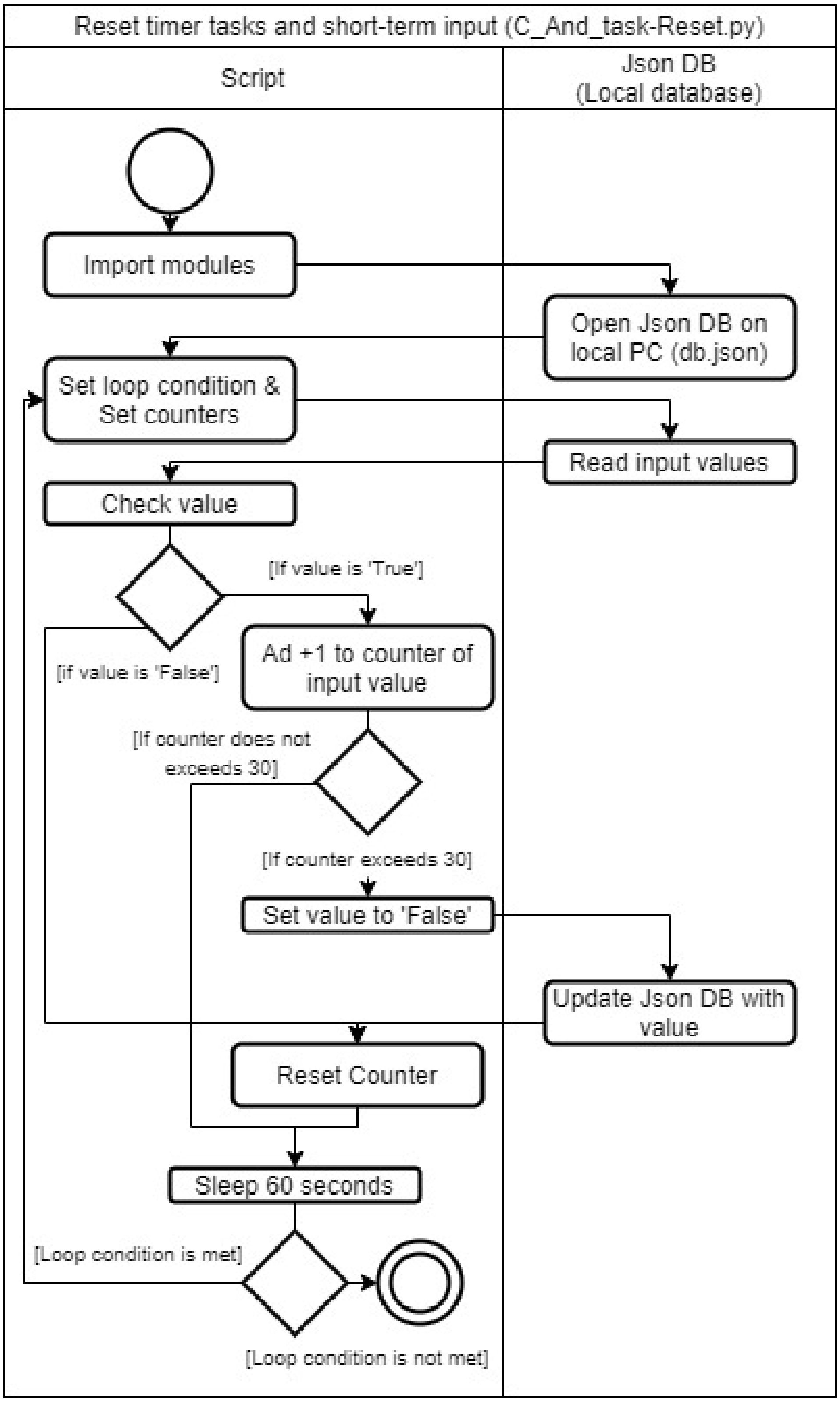
## Appendix 3.1 Push SQL database script UML



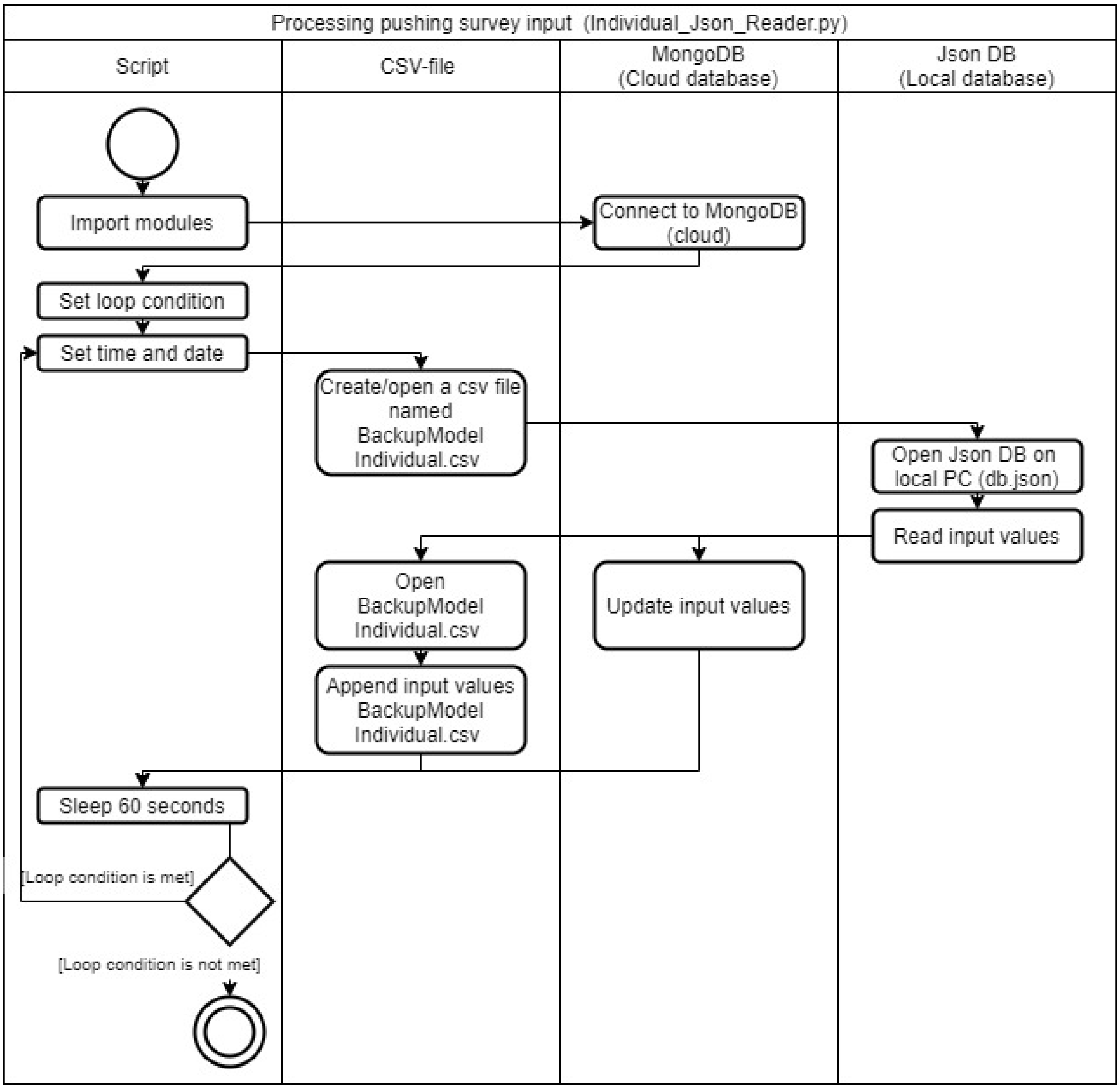
# Appendix 3.2 Local main script UML



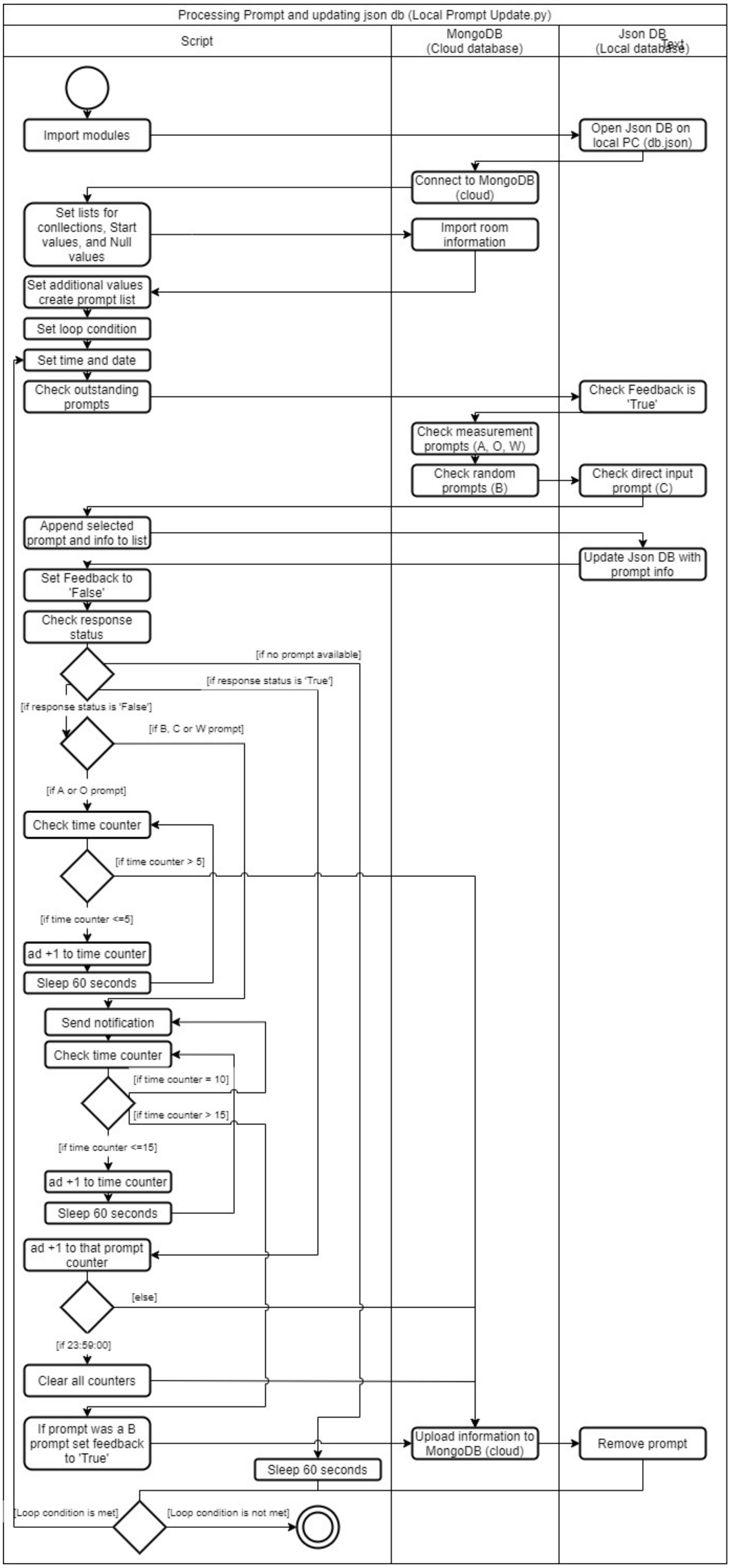
## Appendix 3.3 C and task reset script UML



## Appendix 3.4 Individual Json reader script UML



## Appendix 3.5 Local prompt update script UML



# Appendix 4. Informed consent form

**Informatieblad voor onderzoek “Graduation Project Student 1507834”**

## 1. Inleiding

U bent gevraagd om deel te nemen aan het onderzoek Graduation Project Student 1507834, omdat u uzelf via persoonlijk contact heeft opgegeven als vrijwilliger voor het onderzoek.
Deelname aan dit onderzoek is vrijwillig: u besluit zelf of u mee wilt doen. Voordat u besluit tot deelname, willen wij u vragen de volgende informatie door te lezen, zodat u weet waar het onderzoek over gaat, wat er van u verwacht wordt en hoe wij omgaan met de verwerking van uw persoonsgegevens. Op baiss van die informatie kunt u middels de toestemmingsverklaring aangeven of u toestemt met deelname aan het onderzoek en met de verwerking van uw persoonsgegevens.
U bent natuurlijk altijd vrij om vragen te stellen aan de onderzoeksleider via j.n.a.v.midden@student.tue.nl, of deze informatie te bespreken met voor u bekenden.

## 2. Doel van het onderzoek

Dit onderzoek wordt geleid door Jelle van Midden.
Het doel van dit onderzoek is het aantonen van een proof-of-concept van het gebruik van digital twin technologie als ondersteuning tot thuiswerken in het verbeteren van het comfort van een gebruiker met betrekking tot het binnenklimaat. De onderzoeksgegevens worden gebruikt voor het afstudeer onderzoek van de student Jelle van Midden in een rapport vorm.

## 3. Wat houdt deelname aan de studie in?

- Wij vragen u gedurende een periode van 2 weken gebruik te maken van het aangeleverde programma om informatie te verschaffen en te reageren op het door het programma aangeleverde informatie.
- U neemt deel aan een onderzoek waarbij we informatie zullen vergaren door:

- het monitoren van uw binnenklimaat door middel van sensoren.
- het verwerken van uw interactie met de user interface door middel van vraag & informatie prompts.
- Het verwerken van de door u ingevoerde informatie.

- Er wordt van u verwacht dat u reageert op de prompts vanuit het user interface, dat u eigen input levert wanneer van toepassing (zoals wanneer u begin en eindigt met bepaalde taken) en dat, indien nodig, apparatuur activeert wanneer deze onverwachts probleem ervaart.

## 4. Welke persoonsgegevens verzamelen en verwerken wij van u?

Gewone persoonsgegevens

- **Sekse** (Man of vrouw)
- **Leeftijd** (geboorte datum)

- **Gezinssitutatie** (Kinderen of geen kinderen)

Bijzondere categorieën van persoonsgegevens:

- **Indicatie van mentale en fysieke toestand;**
    - **Menstruatie cyclus** (i.v.m. ervaring van effect op de mogelijkheid om het comfort van het binnenklimaat te bepalen)
    - **Menopauze** (i.v.m. ervaring van effect op de mogelijkheid om het comfort van het binnenklimaat te bepalen)
    - **Ervaren mentale gezondheid** (i.v.m. ervaring van effect op de mogelijkheid om het comfort van het binnenklimaat te bepalen)
    - **Ervaren werkdruk** (i.v.m. ervaring van effect op de mogelijkheid om het comfort van het binnenklimaat te bepalen)
    - **Staat van ziek zijn en/of koorts** (i.v.m. ervaring van effect op de mogelijkheid om het comfort van het binnenklimaat te bepalen)
- **Status als roker** (Roker, niet-roker, stoppend roker)
- **Begin en einde werkdag**
- **Begin nieuwe taak en bijbehorende type**
- **Kleding** (als selectie)

## 5. Potentiële risico's en ongemakken

- Tijdens uw deelname aan deze studie kan u worden gevraagd informatie te verschaffen die u als (zeer) persoonlijk kunt ervaren, vanwege de gevoelige aard van het onderwerp. Wij stellen deze vragen enkel en alleen in het belang van het onderzoek. U hoeft echter geen vragen te beantwoorden die u niet wilt beantwoorden. Uw deelname is vrijwillig en u kunt uw deelname op elk gewenst moment stoppen.

## 6. Vergoeding

U ontvangt voor deelname aan dit onderzoek geen vergoeding.

## 7. Vertrouwelijkheid van gegevens

Wij doen er alles aan uw privacy zo goed mogelijk te beschermen. De onderzoeksresultaten die gepubliceerd worden zullen op geen enkele wijze vertrouwelijke informatie of persoonsgegevens van of over u bevatten waardoor iemand u kan herkennen.

De persoonsgegevens die verzameld zijn via bijvoorbeeld in het kader van deze studie, worden opgeslagen op een beveiligde lokale locatie bij de Technische Universiteit Eindhoven.

De onderzoeksgegevens worden bewaard tot het einde van het afstudeer traject of een maximum van 3 maanden, wat als eerste is. Uiterlijk na het verstrijken van deze termijn zullen de gegevens worden verwijderd of worden geanonimiseerd zodat ze niet meer te herleiden zijn tot een persoon.

De onderzoeksgegevens worden indien nodig (bijvoorbeeld voor een controle op wetenschappelijke integriteit) en alleen in anonieme vorm ter beschikking gesteld aan personen buiten de onderzoeks- groep.

Tot slot is dit onderzoek beoordeeld en goedgekeurd door de ethische commissie van de Technische Universiteit Eindhoven.

## 8. Vrijwilligheid

Deelname aan dit onderzoek is geheel vrijwillig. U kunt als deelnemer uw medewerking aan het onderzoek te allen tijde stoppen, of weigeren dat uw gegevens voor het onderzoek mogen worden ge bruikt, zonder opgaaf van redenen. Het stopzetten van deelname heeft geen nadelige gevolgen voor u of de eventueel reeds ontvangen vergoeding.

Als u tijdens het onderzoek besluit om uw medewerking te staken, zullen de gegevens die u reeds hebt verstrekt tot het moment van intrekking van de toestemming in het onderzoek gebruikt worden. Wilt u stoppen met het onderzoek, of heeft u vragen en/of klachten? Neem dan contact op met de onderzoeksleider.

- Jelle van Midden
- J.n.a.v.midden@student.tue.nl
- (+31) 6 19 377 394

Dit onderzoek wordt uitgevoerd vanuit de Technische Universiteit Eindhoven en is de verwerkingsverantwoordelijke in de zin van de AVG. Indien u specifieke vragen hebt over de omgang met persoonsgegevens kun u deze ook richten aan de functionaris gegevensbescherming van de TU/e door een mail te sturen naar functionarisgegevensbescherming@tue.nl. U hebt daarnaast het recht om een klacht in te dienen bij de Autoriteit Persoonsgegevens.

Tot slot heeft u het recht een verzoek tot inzage, wijziging, verwijdering of aanpassing van uw gegevens te doen. Ga voor meer informatie naar https://www.tue.nl/storage/privacy/. Dien uw verzoek daartoe in via privacy@tue.nl.

***** Scroll naar beneden voor het toestemmingsformulier *****

**Toestemmingsformulier voor deelname volwassene**

Door dit toestemmingsformulier te ondertekenen erken ik het volgende:

1. Ik ben voldoende geïnformeerd over het onderzoek door middel van een separaat informatieblad. Ik heb het informatieblad gelezen en heb daarna de mogelijkheid gehad vragen te kunnen stellen. Deze vragen zijn voldoende beantwoord.
2. Ik neem vrijwillig deel aan dit onderzoek. Er is geen expliciete of impliciete dwang voor mij om aan dit onderzoek deel te nemen. Het is mij duidelijk dat ik deelname aan het onderzoek op elk moment, zonder opgaaf van reden, kan beëindigen. Ik hoef een vraag niet te beantwoorden als ik dat niet wil.

Naast het bovenstaande is het hieronder mogelijk voor verschillende onderdelen van het onderzoek specifiek toestemming te geven. U kunt er per onderdeel voor kiezen wel of geen toestemming te geven.

3. Ik geef toestemming om de persoonsgegevens die gedurende het onderzoek bij mij worden verzameld te verwerken zoals is opgenomen in het bijgevoegde informatieblad. (lees meer in paragraaf 3&4).

   JA ☐ NEE ☐

4. Ik geef toestemming voor de verwerking van bijzondere categorieen persoonsgegevens zoals opgenomen in paragraaf 3 van het informatieblad. (lees meer in paragraaf 3&4).

   JA ☐ NEE ☐

Naam Deelnemer:

Handtekening:

Datum:

Naam Onderzoeker:

Handtekening:

Datum:

# Appendix 5. Descriptive frequencies subject 1

**Date**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 00/01/1900 | 3 | .0 | .0 | .0 |
| | 12/01/2022 | 1437 | 12.5 | 12.5 | 12.5 |
| | 13/01/2022 | 1440 | 12.5 | 12.5 | 25.0 |
| | 14/01/2022 | 1440 | 12.5 | 12.5 | 37.5 |
| | 15/01/2022 | 1440 | 12.5 | 12.5 | 50.0 |
| | 16/01/2022 | 1440 | 12.5 | 12.5 | 62.5 |
| | 17/01/2022 | 1440 | 12.5 | 12.5 | 75.0 |
| | 18/01/2022 | 1440 | 12.5 | 12.5 | 87.5 |
| | 19/01/2022 | 1439 | 12.5 | 12.5 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**At Work**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 5203 | 45.2 | 45.2 | 45.2 |
| | 1 | 6316 | 54.8 | 54.8 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Email**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11437 | 99.3 | 99.3 | 99.3 |
| | 1 | 82 | .7 | .7 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Calling**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11492 | 99.8 | 99.8 | 99.8 |
| | 1 | 27 | .2 | .2 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Meeting**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11464 | 99.5 | 99.5 | 99.5 |
| | 1 | 55 | .5 | .5 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Reviewing documents**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11436 | 99.3 | 99.3 | 99.3 |
| | 1 | 83 | .7 | .7 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Preparing documents**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11327 | 98.3 | 98.3 | 98.3 |
| | 1 | 192 | 1.7 | 1.7 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Presenting**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11491 | 99.8 | 99.8 | 99.8 |
| | 1 | 28 | .2 | .2 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Other work-related tasks**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11519 | 100.0 | 100.0 | 100.0 |

**Cleaning**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11519 | 100.0 | 100.0 | 100.0 |

**Cooking and eating**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11459 | 99.5 | 99.5 | 99.5 |
| | 1 | 60 | .5 | .5 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Sporting**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11519 | 100.0 | 100.0 | 100.0 |

**Relaxing**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11492 | 99.8 | 99.8 | 99.8 |
| | 1 | 27 | .2 | .2 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Social event**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11519 | 100.0 | 100.0 | 100.0 |

**Sleeping**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11519 | 100.0 | 100.0 | 100.0 |

**Other leisure-related tasks**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11519 | 100.0 | 100.0 | 100.0 |

**Positive Prompt**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11508 | 99.9 | 99.9 | 99.9 |
| | 1 | 11 | .1 | .1 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Negative Prompt**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11519 | 100.0 | 100.0 | 100.0 |

**Neutral Prompt**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11517 | 100.0 | 100.0 | 100.0 |
| | 1 | 2 | .0 | .0 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Info Prompt**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11518 | 100.0 | 100.0 | 100.0 |
| | 1 | 1 | .0 | .0 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

**Response Direction**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 11506 | 99.9 | 100.0 | 100.0 |
| Missing | System | 13 | .1 | | |
| Total | | 11519 | 100.0 | | |

**Task Activity Level**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 10965 | 95.2 | 95.2 | 95.2 |
| | 1 | 27 | .2 | .2 | 95.4 |
| | 2 | 356 | 3.1 | 3.1 | 98.5 |
| | 3 | 88 | .8 | .8 | 99.3 |
| | 4 | 83 | .7 | .7 | 100.0 |
| | Total | 11519 | 100.0 | 100.0 | |

# Appendix 6. Descriptive frequencies subject 2

**Date**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | | 2 | .0 | .0 | .0 |
| | 12/01/2022 | 1437 | 20.0 | 20.0 | 20.0 |
| | 13/01/2022 | 1440 | 20.0 | 20.0 | 40.0 |
| | 17/01/2022 | 1440 | 20.0 | 20.0 | 60.0 |
| | 18/01/2022 | 1440 | 20.0 | 20.0 | 80.0 |
| | 19/01/2022 | 1439 | 20.0 | 20.0 | 100.0 |
| | Total | 7198 | 100.0 | 100.0 | |

**At Work**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 3779 | 52.5 | 52.5 | 52.5 |
| | 1 | 3417 | 47.5 | 47.5 | 100.0 |
| | Total | 7196 | 100.0 | 100.0 | |
| Missing | System | 2 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Email**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7087 | 98.5 | 98.5 | 98.5 |
| | 1 | 110 | 1.5 | 1.5 | 100.0 |
| | Total | 7197 | 100.0 | 100.0 | |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Calling**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7197 | 100.0 | 100.0 | 100.0 |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Meeting**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 4526 | 62.9 | 62.9 | 62.9 |
| | 1 | 2671 | 37.1 | 37.1 | 100.0 |
| | Total | 7197 | 100.0 | 100.0 | |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Reviewing documents**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7088 | 98.5 | 98.5 | 98.5 |
| | 1 | 109 | 1.5 | 1.5 | 100.0 |
| | Total | 7197 | 100.0 | 100.0 | |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Preparing documents**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 6727 | 93.5 | 93.5 | 93.5 |
| | 1 | 470 | 6.5 | 6.5 | 100.0 |
| | Total | 7197 | 100.0 | 100.0 | |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Presenting**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7197 | 100.0 | 100.0 | 100.0 |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Other work-related tasks**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7061 | 98.1 | 98.1 | 98.1 |
| | 1 | 136 | 1.9 | 1.9 | 100.0 |
| | Total | 7197 | 100.0 | 100.0 | |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Cleaning**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7197 | 100.0 | 100.0 | 100.0 |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Cooking and eating**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7194 | 99.9 | 100.0 | 100.0 |
| | 1 | 3 | .0 | .0 | 100.0 |
| | Total | 7197 | 100.0 | 100.0 | |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Sporting**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7197 | 100.0 | 100.0 | 100.0 |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Relaxing**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7197 | 100.0 | 100.0 | 100.0 |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Social event**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7197 | 100.0 | 100.0 | 100.0 |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Sleeping**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7197 | 100.0 | 100.0 | 100.0 |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Other leisure-related tasks**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7197 | 100.0 | 100.0 | 100.0 |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Positive Prompt**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7194 | 99.9 | 100.0 | 100.0 |
| | 1 | 3 | .0 | .0 | 100.0 |
| | Total | 7197 | 100.0 | 100.0 | |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Negative Prompt**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7194 | 99.9 | 100.0 | 100.0 |
| | 1 | 3 | .0 | .0 | 100.0 |
| | Total | 7197 | 100.0 | 100.0 | |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Neutral Prompt**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 7194 | 99.9 | 100.0 | 100.0 |
| | 1 | 3 | .0 | .0 | 100.0 |
| | Total | 7197 | 100.0 | 100.0 | |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Info Prompt**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 6838 | 95.0 | 95.0 | 95.0 |
| | 1 | 358 | 5.0 | 5.0 | 100.0 |
| | Total | 7196 | 100.0 | 100.0 | |
| Missing | System | 2 | .0 | | |
| Total | | 7198 | 100.0 | | |

**Task Activity Level**

| | | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|---|
| Valid | 0 | 3910 | 54.3 | 54.3 | 54.3 |
| | 2 | 3175 | 44.1 | 44.1 | 98.4 |
| | 3 | 3 | .0 | .0 | 98.5 |
| | 4 | 109 | 1.5 | 1.5 | 100.0 |
| | Total | 7197 | 100.0 | 100.0 | |
| Missing | System | 1 | .0 | | |
| Total | | 7198 | 100.0 | | |