Occupancy Assessment for Lighting Evaluation using Digital Twin technology

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ABSTRACT: The amount of information on evidence-based design in lighting is mounting, however the facility managers, lighting designers, and researchers are struggling with an implementation of an efficient post-occupancy evaluation system. This research aims to establish a method for Digital Occupancy Assessment for Lighting Evaluation (DOALE) to strengthen evidence-based lighting research supporting value generation for stakeholders. A prototype has been implemented using Azure Digital Twin and the RealEstateCore ontology to investigate how an ontology and a commercial platform, developed to facilitate data integration for smart buildings, can be used for occupancy assessment. The prototype was evaluated using a post occupancy evaluation session where data concerning environmental factors (temperature, illuminance) and data concerning occupants (motion, galvanic skin response, and heart rate) were gathered. Questionnaires concerning occupancy perception were also carried out using mobile technology. Several interviews/discussions were also conducted with the lighting researchers using the prototype to perform the POE. The result indicates that it is possible to use current commercial digital twin technology to implement a post-occupancy evaluation system, but the technology is at present so complex that it is hard for a lighting researcher to adopt the system.

1 INTRODUCTION

It has been estimated that 80–90% of business operating costs are attributable to employee expenses, whereas only 1–3% are associated with energy costs and 8–11% with other facility costs (Clements-Croome, 2006). During the past few decades, increasing evidence has been accumulated on the fundamental impact of indoor environmental quality (IEQ) on health and performance (Kallio et al., 2020). Daylighting and lighting are essential contributors to performance and human well-being in indoor facilities (Van Duijnhoven, Aarts, Aries, Rosemann, & Kort, 2019). Still, even in the context of smart buildings, the needs of building users are often ignored (Jia, Komeily, Wang, & Srinivasan, 2019).

The amount of information on evidence-based design in lighting is mounting, however, the facility managers are struggling with an implementation of an efficient system needed to be able to gather the data for the evidence-based user-oriented operation of buildings having that long-term measurement is the most effective and accurate way to establish databases that contain this information (Li & Lou, 2018).

Lighting simulation tools help lighting designers to analyze different aspects of the lighting quality of the lit environment and assess alternative design solutions (Reinhart & Fitz, 2006). To gain advantages of lighting simulation tools, it is however important to have a good awareness of the correlation between the tools' performance metrics and human perception (physiological and psychological factors) (O'Brien & Gunay, 2015). Traditionally, post-occupancy evaluation (POE) is employed to assess the building performance and gather human perception of a built environment. It is an important task not only for facility managers, and designers but also for researchers. The result of the present research indicates that POEs should be conducted several times for a facility to get a good evaluation of user perception (Kallio et al., 2020). especially regarding daylight (Davoodi, Johansson, & Aries, 2019). It also shows that POE is the most time-consuming part of a simulation-driven evidence-based design process (Davoodi, Johansson, & Aries, 2021).

The "digital twin" concept has emerged over the past decade in the domains of manufacturing, production, and operations. Although there is no commonly agreed definition of the term digital twin (DT) (Sacks, Brilakis, Pikas, Xie, & Girolami, 2020) there is a common understanding concerning the core of the concept mainly focusing on the data-centric management of physical systems and are "generally understood as up-to-date digital representations of the physical and functional properties of a system" (Sacks et al., 2020). According to (Tao et al., 2019), digital twins have three main elements: a physical artifact, a digital counterpart, and the connection that binds the two together. According to (Pan & Zhang, 2021) a DT contains three main components to create a practical loop: a physical entity, a virtual entity, and a data link. The connection of the data link is the transfer of data, between the physical and virtual counterparts, enabled by the development of advanced sensing (e.g., different kinds of sensors), the internet of things (e.g., interconnected assets). Sensors are mostly mentioned as data sources connected to the physical counterpart, but also other sources can be utilized, e.g. users of a facility. Usually, there are two approaches to dynamic mapping in the DT. Inspection data are gathered in the physical world and subsequently transmitted to the virtual world for further analysis. Simulation, prediction, and optimization are achieved in the virtual model by learning data from multiple sources, offering prompt solutions to guide the realistic process and adapt to the changing context (Yitmen, Alizadehsalehi, Akıner, & Akıner, 2021). Several benefits of using DT for facility management have been shown (Zhao, Feng, Chen, & Garcia de Soto, 2022) and the implementation of DT technology in facilities are expanding which in turn have made large software companies such as Microsoft interested in the area[1].

This research aims to establish a method for Digital Occupancy Assessment for Lighting Evaluation (DOALE) to strengthen evidence-based lighting research supporting value generation for stakeholders. In the Lighting Design education at the Jönköping University, a Lighting Living lab is instrumented for gathering data concerning lighting conditions together with human physiological and psychological reactions to lighting conditions. A digital twin prototype was implemented and evaluated having this aim.

2 RESEARCH METHOD

The research process of this study is framed by the design science research methodology (DSR). Design science focuses on solving a practical problem by creating an artifact in the context of the research (Hevner, March, Park, & Ram, 2004; Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007). The implementation performed in the line of design science research methodology mainly referred to as an artifact or prototype is categorized as constructs, models, methods, and instantiations (Hevner et al., 2004). Constructs provide the language such as terms, notations, definitions, and notions that are required for problem formulation as well as identification of potential solutions (Hevner et al., 2004; Johannesson & Perjons, 2014). Models use constructs to represent practical problems as well as their possible solutions (Hevner et al., 2004; Johannesson & Perjons, 2014). Methods define guidelines and processes for how to solve problems and achieve goals (Hevner et al., 2004; Johannesson & Perjons, 2014). Instantiations demonstrate the viability of constructs, models, or methods implemented in a working prototype system (Hevner et al., 2004).

In this research, implementation will be focused on and evaluated. The DSR process model presented by Peffers et al. (2007) is employed to structure this study and is depicted in Figure 1. The communication part of the framework is presented in the discussion section of this paper.

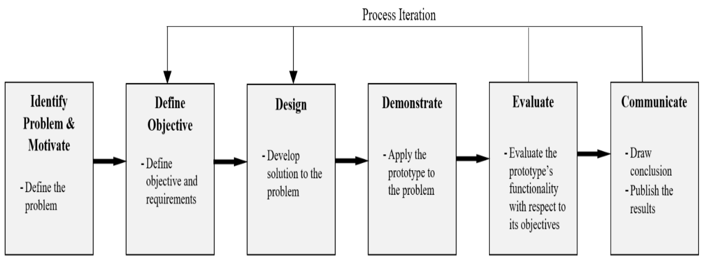

Figure 1 DSR process model (adapted from (Peffers et al., 2007) & (Piirainen, 2010))

3 PROBLEM IDENTIFICATION AND MOTIVATION

As described in the introduction both facility managers and lighting designers and researchers are struggling to gather the data needed to evaluate facilities to improve the built environment. In this paper, the focus will be on researchers and their need of evaluating light environments. Having the research question:

How can DT technology be used for POE of lighting quality in a built environment?

4 OBJECTIVE AND REQUIREMENTS OF THE SOLUTION

Having the situation described above one of the objectives of DOALE is to automate the POE process. One of the main parts of the POE process is data gathering. In this part, data concerning both the physical environment and human perception needs to be collected. The requirements for the artifact were gathered in discussions between the researchers aiming to use the artifact implementation in the DOALE project. The requirements for the artifact

[1] https://azure.microsoft.com/sv-se/blog/accelerating-smart-building-solutions-with-cloud-ai-and-iot/

were formulated as Functional Requirements (FR) and Non-Functional Requirements. The Functional Requirements were formulated as:

- Detection and logging of people that are present in the rooms (geospatial data).
- Detection and logging of environmental factors (temperature, light).
- Detection and logging of occupant data (heart rate, galvanic skin response).
- Detection and logging of occupant perception (aesthetics and personal feelings).

The Non-Functional Requirements were formulated as:

- Sensors should be non-invasive, i.e., people in the labs should not be required to wear heavy equipment or execute special software on their phones.
- All data that is harvested should be stored.
- Both historical and real-time data should be visualized for analysis purposes.

5 DESIGN AND DEVELOPMENT

The research outcome in design science mainly referred to as an artifact, is categorized as constructs, models, methods, and instantiations (Hevner et al., 2004). The artifact implementation in the DOALE project should be categorized as an instantiation but because all categories are of importance the design and development of the artifact will be described using all categories in the DSR framework.

5.1 *Constructs*

Constructs provide the language such as terms, notations, definitions, and notions that are required for problem formulation as well as identification of potential solutions (Hevner et al., 2004; Johannesson & Perjons, 2014).

The RealEstateCore (REC) ontology is developed to facilitate data integration for smart buildings focusing on the operation phase of a building (Hammar, Wallin, Karlberg, & Hälleberg, 2019). REC is intended to be used by property owners to enable them to connect and equip their buildings with new systems to realize smart buildings. The RealEstateCore (REC) ontology is the result of combining Semantic Web technologies with a business-usefulness approach[2]. As a modular ontology, REC is made up of data schemas that explain concepts and relationships in data developed to model buildings and building systems, or data derived from these models. The REC platform, for example, addresses issues like building construction and ownership, occupants, and technical systems like sensors. Having this, REC was chosen as the base vocabulary in the artifact. Since researchers from Jönköping University are involved in the development of REC made the choice of using this ontology rather natural but REC was also chosen to investigate how an ontology developed to facilitate data integration for smart buildings can be used also for occupancy assessment.

The key classes in REC are shown in Figure 2 and are shortly described below:

Space is a 3D spatial object that is a contiguous part of the physical world and that contains or can contain sub-spaces.

Asset is an object which is placed inside of a building but is not an integral part of that building's structure, for example, furniture, equipment, systems, etc.

Logical Device: A physical or logical object defined as electronic equipment or software that com-

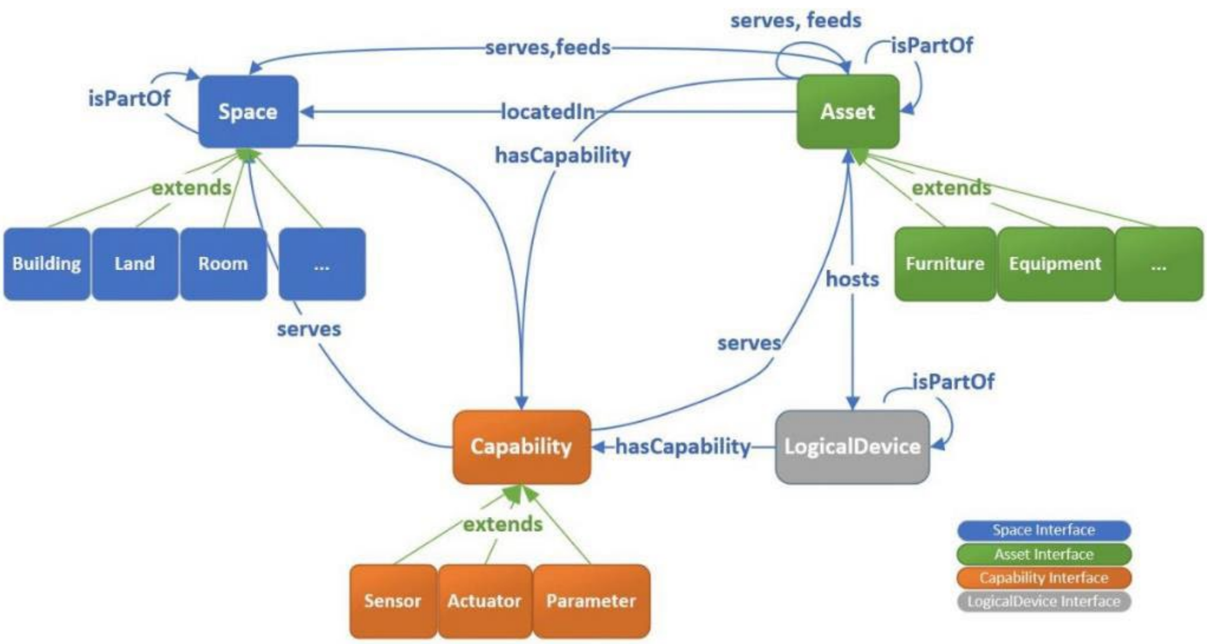

Figure 2. the key classes in RealEstateCore[1].

[2] https://www.realestatecore.io/

municates and interacts with a digital twin platform. A logical device could be an integrated circuit inside of a smart HVAC unit, or a virtual server running on a Kubernetes cluster. Logical devices can have **Capability** instances (through has Capability) that describe their input and output capabilities. If Logical Devices are embedded within Asset entities (through the hosted By property) such capabilities typically denote the capabilities of the asset.

5.2 *Models*

Models use constructs to represent practical problems as well as their possible solutions (Hevner et al., 2004; Johannesson & Perjons, 2014).

A conceptual model or a Semantic Model Graph was first implemented, having REC as the base. The REC is an OWL 2 ontology that is defined in a standard manner using RDFS, and OWL. Having REC as a base for the conceptual model should have made the RDFS, and OWL the natural choice to implement the conceptual model. However, early in the design process, it was chosen to focus on using Microsoft's AZURE Digital twin (ADT) as a base for the implementation. One of the main reasons for doing this was that Microsoft started to show interest in REC and the implementation of the artifact described here created a good opportunity to test and develop the collaboration with Microsoft. The parts of REC needed for the artifact were translated to the JSON-LD-based Digital Twins Definition Language (DTDL)[3]. According to the terminology of ADT, the conceptual model was described as a model graph. The model graph of the artifact can be seen in Figure 3.

The Model Graph was used to instantiate a model of the Digital Twin representation needed for the artifact (Twin Graph according to the vocabulary of ADT).

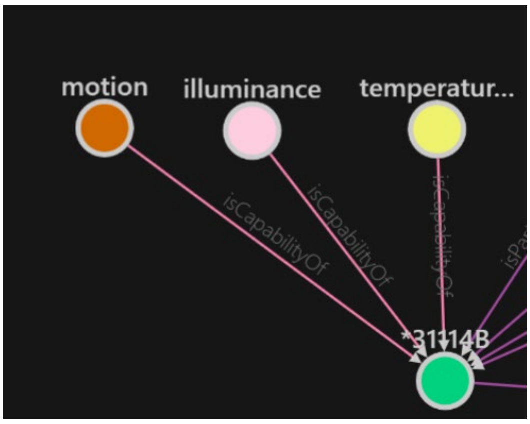

Figure 4. Digital Twin graph representing a space (3114B) and the sensors connected to this space (motion, illuminance, and temperature) (screenshot from Azure Digital Twin Explorer).

5.3 *Methods*

Methods define guidelines and processes for how to solve problems and achieve goals (Hevner et al., 2004; Johannesson & Perjons, 2014).

As indicated in the previous section it was chosen to use the Microsoft Azure Digital Twins platform to implement the artifact. This decision gave the basic guidelines and processes for the implementation[4]. The Constructs, described in section 5.1, and the Models, described in section 5.2, were implemented using Azure Digital Twins Explorer The use of the

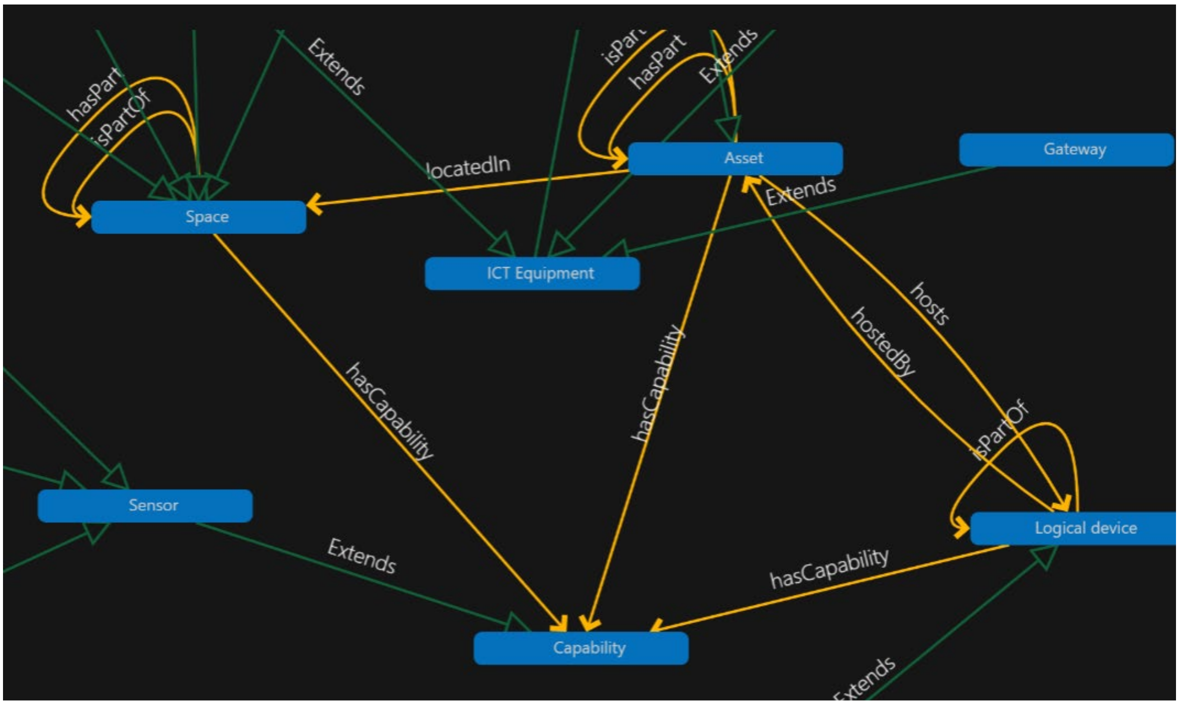

Figure 3. Semantic Model Graph (screenshot from Azure Digital Twin Explorer[1]).

[3]https://github.com/Azure/opendigitaltwins-dtdl/blob/master/DTDL/v2/dtdlv2.md#introduction

[4] https://docs.microsoft.com/en-us/azure/digital-twins/

possible to "bootstrap" Digital Twin functions and facilitate the guidelines and processes needed.

5.4 *Instantiation*

Instantiations demonstrate the viability of constructs, models, or methods implemented in working prototype systems (Hevner et al., 2004).

The instantiation of the artifact was conducted using Microsoft Azure Digital Twins[5] (ADT). ADT is an IoT platform as well as a platform as a service (PaaS). ADT service provides all the required environment for the development of a digital representation of a physical space that replicates a smart space i.e., a multitude of sensors or devices mounted in a space for utilization, by collecting information or detecting activity or conditions in a geospatial space. As described above ADT was augmented with REC. For the visualization of the data connected to the requirement "Both historical and real-time data should be visualized for analysis purposes." it was chosen to use Azure Time Serie Insights[6] (TSI). Having that decision, the main implementation focused on installing the data collection instruments and transporting the data from the data collection instruments and visualizing the data for the researchers.

5.4.1 *Data collection instruments*

To be able to detect and logging of people and environmental factors (motion, temperature, illuminance) Philips's hue sensors[7] were installed in each room near the door entrance, 162 cm above the ground. The initial choice for using this sensor was its easy installation and that it contained the three inbuilt sensor properties needed. The data ingestion from the sensor was propagated using Philips Hue Sensor Bridge[8], installed in the corridor of the rooms.

Detection and logging of occupant data (heart rate, galvanic skin response) are performed using a Galvanic skin response sensor[9] and heart rate sensor (Polar Verity[10]). For the data ingestion, the sensors are connected to a Raspberry Pi microcontroller that is, in turn, connected to the internet.

[5]https://docs.microsoft.com/en-us/azure/digital-twins/overview

[6]https://docs.microsoft.com/en-us/azure/time-series-insights/

[7]https://www.philips-hue.com/en-gb/p/hue-motion-sensor/8719514342125

[8]https://www.philips-hue.com/en-gb/p/hue-bridge/8719514342583#overview

[9]https://www.seeedstudio.com/Grove-GSR-sensor-p-1614.html?queryID=284df7acfced3b3f370f1c57faa6dafe&objectID=1274&indexName=bazaar_retailer_products

[10] https://www.polar.com/uk-en/products/accessories/polar-verity-sense

5.4.2 *Data flow architecture*

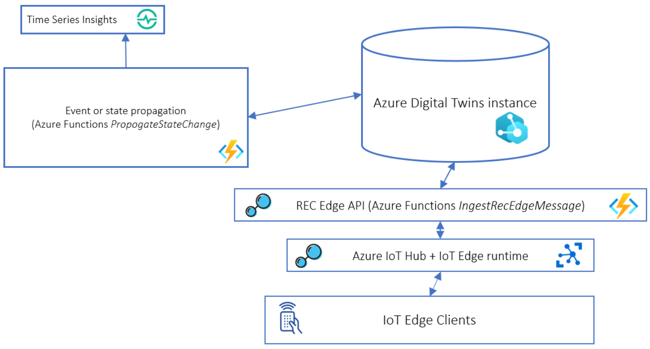

Figure 5. Sensor data flow architecture.

The data flow between the data collection instruments and the Time Series Insight Model is described in Figure 5.

For the data from a real-world device (sensors) to show up in its digital twin it first needs to be connected to the Azure platform. This is accomplished with Raspberry Pi microcontrollers that are connected to the internet. The IoT Edge Client hosted on the Raspberry Pi harvests the data from the sensors. The IoT Edge Client, in turn, communicates with the IoT Hub by sending Rec Edge Messages. The Azure Functions provides the "compute on demand" functionality to update the digital twin model whenever any new events occur. This is used by the IoT Hub to ingest Rec Edge Messages. When the Digital Twin Model is updated the Event Hub is used to update the Time Series Insight Model using the PropagateStateChange function that is connected by Azure Functions. This process resulted in the visualization of the data shown in Figure 6.

5.4.3 *Digital questionnaires*

One of the functional requirements stated: "Detection and logging of occupant perception (aesthetics and personal feelings)". To fulfill this requirement a digital questionnaire was implemented using esMaker[11]. esMaker is a cloud-based survey tool that is frequently used by the public sector in Sweden. The occupants use their smartphones to fill in the questionnaire to give real-time feedback response regarding the environmental factors and their personal feelings. They reached the questionnaire by using a QR-code that was placed on the wall of each space. One of the main reasons for choosing esMaker was the concern for the respondent's integrity. There has been a vast development in this area during the last few years and the current situation, in Sweden, is unclear. When using esMaker the answers from the questionnaires are stored on servers located in Sweden and the answers are handled with respect for the

[11] https://entergate.se/products/esmaker/?lang=en

Figure 6. Time Series Insight Model showing the illuminance, motion, and temperature for space 3114B.

respondent's integrity and in line with GDPR[12]. Still, it was not clear if the implementation was in line with the Swedish law on ethical review of research concerning people[13]. This law is, concerning data integrity, a national adaption of the EU regulation (2016/679)[14]. For this reason, an application was made to the Swedish Ethics testing authority (Etikprovningsmyndigheten[15]). The application was approved by the authority, and it can be concluded that data concerning occupant perception can be gathered in the line of a research study if the procedure concerning the data management must be designed and documented in detail and if the respondent's integrity is taken into consideration.

6 DEMONSTRATION

The objective of this research is to establish a method for Digital Occupancy Assessment for Lighting Evaluation to strengthen evidence-based lighting research supporting value generation for stakeholders. Having the focus on lighting research primary the prototype has been demonstrated for the researcher that should be responsible for the POE sessions where the prototype should be used. This researcher was a member of the project team but not in charge of the implementation of the prototype.

7 EVALUATION

Pfeiffer and Niehaves (2005) present different evaluation criteria including functionality, usability, reliability, performance, and supportability. In this research, the evaluation takes the form of testing the prototype for its functionality and usability in the context of the objective of the prototype use case as well as the defined requirements. Prototype (instantiations) evaluation involves using different evaluation approaches such as code inspection, testing, code analysis, and verification (Pfeiffer & Niehaves, 2005). Additionally, conducting questionnaires, collecting feedback or simulations can be done for the evaluation (Peffers et al., 2007). Testing and collecting feedback were selected for evaluating the prototype in this research. The testing was performed by the same researcher that participated in the demonstration of the prototype. The researcher conducted a POE to evaluate several spaces concerning the light. At the writing of this paper, the POE:s have not been finalized but some preliminary results concerning the evaluation of the prototype have been gathered below.

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[12] https://www.imy.se/en/organisations/data-protection/this-applies-accordning-to-gdpr/

[13] https://lagen.nu/2003:460

[14] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32016R0679#4.2

[15] https://etikprovningsmyndigheten.se/

7.1 *Functionality*

The requirements for the artifact were formulated as Functional Requirements (FR) and Non-Functional Requirements (NFR).

From the demonstration and the test of the prototype, it can be concluded that all the functional requirements were fulfilled.

Concerning the non-functional requirements, the equipment that was needed to be connected to the participants, on top of the participant's mobile phone, was the Galvanic skin response sensor and the heart rate sensor. The heart rate sensor used Bluetooth to connect to the Raspberry Pi but the Galvanic skin response sensor had to be directly connected. This made it necessary for the participant to carry the Raspberry Pi and a Power bank to support it.

7.2 *Usability*

The researcher that tested the prototype stated that all the information needed to perform a POE of the environment can be found in the system. The researcher also stated that it is rather easy to learn and use the tools used to visualize the data from sensors, Time Series Insight Model, and the questionnaires, esMaker. However, combining and merging the data streams from these tools is not supported by the prototype at present. The researcher testing the prototype also found it hard to understand the full implementation. This hindered the researcher to adopt the system.

8 CONCLUSION

This research aims to establish a method for Digital Occupancy Assessment for Lighting Evaluation (DOALE) to strengthen evidence-based lighting research supporting value generation for stakeholders. In the Lighting Design education at the Jönköping University, a Lighting Living lab is instrumented for gathering data concerning lighting conditions together with human physiological and psychological reactions to lighting conditions. A digital twin prototype was implemented and evaluated having this aim. Microsoft Azure Digital Twins[16] (ADT) was chosen as the platform for the implementation. The ADT was augmented with the RealEstateCore (REC) ontology[17]. These choices created an opportunity to investigate how an ontology and a commercial platform developed for facilitating data integration for smart buildings can be used also for occupancy assessment. To also be able to gather data concerning occupant perception a digital questionnaire was implemented using esMaker[18].

The research process of this study is framed by the design science research methodology where the prototype should be evaluated using Testing and collecting feedback. The test is currently being performed by letting a researcher use the prototype for a POE study of a number of rooms to evaluate their lighting conditions. The preliminary result indicates that the requirements stated for the prototype have been fulfilled and that the functionality is sufficient. Concerning the usability of the prototype the different tools used for visualizing the data from the sensors and the questionnaires are user-friendly. However, the possibility to merge the different data streams from the sensors and the questionnaires is missing. The feedback from the test also indicates that, although using commercial tools, the digital twin technology is so complex that it is hard for a lighting researcher to adopt the system.

8.1 *Future work*

This paper gives preliminary results from an ongoing project. The prototype will be further developed. In this development, it is planned to use Microsoft Power BI [19] to merge the different data streams. The evaluation of the prototype will also be further conducted and on top of lighting researchers also facility managers will be involved in the tests.

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