A SEMANTIC DIGITAL TWIN PROTOTYPE FOR WORKPLACE PERFORMANCE ASSESSMENT

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ABSTRACT: *Nowadays, despite the growing attention to indoor environmental quality and comfort, existing workplaces still often fail to meet employees' expectations and needs, affecting their well-being and productivity. In order to improve management decisions, crucial insights can be provided by the timely correlation of objective workplace conditions, observed by sensors, and subjective workers' feedback, collected through Ecological Momentary Assessment (EMA) method. This paper presents a prototypical Digital Twin for the assessment of workplace performance from an occupant-centric perspective, based on the integration of IoT, BIM and Semantic Web technologies. Following the definition of relevant use cases and requirements a layered system architecture is presented and the prototype implementation is discussed. For capturing the workplace's environmental properties, a sensor network based on the Zigbee communication standard is proposed due to its data transmission efficiency. The measured data, converted in the lightweight MQTT protocol, are streamed to an InfluxDB time series database where they are stored along with the incoming workers' feedback collected as survey responses with a dedicated web application. These time series data are queried and transported into a developed web platform for integrating BIM and RDF data within the standardized structure of Information Containers for linked Document Delivery (ICDDs). Inside this platform, the IFC model of the workplace, the measured data from the sensors, and the worker generated RDF data according to the WOMO ontology for occupant-centric workplace management are linked. The capabilities of the workplace Digital Twin prototype are finally demonstrated querying the linked heterogeneous data to fulfil workplace management tasks in a case study provided at the end of the paper.*

KEYWORDS: *Digital Twin, Workplace performance assessment, Well-being and productivity, Linked Data, Information Container for linked Document Delivery (ICDD), Semantic Web, Internet-of-Things (IoT).*

1. INTRODUCTION

Providing high-quality indoor workplaces that meet their occupants' needs is a challenge of utmost importance for Facility Managers (FM) because of the critical impact they have not only on employees' quality-of-life, health and well-being (Vischer and Wifi, 2017), but also productivity (Al Horr, Arif, Kaushik, *et al.*, 2016). However, although the growing adoption of Information and Communication Technologies (ICT) to control and automate building systems (e.g. HVAC, lighting, access, etc.) has enabled an unprecedented granularity and interactivity in the operation of workplaces, evidence suggest that they still fall short of their occupants' expectations (Abbaszadeh *et al.*, 2006). To address this issue, occupant-centric approaches for control and operation of buildings have been recently proposed, shifting the technology-centred paradigm to the recognition of the user, with its individual and dynamic physiological and psychological requirements, as the most critical component in the occupant-building system (O'Brien *et al.*, 2020).

Recent research focused on supporting managers in the assessment of workplace performance providing them a constant holistic understanding of employees' individual activities, preferences, and conditions within their physical and social work environment. In this regard, effective solutions have been proposed for the timely

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collection of occupant- and building-generated data and their semantic integration, processing, and visualization using Building Information Modeling (BIM), sensor networks and Semantic Web technologies (Abdelrahman, Chong and Miller, 2022; Donkers, de Vries and Yang, 2022a). However, the development and implementation of these approaches for workplace management purposes are still in their early stages due to limitations in domain knowledge representation, and heterogeneous data integration strategies that need further investigation.

In order to address these issues, this paper presents the concept of a semantic Digital Twin for the integration and exploitation of heterogeneous workplace data, built on the findings of previous contributions by the authors. The research framework and workplace domain knowledge formalization are discussed in Bruttini *et al*., (2022), while the storage and processing of semantic data pivots on the use of standardized information containers (ISO 21597-1:2020) through a dedicated web platform whose effectiveness has been demonstrated in asset and project management use cases (Sigalov *et al.*, 2021; Hagedorn, Liu, *et al.*, 2023). In the followings, after the discussion of the findings of relevant related works, the system development, prototypical implementation and case study demonstration for a workplace performance use case are provided.

2. BACKGROUND

Over the past decade, the pursuit of the benefits obtainable with data-driven management and control of the built environment with the specialization of the concept of "Digital Twin" for the AECO sector, has witnessed an exponential growth (Sacks *et al.*, 2020). The use of Sematic Web technologies and the diffusion of the Linked Building Data (LBD)[1] approach paved the way for the integration of heterogeneous information from diverse knowledge domains, hence overcoming the initial limitations of BIM. In particular, the possibility to observe building operational conditions, e.g., indoor environmental quality (IEQ) factors and systems status, and contextually evaluate them against the way the occupants behave and perceive a given space, enabled an unprecedented understanding of building-occupant complex interactions, starting the long-awaited paradigm shift towards occupant-centric approaches in building management and operation (O'Brien *et al.*, 2020).

In the following paragraphs, the findings and limitations of recent relevant studies related to occupant-centric building operation and workplace performance assessment are reported. Then, a review on sensor network solutions for building monitoring is presented and the state-of-the-art for the semantic integration of building data is discussed.

2.1. Occupant-centric building operation and workplace performance assessment

An indoor workplace represents a complex system characterized by dynamic mutual interactions between the physical space and its occupants. Therefore, to assess workplace performance, quantifying the extent to which it supports workers' activities and meets their needs and expectations is crucial. In this regard, extensive literature investigated the impact of different physical and non-physical factors on workers' satisfaction, productivity, and well-being, from workplace IEQ parameters (Al Horr, Arif, Katafygiotou, *et al.*, 2016) to workspace layout (Kim and de Dear, 2013) and the degree of user perceived control on the environment (Luo *et al.*, 2016).

To monitor how these and other heterogeneous factors affect the workers, both building objective properties, observed by sensors, and workers subjective conditions must be timely collected and integrated. For the latter, indirect approaches based on inferences from historical building systems' data (e.g., lighting usage for visual quality assessment) are making way to the collection of direct occupant feedback through smartphone and web applications and wearable devices (Nagy *et al.*, 2023). For this purpose, the Ecological Momentary Assessment (EMA) approach (Shiffman, Stone and Hufford, 2008) initially developed for medical and social researches, is progressively replacing Post Occupancy Evaluation (POE) for the collection of frequent, real-time occupants' feedback directly from their workplace environments via the use of micro-surveys (Engelen and Held, 2019).

Nonetheless, a system that enables the semantic integration, processing, querying and visualization of building- and worker-generated data is necessary to support occupant-centric workplace management and performance assessment. In this regard, recent contributions showed the feasibility and opportunities provided by the adoption of BIM, sensor networks and semantic web technologies for the integration of static and dynamic domain-

[1] W3C Linked Building Data (LBD) Community Group - https://www.w3.org/community/lbd/ - (accessed 12/07/2023)

specific data for IEQ and occupant experience assessment (Abdelrahman, Chong and Miller, 2022; Donkers, de Vries and Yang, 2022b, 2022a). However, since indoor workplace management purposes still need to be fully addressed with specific solutions, the authors developed a framework and an ontological representation of worker's conditions and activities in indoor environments which form the conceptual basis of the workplace digital twin prototype proposed in this paper (Bruttini *et al.*, 2022).

2.2. Sensor networks for building monitoring

For the contextualization of subjective worker's data, his surrounding environmental conditions must be objectively observed through a sensor infrastructure which provides for sampling, transferring, and storing of the sensed data. In recent years, Internet-of-Things (IoT) technology has established as the main solution for the implementation of such sensor networks. Most of them make use of a similar multi-level hardware architecture that addresses the above-mentioned challenges. Kifouche *et al.* (2017) describes three levels, the sensor-, gateway- and base-station-level. Li *et al.* (2023) add a further application-layer for data visualization interfaces.

Concerning the sensors, both wired and wireless solution can be deployed. While the former can be more reliable, it needs additional cabling and therefore lacks in flexibility (Tanasiev *et al.*, 2021). Hence most of the studies use wireless solutions, relying on sensor devices that consist of a sensing unit, a microcontroller and a radio adapter for the data transmission. As sensing unit, anything from the widely used temperature and humidity sensors up to a motion or CO_2-level sensor is possible. A microcontroller reads out its data and sends them to a gateway via Wi-Fi, Bluetooth (Li *et al.*, 2023), Zigbee (Kifouche *et al.*, 2017) or LoRa (Kifouche *et al.*, 2017; Tanasiev *et al.*, 2021). As wireless sensors are mostly battery powered, power management is a crucial aspect, finding the right balance between power consumption, bandwidth, and transmission range. While some studies assemble their own sensor devices on a prototypical base, there are approaches as well that make use of out of the shelf sensor devices with proper device housing (Chamari, Petrova and Pauwels, 2023).

The gateway is placed on site and acts as a translator receiving data from the sensors and routing them into the backend system. Thus, the selection of the radio technology and communication protocol, together with the building substance and materials, substantially effects the network range, determining the number of gateways needed for a seamless coverage inside the building (Kifouche *et al.*, 2017). As used within several works (Kifouche *et al.*, 2017; Tanasiev *et al.*, 2021; Li *et al.*, 2023), it is suitable to implement the gateway with a low cost SoC computer like a Raspberry Pi, which connects via Ethernet with the backend system.

Detached from the installation on site, the backend system can be deployed anywhere else, even in the cloud. It implements a software solution for processing and storing the forwarded data. While earlier works made use of individually designed solutions (Kifouche *et al.*, 2017), recent studies showed the effective adoption of the machine-to-machine (M2M) and IoT protocol called Message Queuing Telemetry Transport (MQTT) (Tanasiev *et al.*, 2021; Chamari, Petrova and Pauwels, 2023; Li *et al.*, 2023). Eventually, besides relational databases such as MySQL(Kifouche *et al.*, 2017; Tanasiev *et al.*, 2021; Zhang and Beetz, 2022; Li *et al.*, 2023), for storing sensor observations the adoption of NoSQL, time series databases and RDF data stores is growing especially in semantic information model applications (Chamari, Petrova and Pauwels, 2023).

2.3. Linked Data and information containers for semantic Digital Twins

With the recent advent of the Digital Twin paradigm in the AECO sector, viable solutions for the integration of BIM with both static and dynamic data for the real-time representation of physical built assets became crucial. In this regard, several studies proved that the adoption of Semantic Web technologies and Linked Data approach enable the deployment of semantic Digital Twins where building information can be enriched via linking with heterogeneous domain-specific data, whose representation is in turn demanded to dedicated ontologies (Mavrokapnidis *et al.*, 2021; Eneyew, Capretz and Bitsuamlak, 2022).

However, in a context where a standardized approach for the creation and maintenance of Digital Twins is still missing and systems' requirements are subject to frequent transformation, using BIM data and models as common basis for the implementation of domain-specific Digital Twins with a modular approach can provide the much-needed flexibility and scalability. Kosse *et al.*, (2023) argue how modular Digital Twins can be implemented with the use of standardized information containers which provide a model for storing and exchanging heterogeneous information. In particular, as shown in Polter and Scherer (2023), and Zinke *et al.* (2023), Information Containers for linked Document Delivery (ICDDs), compliant with the ISO 21597-1 (2020), are suitable for this purpose since they implement a vendor-neutral data structure which integrates, besides payload documents to be exchanged, distributed linked data. Moreover, supporting the Linked Data approach, their interconnection to web standards such as HTTP and REST is easily implementable, while Semantic Web technologies enable data retrieval through SPARQL queries. Arbitrary data can be modeled using an ontological layer that can be stored in the container or as web resources, while a specific linking structure supplements the capability of the container to host a Digital Twin. Furthermore, as demonstrated Senthilvel and Beetz (2021), the possibility to nest and interlink ICDD individual container modules opens to a scalable system-of-systems approach where compatibility is ensured by the containers' conformity to ISO 21597.

Likewise, in previous research the authors showed the feasibility and versatility obtainable with the adoption of ICDD containers for the storage, integration, querying and visualization of building and domain-specific information with the development of a dedicated web platform. With differences in implemented functions and user interface, the proposed approach proved effective for different use cases, including infrastructure asset management (Hagedorn, Liu, *et al.*, 2023), and smart contracts-based automated payment and contract management (Sigalov *et al.*, 2021). On this basis, as detailed in the followings, a customized version of the mentioned ICDD platform is proposed for the implementation of the presented workplace digital twin prototype.

3. RESEARCH FRAMEWORK AND METHODOLOGY

The present study is part of a broader research effort which aims at the realization of a data-driven workplace management framework finalized to the enhancement of workers' well-being and productivity through capturing and understanding the dynamic worker-workplace interactions. To achieve this goal, a workplace semantic digital twin, able to integrate heterogeneous occupant- and building-generated data for workplace management purposes, is proposed. With reference to Fig. *1*, this paragraph describes the study's methodology, from the system conceptualization to its prototypical implementation to a room-scale case study.

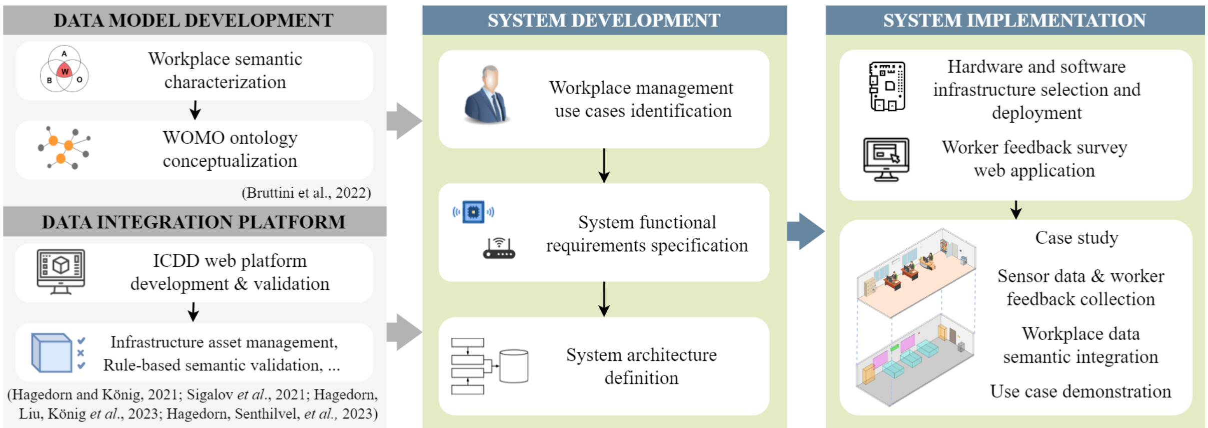

Fig. 1 Research methodology

As discussed above (see §2), the development and implementation of the proposed system stems from previous authors' contributions. The formal representation of workplace knowledge, characterized as the intersection of the worker-building-activity semantic domains, is provided in the Occupant-centric Workplace Management Ontology (WOMO) presented in Bruttini *et al.*, (2022). Workers' objective and subjective features, along with their current activity, are described and interlinked through feedback instances, hence related to the correspondent building spaces and conditions. These are represented by reusing well-established ontologies, such as the Building Topology Ontology (BOT)[2] and Semantic Sensor Network ontology (SSN)[3]. In turn, for the semantic storage and integration of the aforementioned heterogeneous workplace data, standardized information containers (ISO 21597-1, 2020) are adopted. Therefore, the workplace knowledge base, comprising of its IFC model, workers' and sensors' data, is realized through an ICDD container and semantic data integration,

[2] https://w3c-lbd-cg.github.io/bot/ - (accessed 12/07/2023)

[3] https://www.w3.org/TR/vocab-ssn/ - (accessed 12/07/2023)

querying, visualization, and rule-based validation are enabled by a dedicated web platform developed by the authors (Hagedorn, Pauwels, *et al.*, 2023; Sigalov *et al.*, 2021; Hagedorn, Liu, *et al.*, 2023; Hagedorn, Senthilvel, *et al.*, 2023).

The system development involved three main steps, namely: use cases' identification, requirements definition and architecture conceptualization. Then, the criteria for the selection of the hardware and software solutions for the system prototype implementation are described, including the development of a custom web application for the collection of workers' feedback. Eventually, the capabilities of the prototype are evaluated for a case study office room. A workplace performance assessment use case is tested through the querying and visualization of the collected workers' feedback and contextual observed environmental conditions.

4. SYSTEM DEVELOPMENT

4.1. System use cases

According to the research framework's overarching goal and to the scope and purposes that drove the workplace domain knowledge formalization within the WOMO ontology (Bruttini *et al.*, 2022), the system shall inform and support managers' decisions for the improvement of employees' well-being and productivity, providing insights from the correlation between workers' subjective feedback and workplaces' objective conditions. For this purpose, three general use cases have been identified, namely:

- *Workplace performance assessment* – Evaluation of how a workplace supports or hinders its occupants through the correlation of workers' subjective feedback with the objective indoor environmental conditions.
- *Workplace issue discovery* – Evaluation of the factors that contribute to the occurrence of unsatisfactory conditions and identification of latent issues that affect workers' needs (e.g., privacy, focus, lighting, etc.).
- *Worker preference clustering & Spatial recommendation*: Recognition and evaluation of recurrent data patterns and correlations, and implementation of artificial intelligence-enabled methods for learning and predicting ideal conditions for worker groups or profiles (e.g., based on environmental preferences, activity needs, etc.), and for the recommending solutions for underperforming spaces or occurred issues.

The presented system prototype implementation focuses on the *workplace performance assessment* use case, leaving the remaining to future developments.

4.2. System requirements

The system requirements, on which the following system architecture conceptualization and prototype implementation is based, are listed below per functional area:

- *Building-generated data collection* – To monitor workplace's indoor environments, the sensors' typology and communication protocol shall favour easy, flexible, and affordable deployment while providing reasonable accuracy.
- *Occupant-generated data collection* – The collection of worker objective and subjective data shall be using voluntary feedback responses to timely micro-surveys developed according to the EMA methodology. Feedback time and location are mandatory, while customizable feedback request's generation (e.g., scheduled, voluntary), survey's prompts and rating scales shall be granted. Collection of workers' momentary health indicators (e.g., heart rate), environmental preferences (e.g., thermal quality), and self-assessed conditions (e.g., productivity) shall be enabled along with their current activity.
- *Time series data handling and storage*: Both the transmitted building- and occupant-generated data shall be stored and organized in a store specialized for time series data. The database structure shall not be constrained in terms of data sources (i.e., sensors, feedback interfaces) and structure (i.e., building observed properties, worker data and survey fields), and shall allow data storage efficiency (i.e., down sampling), querying and aggregation.
- *Data semantic integration, querying and visualization*: Heterogeneous static and dynamic workplace data shall be integrable to realize an evolving workplace knowledge base where information is semantically structured and interlinked according to acknowledged ontologies, and reasoning, querying, and visualization are enabled. This shall include, but not be limited to, the geometries and properties of building spaces and elements (i.e., IFC model), sensors' observations and workers' feedback.

4.3. System architecture

On these assumptions, a comprehensive four-layered system architecture has been drawn as shown in Fig. *2*. At the bottom, the *physical layer* represents the physical workplace from which the data describing the building operational and environmental properties (e.g., air temperature, window opening, etc.) are collected by the deployed sensors, and workers' objective and subjective data (e.g., location, environmental preference, activity, etc.) are provided via momentary feedback. This layer transfers the data to the upper *data storage layer* where two functionally distinct stores are identified: one dedicated to dynamic data (i.e., timeseries sensors' observations and workers' feedback); the other, dedicated to consolidated data (e.g., aggregated sensor observations) and less frequently changing or static building information. The latter forms the system's core knowledge base, where workplace heterogeneous information (e.g., BIM model, organizational data, timeseries, etc.) are stored according to appointed ontologies and hence semantically interlinked.

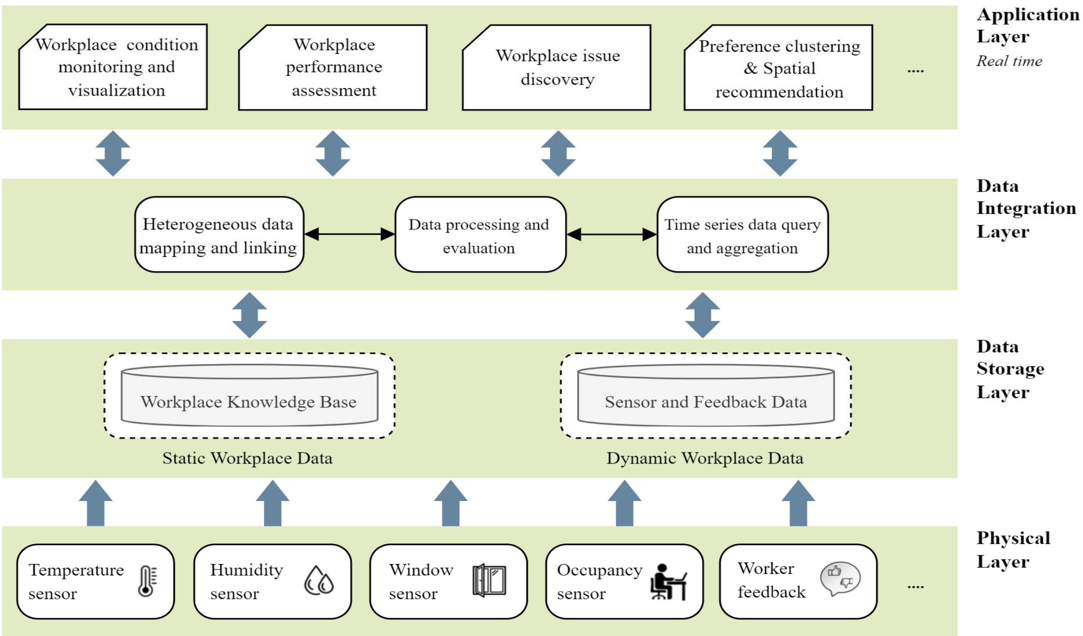

Fig. 2 Workplace digital twin system architecture

In turn, the *data integration layer* provides access to the workplace static and dynamic data, allows for their semantic integration and processing, and mediates the incoming requests from the top *application layer*. This last layer provides the user, i.e., manager, with the digital twin-based services that shall serve the identified use cases, such as: workplace condition monitoring and visualization; building-activity-worker data correlation for workplace performance assessment, issue discovery and spatial recommendation.

4.4. System prototype implementation

This paragraph describes the hardware and software choices taken for the system prototype implementation. As shown in Fig. *3*, the physical workplace can be represented as the combination of several workspaces (i.e., building's spaces) that shares spatial, organizational, or functional properties at different scales and are occupied by the workers during their daily working routines (e.g., a part of an open space, a single room, a workstation, etc). For this implementation, the system's targeted workspaces consist in private or shared office rooms with a gross floor area not exceeding 50 m^2. For workspace properties monitoring, a wireless network based on the Zigbee communication standard has been chosen due to the acknowledged performances in terms of network reliability, ease of deployment and affordability of compatible commercial devices in smart building applications. Three types of sensors have been selected to monitor objective workspace properties, namely: temperature and humidity sensor for the thermal environment; contact sensor for window status; motion sensor for occupancy detection and count. All types of sensors are battery-powered, can be installed without screws and transmit data wireless, allowing for fast and flexible deployment, substitution, and maintenance. A Raspberry Pi[4]

[4] https://www.raspberrypi.com/products/raspberry-pi-3-model-b/ - (accessed 14/07/2023)

SoC provided with a universal USB Zigbee gateway is appointed as network coordinator and transmits sensor data to the system backend via Ethernet connection. Moreover, the mesh topology of the Zigbee network allows for the addition of power-supplied devices acting as repeaters (e.g., smart plugs), hence providing redundancy and easy range extensibility.

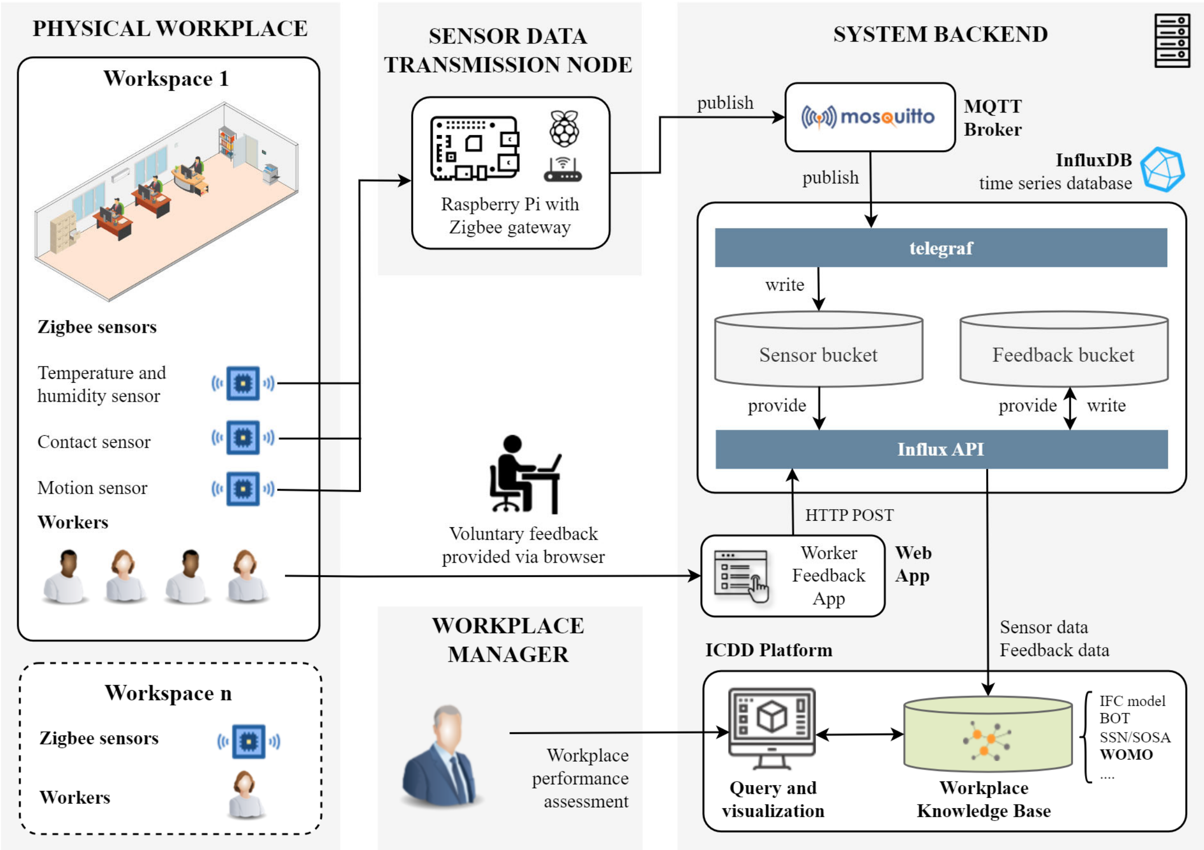

Fig. 3 Workplace digital twin system prototype implementation scheme

The encoding and transmission of the sensors' data has been demanded to the MQTT protocol due to its suitability in IoT applications that requires lightweight, machine to machine, message exchange. The sensors' observations (i.e., actual measurements and metadata) are gathered from the gateway, encoded into individual message packages, and published via MQTT protocol on dedicated topics, one for each sensor, to an Eclipse Mosquitto[5] broker instantiated at the system backend. On the same server, an InfluxDB[6] timeseries database instance connected with an agent (i.e., telegraf [6]) to the MQTT broker and subscribed to all relevant topics receives and stores the sensor-generated data into a dedicated bucket.

For the collection of workers' data, a web application presenting a one-page survey form has been developed. Accessing the form via browser, workers can provide feedback instances on a voluntary base. The survey interface is designed to allow fast responses in order to prevent survey fatigue bias. For this reason, worker ID and current location, corresponding to their allocated workstation, are preset and not editable by the responder. The other survey fields allow for multiple choice response and can be customized to query for the current worker activity and to express their environmental preferences and self-assed conditions. The survey web application uses the HTTP POST method and the Influx API to transmit and write the collected responses to timeseries records within a dedicated feedback bucket in the InfluxDB database.

The last component of the prototype implementation consists in the aforementioned web platform through which the heterogeneous workplace data are stored in a dedicated ICDD container, are semantically interlinked according to predefined ontologies and hence processed, queried, visualized. Here, the workplace IFC model, comprising of the geometrical and functional information necessary for the description of the identified

[5] https://mosquitto.org/ - (accessed 14/07/2023)

[6] https://www.influxdata.com/; https://www.influxdata.com/time-series-platform/telegraf/ - (accessed 14/07/2023)

workspaces, forms the foundation of the workplace digital twin knowledge base. Dedicated platforms' functions retrieve sensors' and workers' data from the timeseries database and stores them as RDF triples accordingly to the SSN ontology. In turn, the building information contained in the IFC model are mapped to BOT ontology classes (i.e., `bot:Space` and `bot:Element`) and linked to sensors' observations and workers' features, preferences, activities and feedback according to the WOMO ontology. Eventually, the resulting knowledge graph can be queried within the platform, and dedicated services provide for the visualization of the results to support workplace performance assessment use cases.

5. CASE STUDY

In this section, the capabilities of the presented prototype are demonstrated with a room-scale case study that involved the collection of worker feedback and sensor data over a period of one week. The collected data are integrated with static workplace information stored in a correspondent ICDD container (e.g., IFC model), then queried and visualized for a performance assessment use case using the dedicated web platform. The appointed room is a shared office in availability of the Chair of Computing in Engineering at the Ruhr University Bochum (Bochum, Germany). The office and case study setup specification are shown in Fig. *4*.

Workspace specification

Workspace type	Shared office
Workstations (Employees)	4 (4)
Lenght x Width x Height	7,35 x 6,00 x 3,75 m
Area	44,10 m^2
Volume	165,38 m^3

Observed properties & Sensors

Air temperature and relative humidity	1x Temperature and humidity sensor (height = 0,70 m)
Occupancy number	4x Presence sensor (1x workstation)
Window status	2x Contact sensor (1x window)

Sensor network characteristics

Network coordinator	Raspberry Pi 3 Model B connected via ethernet to internal network
Zigbee gateway	Phoscon ConBee II Universal USB Zigbee 3.0 gateway

Worker feedback colletion

Workers involved	4 - Allocated to the office
Feedback strategy	Web application (browser) Voluntary (>= 4 times/day)
Test duration	1x Work week (10-14/07/2023)
Worker data	6 - ID, location, activity category and type, thermal preference, self-assessed productivity

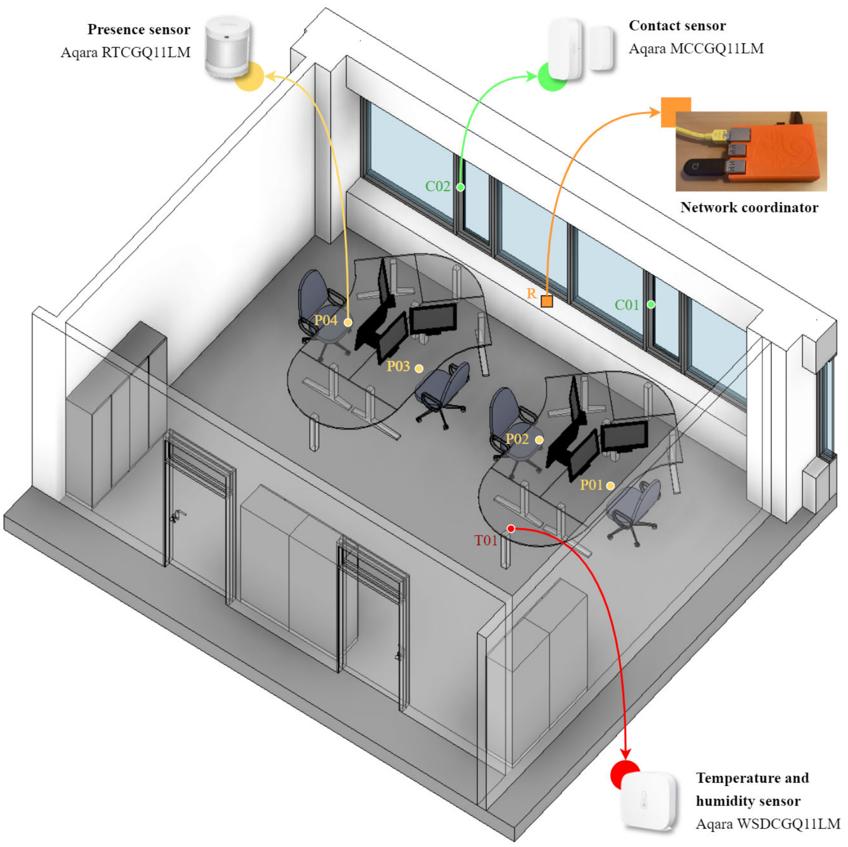

Fig. 4 Case study setup

5.1. Sensor network setup

The deployed sensor network consists of commercial products based on the Zigbee standard and widely adopted in smart building applications. The main characteristics of the installed components are reported below, along with their vendor and model to allow for specification retrieval:

- *Air temperature and humidity sensor (x1)* – It is positioned under the work plane of one of the desks in order to: avoid direct exposure to sunlight or radiators' heat emission; avoid obstruction to other objects; observe occupants' thermal micro-environment (i.e., height 0,70m) during work without being exposed to their body heat emission. [Aqara WSDCGQ11LM]
- *Contact sensor (x2)* – They return the open/closed status of each operable window. [Aqara MCCGQ11LM]

- *Motion sensor (x4)* – They use passive infrared (PIR) detection and are positioned under each of the desks' work planes. The sensor field-of-view is partially obstructed so that the detection of false positives is minimized. Presence at workstations is aggregated to determine room occupancy. [Aqara RTCGQ11LM]
- *Network coordinator* – A Phoscon ConBee II universal USB Zigbee 3.0 gateway connects the sensors and can support other Zigbee compatible devices from different vendors. The gateway is installed on a Raspberry Pi 3 Model B, connected via ethernet to the backend. In turn, on the Raspberry Pi runs an open source Zigbee2MQTT[7] bridge that enables network configuration (i.e., device pairing, removal and setting) with a graphical user interface accessible via browser. The bridge encodes the incoming sensor data into MQTT messages that are published to the Eclipse Mosquitto MQTT broker instance at the backend. The topics' hierarchy focuses on the sensors, and presents three levels: argument, sensor type and ID (e.g., "sensors/contact/c01" for contact sensor "C01"). Therefore, decoupling the sensors' deployment from the network configuration, higher flexibility is provided. Sensor metadata (e.g., observed window) are stored in the workplace knowledge graph.

Eventually, an InfluxDB agent, telegraf, is configured to connect to the MQTT broker, subscribe to all the topics of interest (i.e., "sensors/#"), decode sensor messages' payloads and write the related observations in timeseries within the predisposed sensor bucket.

5.2. Worker feedback web application

The collection of workers' feedback involved the four employees assigned to the case study office for one week (i.e., five workdays, 10-14th July, 2023). A web application has been implemented to collect their momentary feedback as responses to a single-page survey form (Fig. 5). Survey fatigue bias has been minimized presetting the workers' IDs and location and limiting the survey's queries to three. First, the specification of the current activity category and type is requested among five options: solo work, call, group work, break, or other unspecified activity. Then, the expression of the worker preference towards the perceived thermal quality is requested in a three-points scale: prefer cooler, no change, or prefer warmer. Eventually, the self-assessed productivity shall be indicated among not productive, normal or very productive. Rating scales' mid-points represent satisfaction with the environment and baseline productivity. To submit the feedback, at least one query must be responded. The survey response data are posted to Influx DB and stored as timeseries in the dedicated feedback bucket. The subjects involved have been informed about the research purposes, have agreed to voluntarily provide the feedback data and allow for their anonymized use and dissemination.

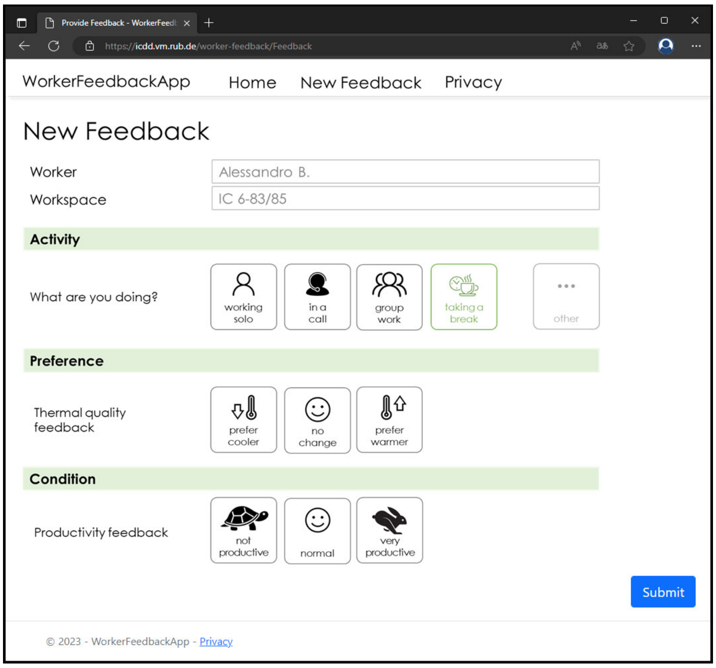

Fig. 5 Worker feedback web application – Survey form

[7] https://www.zigbee2mqtt.io/ - (accessed 17/07/2023)

5.3. Workplace performance assessment

The case study evaluation of the workplace digital twin prototype has been carried out in terms of its capabilities of integration, querying, and visualization of heterogeneous data (i.e., sensors, workers, building) for workplace performance assessment. For this purpose, a use case related to the assessment of the perceived thermal quality has been specified in form of the following competency questions (CQs):

CQ1: *How has a workspace performed for thermal quality in a certain period?*

CQ2: *Which workspace's environmental conditions are related to the reported thermal preferences?*

To address the above CQs, a customized "workplace performance dashboard" service has been implemented within the discussed ICDD web platform (Fig. *6*). On the left-hand panel an authorized user can retrieve and access all the resources and contents organized in separate ICDDs containers, one for each identified workspace (i.e., case study office "IC6-83+85"). In the *Ontology Resource* folder, the data structures necessary for the semantic formalization of the containers contents, link and domain knowledge are stored. The *Payload documents* folder contains the workspace IFC model and the proxy documents corresponding to each installed sensor. In turn, these can be accessed to retrieve the related observations from the timeseries database. Besides, the reified worker, feedback, sensor data and internal links are stored in the *Payload triples* folder.

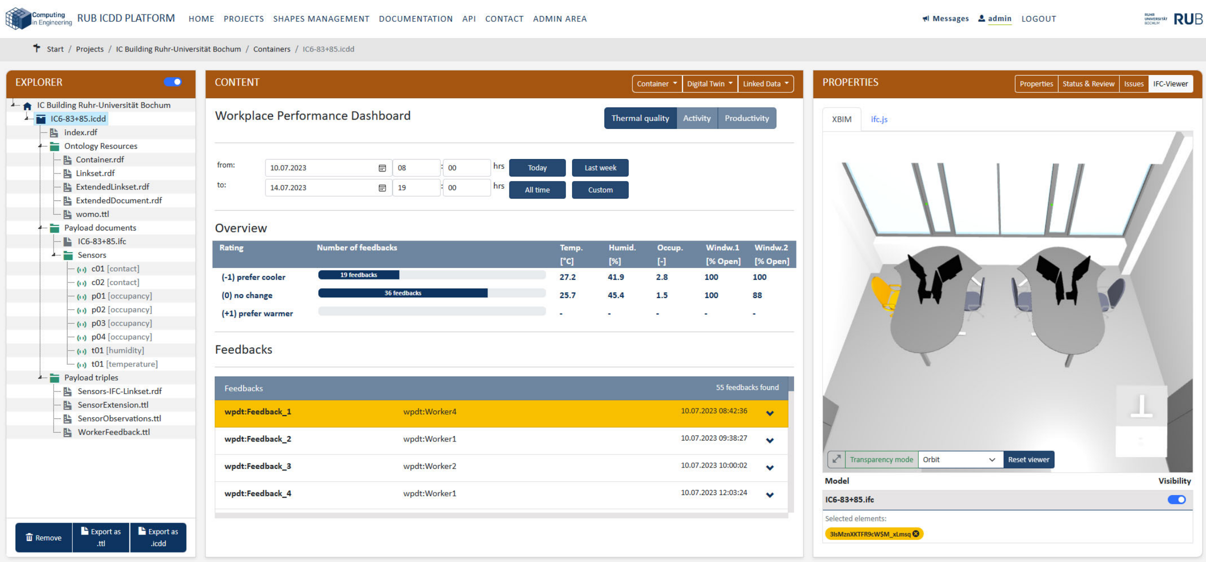

Fig. 6: Workplace performance dashboard (ICDD web platform)

In the central panel the user is provided with a graphical interface for querying and visualizing the data. The proposed approach for workplace performance assessment is centred on the evaluation of the conditions perceived by the employees and expressed with their feedback responses, hence the user has two filtering options to reduce the scope of the query: first, the object of the assessment must be chosen among preferred workspace environmental properties, activities performed by the workers or their experienced conditions; then, the target time interval must be specified. For the presented use case, feedback data are filtered for *thermal quality* preferences expressed within the data collection period of 10-14th July, 2023. In the *Overview* section the distribution of the responses is then returned according to the adopted rating scale and in relation to the mean values of the sensor observations at the corresponding feedback times. Therefore, the manager can not only assess the workplace performance in terms of overall thermal quality (CQ1) but also understand which conditions contributed the occupants' thermal comfort and take better informed actions to mitigate the occurrence of unsatisfying conditions (CQ2). In this regard, the bidirectional link established between the sensor and feedback data with the corresponding element of the workspace IFC model showed in the right-hand viewer contributes to enhance the visualization of the queried data. In fact, selecting one retrieved feedback instance the workspace element related to its source location is highlighted; conversely the selection of another linked element in the model can be used for further filtering the query results (i.e., per workstation).

6. CONCLUSIONS

The improvement of workers' well-being and productivity in existing indoor workplaces can be achieved with the adoption of occupant-centric approaches based on the understanding of the complex building/worker interactions. For this purpose, this paper presents the concept of a semantic digital twin that enables the linking and contextual interpretation of building, sensor, and worker data to support workplace management use cases. The system requirements are identified along with a comprehensive four-layered architecture, and the system's prototypical implementation is discussed. The adoption of commercial Zigbee devices and the MQTT standard protocol for data communication are proved effective for the deployment of an affordable, flexible, and scalable sensor network. An InfluxDB database is implemented to efficiently store and easily access both sensor and feedback timeseries data, the latter collected with a custom developed web survey application. The core digital twin services related to the semantic integration, querying and visualization of the heterogeneous workplace data are realized with the adoption of standardized ICDD containers and Semantic Web technologies, enabled through a custom developed web platform. Eventually, the system prototype's capabilities for the assessment of workplace performance are demonstrated with the correlation of workers' thermal preferences and workspace condition observed for the case study.

At this development stage, the proposed concept still presents several limitations that shall be addressed with further research. The extension of the digital twin prototype in terms of number of monitored workspaces, building and worker features considered, employees involved, and feedback collection period is currently undergoing to test it against a building-scale application scenario. Furthermore, additional platform's services are under development to investigate semantic reasoning opportunities that the system can provide for workplace issue discovery and spatial recommendations.

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