A Semantic Digital Twin for Occupant-Centric Workplace Management

By

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To mum and dad
for always being there
no matter what

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and acknowledgements.

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Abstract

Providing high-quality indoor workplaces that meet occupants' needs and support their activities is essential for employee health, well-being, and productivity. Established Facility Management (FM) approaches—focused on monitoring environmental parameters and viewing occupants as passive recipient of averaged ideal conditions—have shown limited success in fully meeting these expectations. Additionally, conventional Post-Occupancy Evaluation (POE) surveys, which often lack the contextual data necessary for a nuanced understanding of occupant experiences, constrain the assessment of workplace performance and thereby limit opportunities for improvement. To overcome these limitations, occupant-centric approaches has recently gained momentum, emphasizing dynamic monitoring of occupant-environment interactions to generate insights that inform workplace management decisions and optimise both physical and organisational factors.

However, despite promising progress, conceptual and technical solutions for occupant-centric workplace management remain in their infancy. This thesis contributes to address this gap by developing a framework for a Workplace Semantic Digital Twin (WSDT) and testing and evaluating a prototype implementation in a case study. The framework comprises the collection and integration of static building information, dynamic sensor observations, and subjective occupant feedback obtained through micro-surveys using an Ecological Momentary Assessment (EMA) approach, along with their processing to extract meaningful insights that support workplace management decisions.

Following an extensive literature review on factors characterizing indoor workplace ecosystems and current Digital Twin (DT) solutions for Facility Management (FM), the use cases, as well as functional and technical requirements of the proposed WSDT system, were identified, guiding the definition of its conceptual and technical architecture. The system integrates BIM, IoT, and Semantic Web technologies using a Linked Data approach, and is designed to store, interlink, and process heterogeneous workplace data within information containers compliant with the Information Container for linked Document Delivery standard according to predefined ontologies. To build and structure the workplace semantic knowledge base, the Occupant-centric Workplace Management Ontology (WOMO) was developed, characterizing worker-activity-workspace concepts and their interrelationships. A dedicated web platform, previously developed at the Ruhr University Bochum (RUB), was adopted to support the creation and management of the ICDD containers and customized to provide the system's data querying and visualization functions within user-friendly dashboards. Time series data from sensors and occupant feedback are stored in a time series database, allowing platform services to retrieve data on demand and separating bulk data storage from the consolidated workplace knowledge base, which enhances efficiency.

The system was implemented and tested in two stages. The first prototype was realized to monitor a single workspace at RUB, deploying a lightweight sensor network based on commercial smart home devices and using a developed web application to collect voluntary feedback from four employees. This prototype confirmed the capability of the deployed system components and functions to gather and integrate workspace and worker data, supporting a workplace performance assessment use case. Insights gained from this initial room-scale

implementation informed the further development of an extended case study encompassing 14 workspaces within the same department, aiming to assess the system's feasibility in a setting that more closely reflects real-world demands. Upscaling the system involved expanding the sensor network with additional sensors and routers to enhance signal coverage and adapting the workplace knowledge base configuration to a multi-containerized setup, enabling efficient data management at both workspace-specific and workplace-wide levels. Moreover, to address further system use cases, additional features were conceptualized for the web feedback application to capture more worker features, and four new platform dashboards were designed, although the technical implementation and evaluation of these enhancements is left for future works.

This thesis contributes to enabling the adoption of occupant-centric approaches in workplace management by proposing a WSDT framework and demonstrating its feasibility through the implementation of BIM, IoT, and Semantic Web technologies to semantically integrate heterogeneous building and occupant data in a containerized solution. This integration allows for the extraction of meaningful insights to enhance workplace quality, thereby improving employee well-being and productivity, and paves the way for applying advanced reasoning and learning capabilities to proactively optimise workplace environments for their occupants.

Zusammenfassung

Die Bereitstellung qualitativ hochwertiger Büroarbeitsplätze, die den Bedürfnissen und Aktivitäten der Nutzer entsprechen, ist entscheidend für die Gesundheit, das Wohlbefinden und die Produktivität der Mitarbeiter. Traditionelle Facility Management (FM)-Ansätze, die sich auf die Überwachung von Umweltparametern konzentrieren und die Nutzer als passive Empfänger betrachten, erreichen diese Ziele jedoch oft nicht. Herkömmlichen Post Occupancy Evaluation (POE) Befragungen mangelt es an kontextbezogenen Daten, die für eine differenzierte Bewertung der Arbeitsplatzperformance notwendig sind. Um diese Einschränkungen zu überwinden, wurden nutzerzentrierte Ansätze entwickelt, die sich auf die dynamische Überwachung von Nutzer-Umwelt-Interaktionen konzentrieren, um Entscheidungen im Arbeitsplatzmanagement zu unterstützen.

Trotz vielversprechender Fortschritte sind Lösungen für ein nutzerzentriertes Arbeitsplatzmanagement noch wenig entwickelt. Diese Dissertation adressiert diese Lücke durch die Entwicklung eines Frameworks für einen Workplace Semantic Digital Twin (WSDT) und die Evaluierung seiner prototypischen Implementierung. Das Framework integriert statische Gebäudedaten, dynamische Sensorbeobachtungen und subjektives Nutzerfeedback, das mittels Mikrobefragungen nach dem Ansatz des Ecological Momentary Assessment (EMA) erhoben wird, um verwertbare Erkenntnisse für das Arbeitsplatzmanagement zu generieren.

Eine umfassende Literaturrecherche diente der Identifikation von Anwendungsfällen und Anforderungen für das WSDT und leitete die Definition seiner konzeptionellen und technischen Architektur. Das System nutzt BIM-, IoT- und Semantic-Web-Technologien und verwendet einen Linked-Data-Ansatz, um heterogene Daten innerhalb von ICDD-konformen Informationscontainern zu verknüpfen und zu verarbeiten. Zur Strukturierung der semantischen Wissensbasis wurde die „Occupant-centric Workplace Management Ontology“ (WOMO) entwickelt, die Beziehungen zwischen Mitarbeitern, Tätigkeiten und Arbeitsräumen charakterisiert. Eine angepasste Webplattform unterstützt die Datenabfrage und -visualisierung durch benutzerfreundliche Dashboards, während eine Zeitreihendatenbank Sensordaten und Nutzerfeedback effizient verwaltet.

Das System wurde in zwei Phasen implementiert und getestet. Der erste Prototyp, der an der Ruhr-Universität Bochum (RUB) zur Überwachung eines einzelnen Arbeitsraumes eingesetzt wurde, nutzte ein leichtgewichtiges Sensornetzwerk auf der Basis kommerzieller Smart-Home-Geräte und eine Webanwendung, um freiwilliges Feedback von vier Mitarbeitern zu sammeln. Diese Phase bestätigte die Fähigkeit des Systems, Arbeitsplatz- und Benutzerdaten zu integrieren, um die Leistungsbewertung von Arbeitsplätzen zu unterstützen. Die Erkenntnisse aus dieser räumlichen Implementierung flossen in die Entwicklung einer erweiterten Fallstudie mit 14 Arbeitsplätzen in derselben Abteilung ein, um die Durchführbarkeit des Systems unter realistischeren Bedingungen zu bewerten. Die Skalierung umfasste die Erweiterung des Sensornetzwerks mit zusätzlichen Geräten zur Verbesserung der Signalabdeckung sowie die Neukonfiguration der Wissensbasis in einer Multi-Container-Struktur, um die Datenverwaltung auf Raum- und Abteilungsebene effizient zu gestalten. Um breitere Anwendungsfälle abzudecken, wurden zusätzliche Funktionen für die Feedback-Applikation sowie neue

Dashboards konzipiert, deren technische Umsetzung jedoch zukünftigen Arbeiten vorbehalten bleibt.

Diese Dissertation leistet einen Beitrag zur Weiterentwicklung nutzerzentrierter Ansätze im Arbeitsplatzmanagement, indem sie die Machbarkeit der Integration von BIM-, IoT- und Semantic-Web-Technologien innerhalb eines containerisierten WSDT-Frameworks demonstriert. Durch die Gewinnung von Erkenntnissen zur Verbesserung der Arbeitsplatzqualität legt es den Grundstein für den Einsatz fortschrittlicher Analyse- und Lernfähigkeiten, um Arbeitsumgebungen proaktiv für ihre Nutzer zu optimieren.

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Finally, my deepest gratitude goes to my mum and dad, and to my family. Even if we're not the sentimental type, and I may not say it often, family isn't just important—it's the only thing that counts. Thank you also to those who chose not to be there when I needed them. You helped me prune and clarify my relationships—something that, in the end, is key to a good life.

Alessandro Bruttini
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Acronyms and Abbreviations

AECO	Architecture, Engineering, Construction and Operation
BIM	Building Information Model, Building Information Modeling
BOT	Building Topology Ontology
CQ	Competency Question
DT	Digital Twin
EMA	Ecological Momentary Assessment
FM	Facility Management
IAQ	Indoor Air Quality
ICDD	Information Container for linked Document Delivery
ICT	Information and Communication Technology
IEQ	Indoor Environmental Quality
IFC	Industry Foundation Classes
LD	Linked Data
LBD	Linked Building Data
O&M	Operation and Maintenance
OWL	Web Ontology Language
POE	Post occupancy evaluation
RDF	Resource Description Framework
SPARQL	SPARQL Quey Language for RDF
SW	Semantic Web
SOSA	Sensor, Observation, Sample, and Actuator ontology
SSN	Semantic Sensor Network ontology
Turtle	Terse RDF Triple Language
URI	Uniform Resource Identifier
WM	Workplace Management
WOMO	Occupant-centric Workplace Management Ontology
WSDT	Workplace Semantic Digital Twin

Glossary

A

Acoustic comfort (indoor)
Reaction of occupants to the indoor acoustical environment, described in terms of sound pressure level and audibility. (ISO 16813:2006)

Occupant satisfaction with the indoor acoustic environment, described in terms of sound pressure level, reverberation and noise level. (ISO 6707-3:2022)

Activity
Task or tasks that contribute to the completion of deliverables. (ISO 41011:2024)

B

Building Information Model (BIM)
A shared digital representation of physical and functional characteristics of a built environment asset. (NBIMS-US V4, 2024)

Building Information Modeling (BIM)
Use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions. (ISO 19650-1:2018)

C

Condition (Occupant condition)
Observed or potentially observable aspects of the subjective state of an occupant, expressed through self-assessment.

D

Deliverable
Measurable and verifiable outcome, result or item to be produced within a specific timeframe to complete a project or part of a project. (ISO 41011:2024)

E

Ecological Momentary Assessment
Range of subject assessment methods that shares the following key features: data are collected in real-world environments, as subjects go about their lives (ecological aspect); assessments focus on subjects' current state (momentary aspect); moments are strategically selected for assessment, whether based on particular features, or by random or other sampling schemes; subjects complete multiple assessments over time. (Shiffman et al., 2008)

Environment (work environment)
Physical, chemical, biological, organisational, social and cultural factors surrounding a worker. (ISO 6385:2016)

Equipment (work equipment)
Tools, including hardware and software, machines, vehicles, devices, furniture, installations and other components used in the work system. (ISO 6385:2016)

F

Feedback
Information describing occupant objective and subjective conditions, provided through survey responses or collected through sensing devices.

Information provided to people, groups or organisations regarding performance or activities. (ISO 30400:2022)

Information given back by end-users. (ISO/TS 16710-1:2024)

Facility Management (FM)
Organisational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business. (ISO 41011:2024)

I

Indoor Air Quality (IAQ)
Quality of air inside non-industrial buildings, described in terms of odour, chemical and biological pollutants, is related to the ventilation rate, air distribution patterns and pollution sources to ensure human health, olfactory comfort and perceived comfort. (ISO 16813:2006)

Indoor Environmental Quality (IEQ)
Quality of a building's internal environment in relation to the health, comfort and well-being of those who use space within it. (ISO 41011:2024)

K

Knowledge worker
"Knowledge workers have high degrees of expertise, education, or experience, and the primary purpose of their jobs involves the creation, distribution, or application of knowledge. Knowledge workers think for a living. They live by their wits—any heavy lifting on the job is intellectual, not physical." (Davenport, 2005)

O

Occupant
Person occupying a building space and actively interacting with and responding to the indoor environment.

Occupant-centric building design and operation
Occupant-centric building design and operation means to place occupant needs (comfort and health) as a priority and to use explicit occupant modeling to design for and recognize, the bi-directional interaction between occupants and buildings. (O'Brien et al., 2020)

Ontology
A formal explicit description of concepts used to capture knowledge about a domain of interest along with their features, attributes, restrictions, and relationships.

Operational phase
Part of the life cycle during which an asset is used, operated and maintained. (ISO 19650-1:2018)

P

Post occupancy evaluation (POE)
Process of analysing how functional and comfortable a building is after users have been occupying it for some time. (ISO 41011:2024)

Preference
A subjective feature of a worker, provided through feedback, that relates to a specific property of their surrounding workspace or a workspace element, given at a particular time and location within the workplace.

Productivity
Ability to generate, create, enhance or deliver products, services and knowledge. (ISO 10014:2021)

Ratio of work product to work effort. (ISO/IEC/IEEE 24765:2017)

S

Space
A part of the physical world or a virtual world whose 3D spatial extent is bounded actually or theoretically, and provides for certain functions within the zone it is contained in. (From the definition of "Space" provided in the BOT ontology, Rasmussen et al., 2021)

Semantic Web
Version of the internet following Web 2.0 which rather than simply connecting internet addresses and data in their formal form additionally does effect data linking through and in favour of their semantic content or meaning thus providing enriched and enlarged information answering requests. (ISO 5127:2017)

Semantic Web technologies enable people to create data stores on the Web, build vocabularies, and write rules for handling data. Linked data are empowered by technologies such as RDF, SPARQL, JSON-LD, OWL, SHACL and SKOS. (W3C - Semantic Web Standards)

T

Thermal comfort
Condition of mind derived from satisfaction with the thermal environment. (ISO 16813:2006)

V

Visual comfort
Occupant satisfaction with the indoor visual environment, described in terms of illumination level, glare, visibility, reflection and psychological and physiological content with natural and artificial illumination. (ISO 16813:2006)

W

Well-being
Sustainable internal state resulting from satisfaction of the physical and cognitive needs of the worker during his/her activity. (ISO 6385:2016)

Fulfilment of the physical, mental, social and cognitive needs and expectations of a worker related to their work. (ISO 41011:2024)

Worker
Person performing one or more activities to achieve a goal within a work system. (ISO 6385:2016)

Person performing work or work-related activities that are under the control of the organisation. (ISO 45001:2018)

Workplace
Building location where work is performed by the occupants.

Physical location where work is performed. (ISO 41011:2024)

Place under the control of the organisation where a person needs to be or to go for work purposes. (ISO 45001:2018)

Workspace
Building topological unit in which the workplace can be physically or conceptually structured. Relates to the concept of space from the Building Topology Ontology: a part of the physical world or a virtual world whose 3D spatial extent is bounded actually or theoretically, and provides for certain functions within the zone it is contained in.

Zone for completing a work task. (ISO 41011:2024)

Volume allocated to one or more persons in the work system to complete the work task. (ISO 6385:2016)

Workstation
Location containing furniture and supporting equipment (including telephony, information technology and power connections), specifically designed or suitable for work-related activities. (ISO 41011:2024)

Combination and spatial arrangement of work equipment, surrounded by the work environment under the conditions imposed by the work tasks. (ISO 6385:2016)

1

Introduction

This thesis aims to improve workers' well-being and productivity in indoor workplaces by leveraging the integration of building- and user-generated data to inform and enhance management processes. In this chapter, the *motivation* and *background* are provided. Then, the identified *research questions* are introduced along with the related *contributions* of this dissertation. The thesis *scope* and *assumptions* follow. Eventually, the thesis *outline* is provided to assist the reader in navigating through the content.

One size does not fit all.

- Frank Zappa

1.1. Motivation and Background

Nowadays, providing indoor workplaces that satisfy occupants' expectations and support their activities stands as a fundamental priority for organisations and policy makers. There are three reasons for this. First, the quality and sustainability of indoor environments have a crucial impact on human life, health, and well-being. In developed countries, people spend up to 90% of their lives inside buildings (ASHRAE, 2016). Moreover, with two-thirds of the world population expected to live in urban areas by 2050 (UN Habitat, 2019) and the global economy shifting from manufacturing towards knowledge-based services (World Green Building Council, 2014), the physical and functional characteristics of the spaces we work in will become increasingly important. Second, workers' satisfaction with the workplace is strongly related to productivity. Therefore, this has a tangible effect on organisations' bottom line (Al Horr, Arif, Kaushik, et al., 2016) where employees' annual salaries typically account for about 90% of costs and can exceed building operation and rental costs by a factor up to 25 (Croome, 1999; Fisk, 2000). And third, the majority of the building stock for tertiary sector that will exist in 2050 has already been built (United Nations Environment Programme, 2009), hence both industry experts and academic researchers are called to multiply and join their efforts to improve the operation of existing workplaces.

In this regard, despite in the past two decades numerous advancements have been brought to Facility Management (FM) practice by the growing adoption of Information and Communication Technology (ICT), sensors, and system automation, evidence suggests that tertiary buildings still mostly fail to meet the needs of their occupants. Among the root causes stands the idea that building occupants are average "passive" recipients for which "ideal" indoor conditions can be provided considering just physical environmental parameters. On the contrary, this research recognises the user as the most critical system component and pursues a long-awaited paradigm shift from the building to the occupant (International Energy Agency, 2018; O'Brien et al., 2020) to enable workplaces that favour workers' well-being and productivity.

However, to be effective, such an "occupant-centric" approach requires a more granular understanding of the dynamic mutual interactions between the building and its occupants, which goes beyond relying solely on sensors measuring Indoor Environmental Quality (IEQ) properties. In fact, rather than attempting the impractical deployment of sensors at an extremely high resolution to capture every microclimate variation—and still failing to account for the dynamic and highly individual spatial perceptions and preferences of building users—a more effective approach is to integrate subjective occupant feedback (M. M. Abdelrahman et al., 2022).

For this purpose, the real-time convergence of dynamic data—both building- and occupant-generated—into building digital representations must be enabled, creating a data environment where human behaviour can be quantified and analysed to inform the operation of better physical spaces. This shift requires moving beyond the established Building Information Modeling (BIM) paradigm toward the current and future generations of Digital Twin (DT) information systems for the built environment (Sacks et al., 2020).

Conceived to support asset management and operational decision-making, DTs in the built environment initially emerged through the integration of static BIM models with dynamic data processing and visualization features (Borrmann et al., 2018). Nowadays, despite the growing number of implementations, most DT applications remain focused on basic monitoring, leaving unaddressed the most challenging use cases where reasoning and simulation are required to enable proactive operational approaches.

Although no unified framework or definition has yet been established (M. Abdelrahman et al., 2024), recent research suggests that the evolution of the DT paradigm demands a deeper integration of ontologies and Semantic Web technologies (Boje et al., 2022). These technologies are needed to structure and contextualize the increasing volume of available building data, facilitating the extraction of usable knowledge and enabling AI-driven capabilities such as predictive analytics, automated decision-making, and enhanced user interaction. Nonetheless, the potential of occupant-centric DTs remains constrained by interoperability challenges and the lack of standardized approaches for integrating real-time sensor data, semantic data, and subjective human feedback.

This thesis introduces a framework and investigates the realization of a Digital Twin for occupant-centric workplace management. A formal representation of the workplace knowledge domain is proposed to enable the semantic integration of building- and worker-generated data. A DT system is developed and implemented in a prototypical single-room application and extended for a department scale case study. From the discussion of the results of the system's implementation, it concludes that not only the proposed Workplace Digital Twin framework is feasible but that with further steps in this direction better, more sustainable, occupant-centred workplaces are within reach.

1.2. Research Questions and Contributions

Occupant satisfaction with an indoor environment is the result of the dynamic interaction of a sheer number of factors, both objective (e.g., air temperature, relative humidity) and subjective (e.g., gender, age). While building science literature recognizes the importance of subjective physiological and psychological peculiarities in the perception of space quality, the state-of-the-art in building operation is currently limited to reacting to the fluctuations of a few monitored IEQ properties. Window shading that adjusts automatically to prevent excessive exposure to direct illumination and overheating. Mechanical ventilation that increases the air changes to balance rising concentrations of CO_2 and other pollutants in the indoor space. Numerous further examples of such automations exist and commonly win "smart" labels to buildings. However, they work only to maintain a set of environmental properties within predetermined ranges, while ignoring the occupants who are present and directly affected.

Despite extensive research on occupant-building interactions is providing encouraging results, a more granular understanding of occupants' behaviours and satisfaction requires sophisticated multi-disciplinary considerations centred on subjective factors. In turn, this explains the tendency of organisations and policy makers to avoid such complexity. In fact, the pragmatic need to provide environments that match their occupants' needs and expectations must be currently met with their scarce, when not completely absent, knowledge.

This research aims to bridge this gap by *exploring the collection, integration, and processing of objective and subjective, building- and worker-generated data and by proposing a Digital Twin system that can enable occupant-centric workplace management to improve workers' well-being and productivity*. This overall goal can be broken down into addressing the following five Research Questions (RQs):

RQ1: *What are the key factors that characterize an indoor workplace environment?*

RQ2: *What are the key factors that affect worker well-being and productivity in an indoor workplace environment?*

RQ3: *What methods or tools can be used to collect data on worker and workplace environmental factors?*

RQ4: *How can worker data and building environmental data be integrated to provide actionable workplace knowledge?*

RQ5: *How can integrated worker-building knowledge be applied to enhance workplace management and decision-making?*

The thesis addresses these research questions by developing, implementing, and evaluating a novel framework for the realization of a Digital Twin for occupant-centric workplace management (Chapter 3). The framework is informed by the review of the literature (RQ1-5, Chapter 2) which investigated the complex domains of well-being and productivity within indoor environments and the state-of-the-art for the collection, integration, and processing of data from the building and its occupants.

At the core of the framework, the need for a formal representation of the knowledge describing objective workplace conditions while pivoting on subjective occupant perceptions (RQ4) is addressed with the development of the Occupant-centric Workplace Management Ontology (WOMO) [1], discussed in detail in Chapter 4.

Eventually, the answer to RQ5 is provided in Chapter 5 with the development of the Workplace Semantic Digital Twin (WSDT) system, which fulfils the goals of the research framework. This is followed by a prototypical implementation presented in Chapter 6. Subsequently, the evaluation of the prototype informs the system's extension at a department-scale case study discussed in Chapter 7.

In responding to these questions, the present work suggests that where workers' subjective (e.g., perceptions) and objective (e.g., indoor location, physiological parameters) data can be collected and processed in spatial-temporal relation to the workplace conditions, the dynamic interplay between individual experiences and the physical environment can be harnessed and exploited. Organisations can unlock valuable insights into employees' well-being, productivity, and overall satisfaction and enable targeted interventions, fostering a more adaptive and supportive work environment that aligns with the diverse needs of the workforce. Individual preferences can be learnt and clustered to identify issues and provide recommendations on potential optimisations at different scales, from real-time suggestion customized for the worker

[1] http://w3id.org/womo# - Accessed 05/05/2025 - WOMO documentation is also reported in Appendix A.

to strategic workspaces re-organisation. However, this dissertation also acknowledges that to support this paradigm shift from a building- to an occupant-centric approach in the operation and management of workplaces, new conceptual frameworks and tools need to be developed, and methods that historically have not been part of building science's research and practice shall be adapted and adopted. This research aims to achieve this ambitious objective through its theoretical and practical contributions.

1.3. Scope and Assumptions

This dissertation is the result of a research trajectory that started with a simple and broad motivation: improving workers' well-being and productivity at workplace. From there, practical and disciplinary reasons had then determined the final narrower scope and assumptions within which the presented outcomes should be interpreted.

Let alone the unsettled and complex definition of "well-being" and "productivity", when dealing with the core concepts of *work*, *worker*, and *workplace*, countless possible scenarios and variables unfold. The first—and perhaps most noticeable—limitation of the study is therefore related to its scope. Due to the motivations mentioned above, the considered workplaces were limited to indoor environments, and the work activities to knowledge-based occupations, where the intellectual component is prevalent, and the physical demand is negligible. This narrows the scope significantly, excluding sectors (e.g., agriculture, manufacturing, etc.) that are crucial for the global economy, and a large share of the active population. Nonetheless, we are confident that part of theoretical and practical outcomes of this work could be transported and exploited also outside its scope.

Once identified the extents of the subject matter, it's important to define which disciplines and hence approaches, cultural backgrounds, and methodologies are involved. All the considerations made in this thesis are for existing buildings, hence their potential application to improve the design of new workplaces is only addressed in the conclusions (Chapter 8). The operational phase of a built asset is a complex activity that requires the alignment of different processes and expertise, from building science to economics and more. In this regard, Facility Management (FM) has been long established as the jack-of-all-trades (Tay & Ooi, 2001) discipline, although, even on its definition, consensus has been reached only recently with the publication of the standard ISO 41011 in 2017[2]. As discussed in the followings, the current standard definition of Facility Management is used to draw the scope of the developed research framework, and Workplace Management (WM) is used to refer to those specific sub-set of activities that directly affects the physical and functional organisation of workspaces and that impact on the experience of the employees. Furthermore, it must be stressed that a thorough investigation of all the concepts belonging to the spheres of human and behavioural sciences that will be touched in relation to occupants' well-being and productivity, will remain outside the scope of this dissertation.

The research framework (Chapter 3) developed in this thesis is based on the scope described above and relies on the results of the review of the literature carried out on three main areas:

[2] The standard ISO 41011 "Facility Management – Vocabulary", first published in 2017, is currently withdrawn and substituted by its updated second edition (ISO 41011:2024).

Facility Management and workplaces (§2.1), occupant-centric building operation (§2.2), and Digital Twin systems for the operation of the built environment (§2.3). Leaving the details to Chapter 2, it is worth mentioning here three key principles that emerged in the conceptualization of a building space, hence also of a workplace, and that formed the core assumptions on which this thesis is based:

- *Space is relational* – It should not be conceptualized in and of itself in absolute terms, as it is the product of relations between social phenomena (Zaki et al., 2018).
- *Space is heterogeneous* – Environmental conditions within a building space have a high spatial variability so that is challenging to capture by generalizing their objective properties from the measurements of one sensor located at one point (M. M. Abdelrahman et al., 2022).
- *Spatial-temporal variability of space usage and perception* – Usage and perception of space varies with time and location, and it's influenced by the proximity to other individuals and elements. Therefore, the quality of a space can only be assessed in relation to each specific user and varies over time depending on objective and subjective factors.

1.4. Thesis Outline

The research workflow adopted in this thesis is outlined in Figure 1.1. First, in Chapter 2, the literature is reviewed with a focus on the three principal areas of this research, namely: the workplace, characterized by its complex physical and social phenomena; occupant-centric approaches for building management and operation, including their acknowledged concepts and applications; and, last but not less important, the paradigm of Digital Twin for buildings and facilities, with the methodological and technological aspects behind their development and deployment. From the realized state-of-the-art and the identified open issues, a conceptual framework for a Workplace Digital Twin system is drawn and the methodology for its development is proposed in Chapter 3.

In the following chapters the system development is presented. Starting from the identification of the relevant knowledge domains for occupant-centric management purposes, Chapter 4 proposes a novel workplace characterization and the related ontological representation. Four conceptual modules are defined—worker, workplace, activity, and feedback—and their concepts and properties are formally described along with examples of the intended semantic patterns. Once addressed the need for a core data schema, the system's requirements, conceptual architecture, and technical implementation are reported in Chapter 5. The implementation of a system prototype, which involved the deployment of sensors and the monitoring of an office shared by four employees within the Chair of Computing in Engineering, at the Ruhr University Bochum (Bochum, Germany), is described in Chapter 6.

The prototype's feasibility and the usability of the insights provided by workplace data integration were evaluated. This evaluation informed the next system iteration, leading to the development and implementation of a department-scale case study discussed in Chapter 7. Chapter 8 concludes the thesis by assessing its contributions and limitations and outlining directions for future research, drawing on the lessons learned.

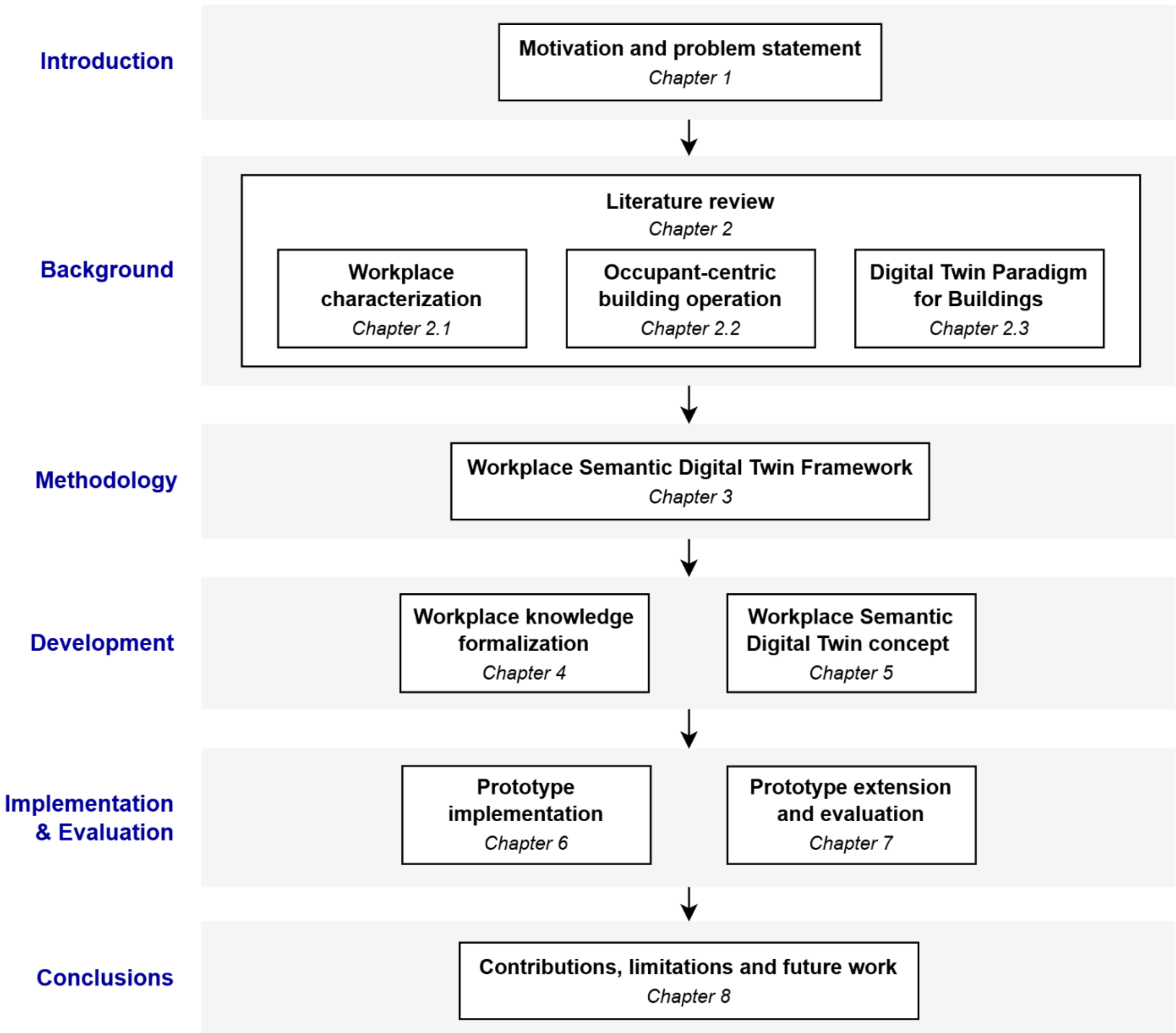

Figure 1.1 Research workflow and thesis outline.

Along the path described above, parts of the ongoing results of the research have been reviewed, presented, and published at international conferences:

- Bruttini et al., (2022): *Linked data approach for occupant-centric workplace management*
- Bruttini et al., (2023): *A semantic digital twin prototype for workplace performance assessment*

The present thesis has benefitted from these occasions of discussion and constructive feedback.

2

Literature Review

This chapter provides a critical synthesis of the literature findings that informed the research framework and the development of the Workplace Digital Twin system. The first section sheds light on the evolution of the FM discipline, the complex factors characterizing the workplace eco-system, and their current monitoring strategies (§2.1). Then, the urgent paradigm shift towards occupant-centric approaches in workplace operation is discussed with reference to the aspects that affect workers' well-being, productivity, and satisfaction (§2.2). The third section investigates methods and solutions for the deployment of Digital Twins and their adoption for the building operational phase (§2.3). Eventually, the emerged research gaps are reported (§2.4).

To make knowledge work productive will be the great management task of this century, just as to make manual work productive was the great management task of the last century.

- Peter Drucker (1969)

2.1. Understanding the workplace

While everyone is familiar with the term "*workplace*", this section devotes entirely to gaining a sufficient understanding of this dynamic and complex *ecosystem*[3] from a multidisciplinary perspective. The exploration of the literature focused first on the evolution of the discipline appointed to the operation of built assets: *Facility Management* (FM). Decades of research and practice solidified only recently in the current standard definition of FM (ISO 41011:2024) which emphasizes the improvement of "the *quality of life of people and the productivity of the core business"* beyond any other aspect specific to building management, maintenance, or operation. As discussed below, this core principle underpins the framework of this research (Chapter 3). Afterwards, the findings of multidisciplinary studies which unravelled the complex interactions that affect the relationships among building-worker-activity are presented to motivate three main assumptions on the workplace ecosystem made in this thesis. Eventually, an overview of the tangible and intangible factors which are relevant for the characterization of an indoor work environment is presented to stress the limitations of building-centred approaches for workplace operation.

2.1.1. Facility management: the evolution of a multidisciplinary field

From a spatial perspective, an indoor workplace corresponds to a building or a part thereof. Improving on its operation also implies the optimal organisation of its employees and their activities. In turn, this requires the integration of different areas of expertise ranging from building and environmental sciences to economics, ergonomics, psychology, and behavioural sciences. Since the 1980s, *Facility Management* spread into the industry to label such a complex and multidisciplinary practice together with the establishment of the first professional FM institutions around the world (e.g. IFMA in the USA, JFMA in Japan, BIFM in the UK, FMA in Australia, etc.). However, the lack of consensus about its definition and scope lasted until 2006 when the first international standard in FM was released (EN 15221-1:2006). This paragraph aims to collocate *workplace management* within the scope and purpose of the FM discipline, providing an overview of its evolution from early definitions to its current trajectory.

Although its formal recognition is relatively recent, FM arguably existed as long as building (Becker, 1990). Elements of FM entered human history since our ancestors first sought shelter in caves and dwellings. Waste management, cleaning, repairing, and all the maintenance works that ensure building occupants' health, comfort, and well-being, have always been indispensable tasks that evolved together with building technology (Appleby, 2018). Up to the present time, looking at the sample of FM definitions provided in Table 2.1, it can be noticed how the scope of the discipline tended to identify with workplaces and their management, with a shift in focus from "hardware" to "software" (Azman Noor et al., 2014). In the early 1990s, FM efforts concentrated on the management of the building and its systems, equipment, and furniture (Becker, 1990), with minor involvement in the corporate strategic planning (Nourse, 1990).

[3] Ecosystem: any complicated system consisting of many different people, processes, activities, etc., especially relating to technology, and the way that they affect each other.
Source: https://dictionary.cambridge.org/dictionary/english/ecosystem - Accessed 05/05/2025.

Table 2.1 Sample of Facility Management definitions from 1990 to 2024 – Source type: R = Research; I = Industry; S = Standard. (Integration and update of "Table I – Sample of FM Definitions" of Tay & Ooi, 2001).

Year	Type	Author/Source – FM Definition
1990	R	(Becker, 1990) - FM is responsible for co-ordinating all efforts related to planning, designing and managing buildings and their systems, equipment and furniture to enhance the organisation's ability to compete successfully in a rapidly changing world.
1990	R	(Nourse, 1990) - FM unit is seldom aware of the overall corporate strategic planning and does not have bottom line emphasis.
1996	I	(NHS Estates, 1996) - The practice of coordinating the physical workplace with the people and work of an organisation; integrates the principles of business administration, architecture, and the behavioural and engineering science.
1999	R	(Then, 1999) - The practice of FM is concerned with delivery of the enabling workplace environment – the optimum functional space that supports the business process and human resources.
1999	R	(Hinks & McNay, 1999) – […] common interpretations of FM remit: maintenance management; space management and accommodation standards; project management for new-builds and alterations; the general premises management of the building stock; and the administration of associated support services.
2000	R	(Varcoe, 2000) – […] a focus on the management and delivery of the business "outputs" of both these entities (the real estate and construction industry); namely the productive use of building assets as workplace.
2000	R	(Nutt, 2000) - The primary function of FM is resource management, at strategic and operational levels of support. Generic types of resource management central to the FM function are the management of financial resources, physical resources, human resources, and the management of resources of information and knowledge.
2001	R	(Tay & Ooi, 2001) - The integrated management of the workplace to enhance the performance of the organisation.
2001	R	(Springer, 2001) - Facilities management (FM) is a multidisciplinary or transdisciplinary profession drawing on theories and principles of engineering, architecture, design, accounting, finance, management, and behavioural science. […] Facilities management, as a new discipline, builds on this foundation to create a new set of theories and practices.
2004	R	(Chotipanich, 2004) - FM is the support function coordinating physical resources and workplace, and support services to user and process of works to support the core business of the organisation. The central issues of FM practice consist of place or facility, people or user of the building, and process or activities in the facility.
2006	S	(EN 15221-1, 2006) - Facilities management is the integration of processes within an organisation to maintain and develop the agreed services which support and improve the effectiveness of its primary activities.
2014	R	(Azman Noor et al., 2014) - […] the focus of facility management has changed to concentrate on the effective management of scarce resources. The underlying premise is space; ultimately it is not about real estate. It is about using all of an organisation's scarce resources to their fullest potential to meet pressing business challenges. Those scarce resources include finances, physical assets (from whole buildings down to pieces of furniture), information and, above all, people and their skills and knowledge.
2017	S	(ISO 41011, 2017) - Organisational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business. [Same definition in the updated (ISO 41011:2024)]
2017	I	(Saap, 2017) - Facilities operation and maintenance encompasses a broad spectrum of services, competencies, processes, and tools required to assure the built environment will perform the functions for which a facility was designed and constructed. (Cotts et al., 2010) Maintenance: the work necessary to maintain the original anticipated useful life of a fixed asset. […] Repair: work to restore damaged or worn-out property to normal operating condition.
2018	R	(Appleby, 2018) - Since humans first sought shelter in caves and dwellings, an element of facilities management entered into their lives. From managing waste, cleaning and repairing the fabric to ensuring catering arrangements are maintained, there has always been a maintenance element to ensuring the health, comfort and well-being of building occupants.
2019	R	(Xu et al., 2019) - (Cognitive FM) The active intelligent management of a facility, which has the ability of perception through cognitive systems, learning in the manner of human cognition with the power of cognitive computing, and active, adaptive, and efficient action via automated actuators, to improve the quality of people's life and productivity of core business.
2020	I	D. Levine, Executive Director, IFMA Foundation in (van Sprang & Drion, 2020) - Facility management is the integration of people and business processes of an organisation with its physical workspace impacting the triple bottom line of economy, equity, and environment.
2024	I	(IFMA, 2024) - Facility or facilities management (FM) is a profession dedicated to supporting people. It ensures the functionality, comfort, safety, sustainability and efficiency of the built environment - the buildings we live and work in and their surrounding infrastructure.

Towards the end of the decade, the focus shifted to the enhancement of the performance of the organisation (Tay & Ooi, 2001) through the coordination of the physical workplace and its resources with the people, activities, and support services (NHS Estates, 1996; Then, 1999). During the 2000s, the industry became increasingly aware of the complexity of the FM practices with several attempts to position the discipline within a comprehensive theoretical framework. As highlighted by Chotipanich (2004) in his literature review, 61 diverse services could be counted for FM and grouped in nine key areas that span from real estate and property management to employee support and services. Shortly after, the urge for standardization culminated in the release of the first international standard from the European Committee for Standardization and, with it, the first recognized definition of FM (EN 15221-1, 2006). Here, the role of the organisation is paramount, and the focus is put on the "integration of processes" to "support and improve the effectiveness of its primary activities". Although fundamental aspects of the discipline had been temporarily left out, this definition has the merit of starting the seven-part standard series EN 15221 on FM (see Figure 2.1) that will sever the discipline from real state and pivot on the management of an organisation's limited resources (e.g., finances, physical assets, information and, above all, people and their skills and knowledge) to meet business challenges (Azman Noor et al., 2014).

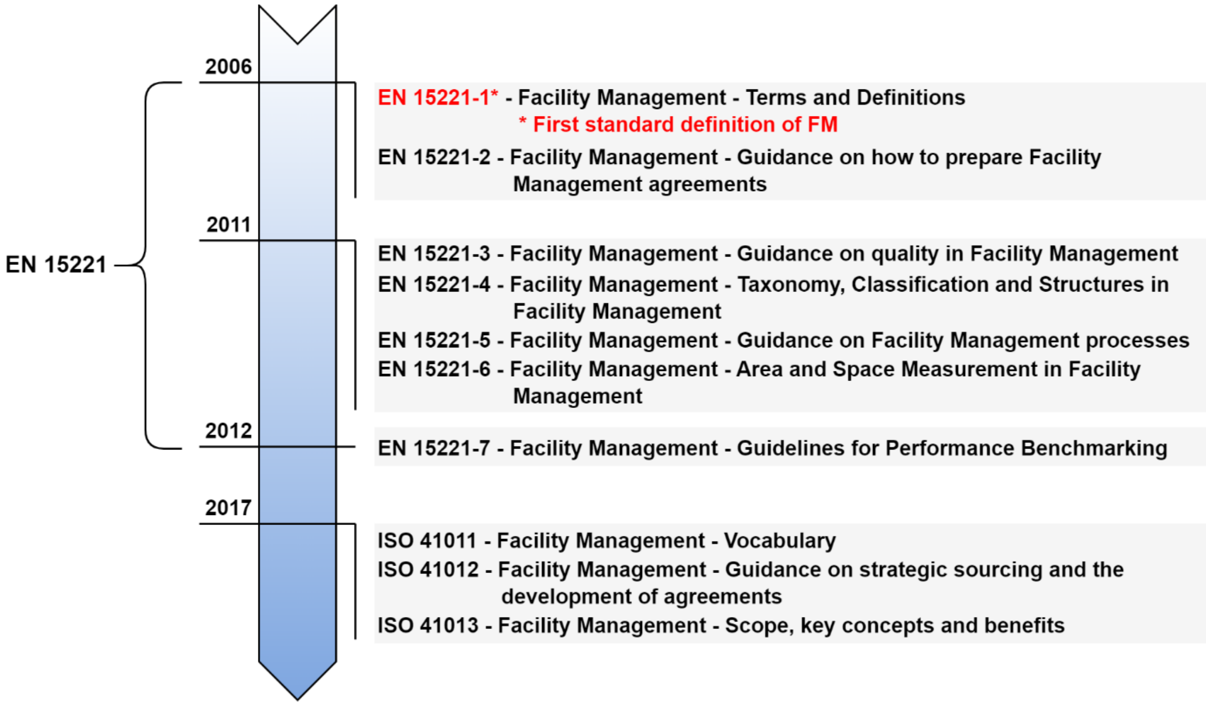

Figure 2.1 Evolution of standards in Facility Management.

A decade after, with the release of the standard ISO 41011:2017 (now ISO 41011:2024) the discourse on the discipline's scope and purpose will be finally settled in a new and more comprehensive definition that successfully integrates its diverse natures (see Figure 2.2). Facility Management is reaffirmed as a key function of the organisation, which determines its operational boundaries and whose benefit is the ultimate purpose. However, compared to EN 15221-1, three aspects are better clarified. First, the integration goes beyond the "processes" and includes "people" and "place", hence stressing the adoption of a holistic approach based on these three core elements. Second, explicit reference is made to the "built environment" that, although broadly, defines the physical boundaries of the discipline's scope. Most importantly, FM purposes are clearly framed within a sustainability perspective, mentioning in fact both the improvement of the quality of life of people and the productivity of the core business. On one hand, this draws a strong relationship between the satisfaction, health, and well-being of the people that inhabit the built environment and the productivity of the organisations that are responsible for its management. On the other hand, the choice of the term "improving" poses a continuous challenge to the FM discipline whose aspiration shall reach beyond the achievement, or the preservation of a given performance threshold considered acceptable but rather seek a continuous improvement that follows the evolution of the people (and core business) needs.

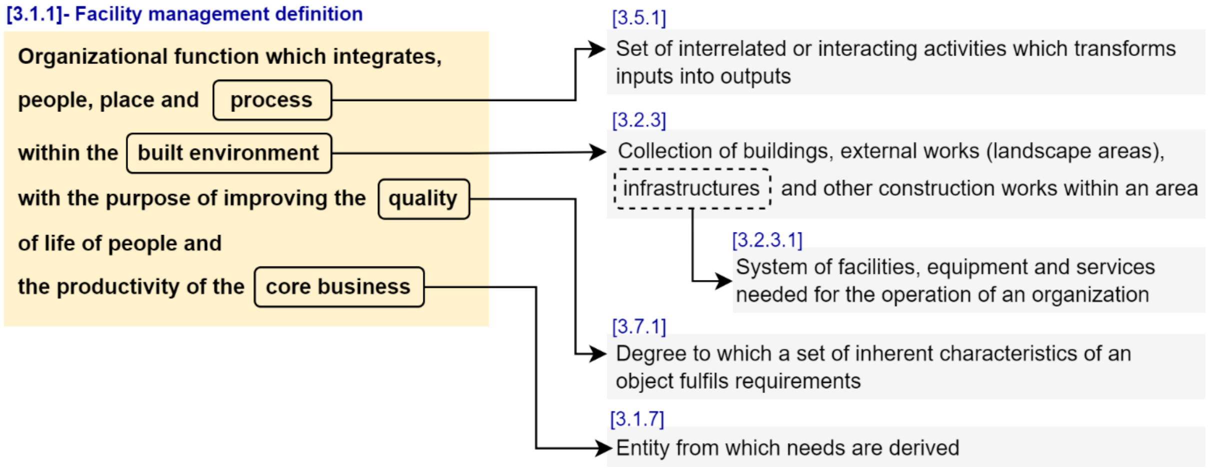

Figure 2.2 Definition of "Facility management" and related terms according to (ISO 41011:2024). In square brackets the number assigned to the definition of each term.

From the above it is clear that the current industry perspective on FM practice has long overcome the reduction to those, yet fundamental, maintenance activities required to operate facilities that meet the designed performance (Saap, 2017). On the contrary, as it is further discussed in §2.2, the occupants are becoming central to the operation of the existing buildings (van Sprang & Drion, 2020), pushing toward the development and adoption of cognitive systems that can perceive and learn the human presence and automatically adapt the environment to meet their needs or inform the decision-making process to improve their quality of life and productivity of core business (Xu et al., 2019).

In this dissertation, although being collocated within the same boundaries, *workplace management* is used instead of *facility management* to restrict its original scope in terms of the people (i.e., employees), place (i.e., workspaces), and processes (i.e., work activities). Nonetheless, the fundamental principles which are included in the current FM standard definition, informed also the framework of this research, as discussed in Chapter 3.

2.1.2. A complex ecosystem

Assuming addressed the theoretical collocation of *workplace management* into the broader scope and purpose and the ever-evolving practice of the FM discipline, the next fundamental step regards the definition of *workplace* adopted in this dissertation. Also, in this regard, the definition provided in the standard FM vocabulary (ISO 41011:2024) – *physical location where work is performed* – proves outstandingly effective in focusing on the core concepts involved, i.e., *space* (physical location), *activity* (work), and hence, implicitly, *performing agent* (worker).

Therefore, even considering our scope limited to office environments and activities, it results evident that the concept of workplace extends beyond a building space and encapsulates a multi-dimensional, dynamic, and complex system in which workers, activities, and building elements mutually interact.

A sample of this complexity can be appreciated observing the simplified shared office model reported in Figure 2.3 and its main entities defined in Table 2.2. The discussed definition of *workplace* does not specify the spatial scale of the physical location. Therefore, depending on the use case, it can encompass any of the topological units within a building, ranging from the entire facility itself to individual departments, and even down to single rooms or parts thereof, such as a workstation. Focusing on the room scale, from a physical perspective an office presents both static and dynamic properties. The area, volume, form factor, layout (including workstation, furniture, equipment, and HVAC terminal position), windows, and doors are inherent aspects of the building and establish environmental constants. Within these constraints other measurable properties change continuously with position and time. Thermal gradients follow external (e.g., air temperature, solar radiation) and internal (e.g., people, equipment, lighting) loads and can deviate sensibly from the room average value depending on the proximity to certain elements such as HVAC terminals or windows. From a visual perspective, light distribution, colour, and mix change during the day and are affected by the period of the year, external sky conditions, and occupants' behaviours in relation to shading devices and artificial lights. Likewise, the acoustic and indoor air properties are very sensible to position and room operational conditions. At any given time, the observable level of sound pressure returns the contribution of external (e.g., from traffic or other rooms) and internal (e.g., people, equipment) sources and is affected by the properties of the surrounding elements (e.g., floor, wall, ceiling, furniture, etc.). In turn, the presence of occupants and their activities influence the concentration of moisture, dust, and other airborne pollutants for which adequate natural or mechanical ventilation is required. In this highly variable indoor environment, workers perform their work or work-related activities in a continuous process of interaction (active) and adaptation (reactive) to the environment. In addition, social and psychological dynamics concur to influence workers' physical and cognitive states, thus increasing the number of factors influencing their satisfaction, health, well-being, and productivity.

The quest for a granular understanding of this complex ecosystem kept researchers engaged for several decades, when the growth of the economy of services manifested the urge for more effective ways to organise and operate workplaces dedicated to knowledge workers. In particular, the transition from conventional private spatial configuration to a modern open-plan concept was believed to be the ideal solution. Increased net usable area, higher occupant density, and ease of reconfiguration were supposed to facilitate communication and interaction between co-workers, improve individual work performance, and ultimately organisational productivity. However, while these assumptions have never been empirically proven, extensive research identified the negative impacts of open-plan office layouts on occupants' perception of their office environment, with noise and lack of privacy being the key sources of dissatisfaction, and excessive uncontrolled social contact and interruptions due to close proximity to others leading to overstimulation and loss of productivity (Kim & de Dear, 2013). In turn, organisations started to prioritize employees' health, well-being, and satisfaction with the workplace for its causal link with productivity, making the assessment of the extent to which a building matches occupants' needs and expectation a crucial indicator of management performance (Veitch, 2018).

Figure 2.3 Simplified model of a sample indoor workplace.

Table 2.2 Standard definition of entities commonly comprised within an indoor workplace.

Entity	Description
Workplace	Physical location where work is performed. (ISO 41011:2024)
Worker	Person performing work or work-related activities that are under the control of the organisation. (ISO 45001:2018)
Workstation	Location containing furniture and supporting equipment (including telephony, IT and power connections), specifically designed or suitable for work-related activities. (ISO 41011:2024)
Furniture	Equipment for occupant use, not usually fixed to the building. (ISO 6707-1:2020)
Window	Construction for closing a vertical or near-vertical opening in a wall or pitched roof, which will admit light and can provide ventilation. (ISO 6707-1:2020)
HVAC terminal	Terminal unit of an HVAC system. | HVAC system: System that provides heating, ventilation or air conditioning for buildings. (ISO 16814:2008)
IEQ sensor	(Sensor): Device or instrument designed to detect or measure a variable. (ISO 16484-2:2004)
Controller	Device for regulation and/or logic control as well as monitoring and processing of information, e.g. temperature, humidity, pressure. (ISO 16484-2:2004)
Equipment	Aggregation of functional elements or assembly of components and modules, that belong together in one physical unit of a plant or in a functional unit of a system. (ISO 16484-2:2004)

Vischer and Wifi (2017) emphasize that the environmental quality experienced by workplace occupants directly impacts their quality of work life and, consequently, their overall quality of life (see Figure 2.4). While most building standards focus on preserving occupant health and safety by improving physical comfort, they argue that two additional dimensions are crucial for achieving environmental quality: functional comfort and psychological comfort. Functional comfort refers to how workspace features facilitate or hinder the occupants' ability to perform their tasks efficiently and effectively. Psychological comfort, on the other hand, addresses the worker's experience from a behavioural perspective. Once the occupants' physical and functional needs are met, the workspace should ensure three key psychological factors: territoriality, which allows individuals to develop a sense of belonging and ownership; privacy, which enables control over one's accessibility to others; and control, both in adjusting the physical environment to personal preferences and in participating in decision-making with colleagues sharing the workspace.

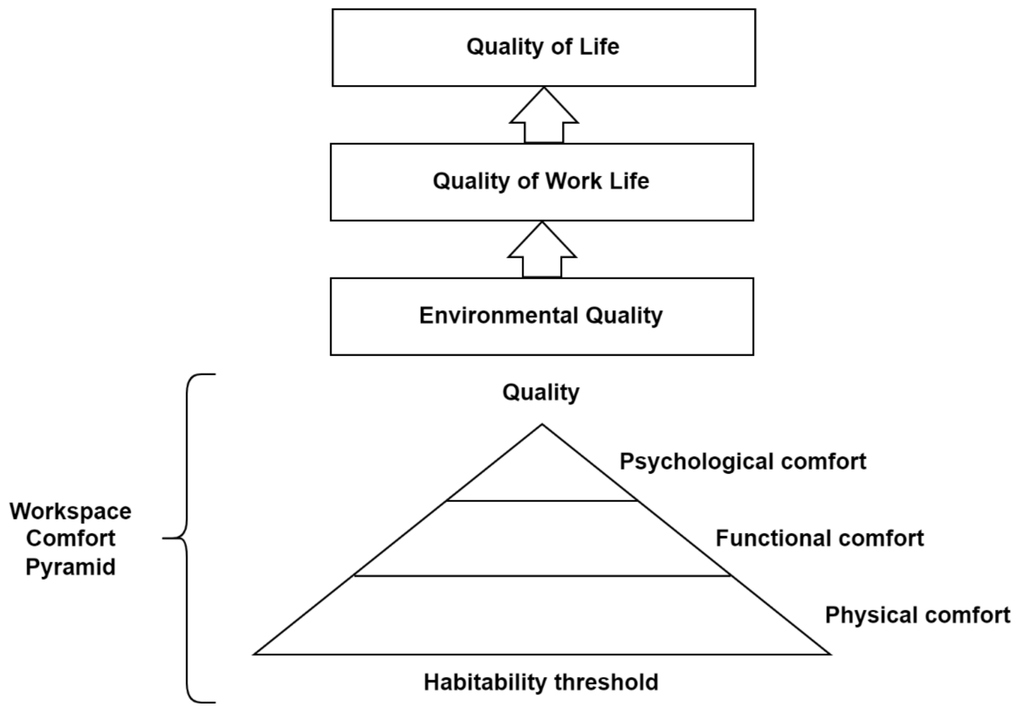

Figure 2.4 Effect of workspace comfort dimensions on quality of life at work. Edited from Figure 1 and Figure 2 of Vischer and Wifi (2017).

Despite adherence to the best design and construction regulations, achieving high workplace quality and enhancing workers' quality of life requires more than just technical compliance. A holistic approach, incorporating both building- and occupant-related factors, as well as continuous monitoring and improvement of the operational capacity to meet occupants' needs and preferences, is essential. However, collecting and interpreting the numerous factors influencing worker experience remains a complex and challenging task, which has attracted growing multidisciplinary research interest. Before discussing findings from diverse fields of study (§2.1.3), it is stressed that this thesis operates under three core assumptions centred on the occupants, which define how the worker-workplace relationship is approached:

- *Space is relational* – It should not be conceptualized in absolute terms, as it is the product of relations between social phenomena (Zaki et al., 2018). While this assumption applies to various spatial scales within the built environment, including outdoor spaces, it is particularly relevant to workspaces. Functional, social, emotional, and symbolic factors all shape how workers perceive their environment. In particular, beyond the physical aspects of the individual-environment relationship, the social interactions between individuals introduce a "hidden" dimension to space, which plays a significant role in workers' psychological well-being. Since Hall's (1966) pioneering work on proxemics (Hall, 1990), which explored how humans use space and its cultural variations, research has emphasized the importance of personal and public space, particularly in designing shared workplaces. For example, the arrangement of workstations and allocation of workers should optimise distances for work-related interactions and avoid excessively close positions that may cause feelings of intrusion (Oseland, 2009).

- *Space is heterogeneous* – Environmental conditions within a building space have a high spatial variability so that is challenging to capture by generalizing their objective properties from the measurements of one sensor located at one point (M. M. Abdelrahman et al., 2022). For example, during the heating season, two occupants in the same room may experience different levels of thermal comfort, even though the thermostat and HVAC settings indicate acceptable conditions One occupant may sit near a drafty window and feel discomfort, while another, closer to a radiator, may feel perfectly comfortable. This variability extends to other dimensions of physical, functional, and psychological comfort, where spatial proximity to building elements (e.g., windows, systems, equipment) and other occupants affects individual perceptions. However, accurately capturing this continuous spatial variability is not feasible with current sensor technology, which relies on measuring environmental conditions at discrete points within monitored spaces.
- *Spatial-temporal variability of space usage and perception* – The way individuals use and perceive space is highly personal, varying based on their conditions, time, and location, as well as influenced by proximity to other individuals and spatial elements. Both objective and subjective factors shape the quality of a space, which can ultimately only be assessed in relation to a specific person. This has become even more critical in the post-COVID-19 era, where the widespread shift to remote work has challenged traditional concepts of comfort and productivity in the workplace, emphasizing the need to address individual needs and expectations. While recent studies report that home environments are generally perceived as more comfortable, whereas office spaces are seen as more productive (Srivastava et al., 2024), understanding employees' specific needs and expectations will be crucial for improving workplace design and operations.

2.1.3. Characterizing factors

To conclude our exploration of the complexity of indoor workplace ecosystems, this section aims to provide a comprehensive, although not exhaustive, overview of the literature investigating the numerous factors that play a crucial role in determining the overall comfort and performance of occupants in office environments (Figure 2.5).

Starting with measurable physical factors, four key indoor environmental quality (IEQ) domains are commonly acknowledged as the most relevant for occupant comfort and satisfaction: acoustic quality, indoor air quality (IAQ), thermal quality, and visual quality (Fissore et al., 2023; Mewomo et al., 2023). Al Horr, Arif, Katafygiotou, et al. (2016), in their review of the links between IEQ factors and occupant satisfaction and well-being in office buildings, emphasize the mutual influence of environmental and personal factors in particular for the perception of the thermal environment.

Objective properties such as air temperature, mean radiant temperature, relative humidity, and air velocity can be experienced very differently depending on geographic location, climate, and time of the year, but also on individual characteristics like metabolic rate (a proxy for activity) and clothing insulation. Subjective factors, including physiological thermal adaptation, psychological habituation or expectations, and demographics like gender, age, job type, and cultural background, must also be considered (Frontczak & Wargocki, 2011).

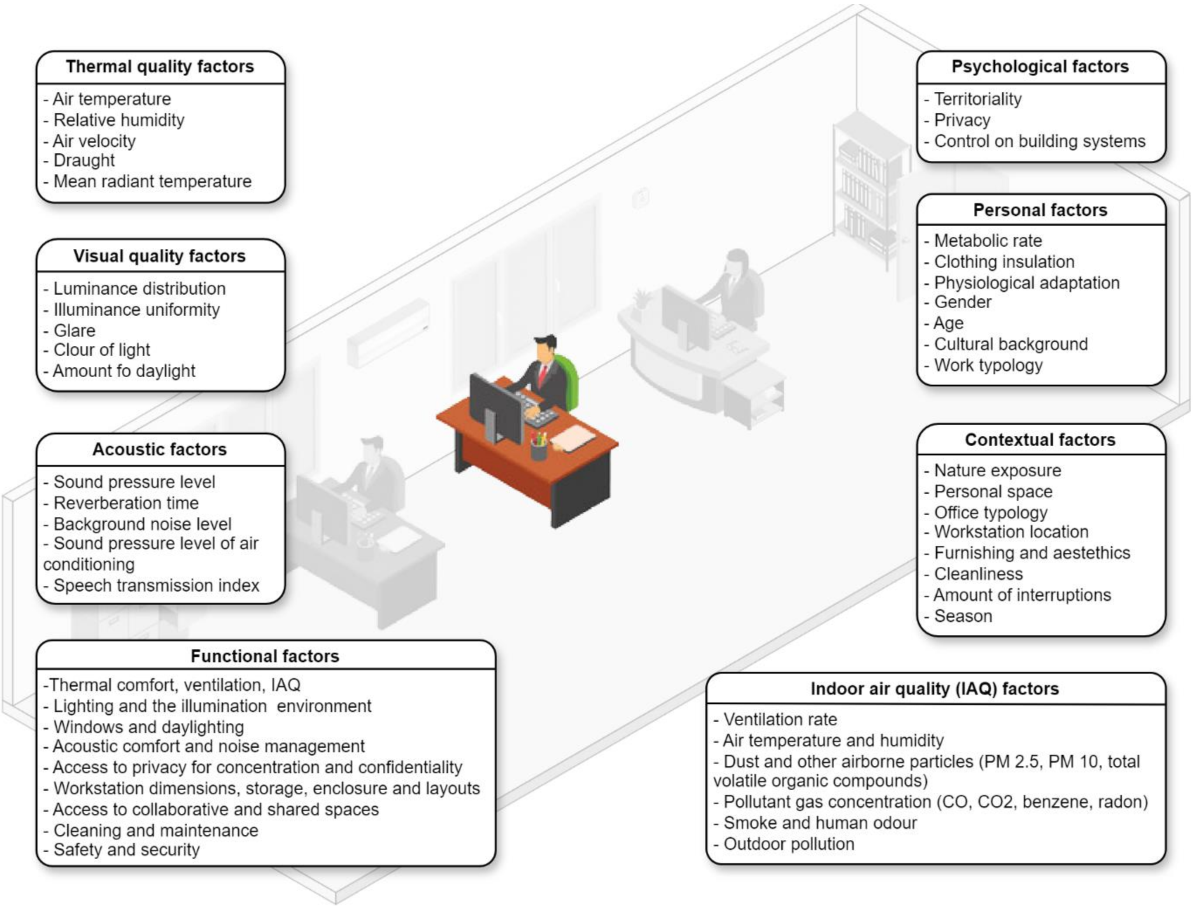

Figure 2.5 Indoor workplace characterizing factors considered in the literature.

Beyond measurable physical properties, intangible factors are equally, if not more, significant in shaping workers' experience of the workplace. For instance, allowing occupants control over their indoor environment has been shown to significantly enhance satisfaction across all IEQ aspects (Frontczak & Wargocki, 2011). The psychological and physical effects of this link between personal control and thermal comfort were notably demonstrated in a chamber experiment by Luo et al. (2016). Subjects who believed they had control over their thermal environment, despite no actual changes to the HVAC system, reported improved comfort in both warm and cool conditions. The more severe the thermal conditions, the greater the perceived benefit of control, underscoring the importance of this psychological factor. Similar results were confirmed in an experiment conducted by Brambilla et al. (2017), where higher occupant satisfaction was observed in an office room with operable windows and shading compared to a fully automated room.

However, it is important to note that comfort should not come at the expense of productivity. Boerstra et al. (2015) found, in a laboratory study involving 23 individuals, that although occupants felt more comfortable when in control of their thermal environment, they were slightly more productive when control was removed, provided an automatic system precisely matched their preferences, thereby minimizing distractions from manual adjustments.

From a functional perspective, comfortable workspaces enable workers to focus their energy on tasks rather than on overcoming environmental conditions that hinder performance, thus reducing stress. Vischer and Wifi (2017) after examining extensive research on functional comfort through structured feedback from building users, argue that a limited number of environmental dimensions directly impact task performance. These include physical comfort factors, access to windows and daylight, noise management, privacy for concentration and confidentiality, workstation dimensions, storage, layout and enclosure, access to collaborative spaces, cleaning and maintenance, and safety and security. Al Horr, Arif, Kaushik, et al. (2016) reached similar conclusions in their review of the relationship between IEQ and productivity, identifying eight IEQ factors and related physical parameters, notably including biophilia, views, aesthetic quality, materials, location, and amenities, which are considered across various facility scales. Furthermore, a recent review by Harris (2019) examined the literature on factors affecting productivity in office environments, categorizing them into four groups: efficiency (optimising space, time, and information use), effectiveness (enabling workers to perform their tasks), engagement (providing a positive work experience), and health (supporting and improving well-being at work). The findings confirmed that office workers' productivity is directly linked to their physiological and psychological well-being. Therefore, management approaches aimed at identifying and addressing both impeding and enhancing factors, alongside continuous improvement of the quality of work life, are recommended to positively impact worker output.

Despite continuous research efforts in predicting occupant comfort and acceptable conditions using models that primarily consider environmental parameters, current building operations and standards continue to rely on generalized approaches established several decades ago, often focusing on individual IEQ domains (e.g., Fanger, 1967, and ISO 7730:2005 for thermal comfort). Zhao and Li (2023) emphasize that occupant satisfaction is influenced by the combined interaction of various IEQ factors across multiple domains. Their review underscores the scarcity of studies that integrate factors from more than one domain, the inconsistency in findings, and the reliance on generalized models. They advocate for the development of personalized models that account for multi-domain factors, as well as the subjective characteristics and adaptive behaviours of individuals.

A seminal study by Kim and de Dear (2012) also shed light on the non-linear relationship between individual IEQ factors and overall workspace satisfaction. By analysing responses from 43,021 post-occupancy evaluation questionnaires across 351 office buildings, they categorized IEQ factors into “basic” and “proportional” based on an adapted Kano satisfaction model for building occupants. Basic factors (e.g., temperature, noise level) have a greater impact on overall satisfaction when inadequate, whereas proportional factors (e.g., air quality, visual comfort) affect satisfaction in a linear manner. Based on the same database of survey responses, Kim and de Dear (2013) also explored how workspace spatial configuration influences satisfaction with various IEQ factors. The comparison between open-plan and enclosed offices showed that, contrary to the industry’s belief in open-plan layouts improving communication, the lack of privacy and poor acoustic quality in such spaces can significantly diminish overall satisfaction. Additionally, exposure to nature was found to be a critical factor in improving office workers' restoration, motivation, health, stress levels, and coping capacity, suggesting that a holistic approach is necessary to address factors impacting employee well-being and performance (Sadick & Kamardeen, 2020).

The growing recognition of a holistic approach to health, well-being, and productivity in indoor workplaces is reflected in recent initiatives by AECO industry associations that have promoted standards and guidelines aimed at designing and operating more sustainable buildings that address occupant needs and expectations (International WELL Building Institute, 2024; World Green Building Council, 2014). Building on these insights, the next section explores the ongoing paradigm shift from a building-centric to an occupant-centric approach to monitoring and management of indoor workplaces.

2.2. From the building to the occupant: a paradigm shift

The studies reviewed in the previous section provide an overview of the challenges and complexities involved in understanding an indoor workplace ecosystem. While there is no clear consensus on the scope of the domains required for designing, operating, and managing workplace buildings, a growing interest is emerging in multidisciplinary management approaches aimed at overcoming the limitations of traditional methods, which primarily focus on observable physical building factors. Both academia and the building industry recognize the user as the most critical system component (International Energy Agency, 2018; O'Brien et al., 2020). This section delves into the "occupant" dimension and its role within the workplace ecosystem, addressing the psycho-physiological aspects linked to workers' comfort, satisfaction, and well-being, as well as their interactions with work activities and productivity. Subsequently, the literature on conceptual frameworks and technical solutions for enabling occupant-centric workplace management are reviewed, alongside methods for assessing worker conditions.

2.2.1. Well-being and comfort

This thesis seeks to support workplace managers and organisations in providing healthy and comfortable work environments that enable occupants to perform at their best while maintaining a high quality of work life. To achieve this, the recognized definitions of the key concepts of "well-being" and "comfort" are examined to identify their specific requirements within the workplace context.

In simple terms, "well-being" can be understood as *the state of feeling healthy and happy*[4] throughout an individual's life. For the purposes of this thesis, the concept is examined from the perspectives of two key disciplines: Ergonomics and Facility Management (Table 2.3). Ergonomics is the *scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and applies theory, principles, data, and methods to design in order to optimise human well-being and overall system performance*[5]. From an ergonomics perspective, well-being is derived from the satisfaction of one's needs, which involves considering a worker's activities, as well as physical and cognitive aspects, with an emphasis on sustainability over time. On the other hand, FM's definition focuses more on specifying the needs of workers by incorporating mental and social dimensions, including work organisation and social factors, as equally important as physical factors and hazards.

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[4] Source: https://dictionary.cambridge.org/dictionary/english/well-being - Accessed 05/05/2025.
[5] International Ergonomics & Human Factors Association (IEA) – Source: https://iea.cc/about/what-is-ergonomics/ - Accessed 05/05/2025.

The fulfilment of a worker's needs lies at the core of the concept of comfort and is fundamental to assessing various aspects of indoor environmental quality, as shown in the standard definitions in Table 2.4. The concept of IEQ refers to the relationship between the environment and its measurable impact on occupants' health, comfort, and well-being. Although occupants are simultaneously exposed to multiple environmental stimuli that interact in complex ways, building scientists typically simplify the observation and assessment of occupant experiences by focusing on four key domains related to sensory perception: thermal quality (thermal homeostasis), acoustic quality (hearing), visual quality (sight), and indoor air quality (olfaction).

Table 2.3 Definitions of well-being in relation to different domains.

Domain	Well-being definition
Works system	(ISO 6385:2016) - Sustainable internal state resulting from satisfaction of the physical and cognitive needs of the worker during his/her activity. Note 1: Well-being can contribute to the quality of working life.
Facility Management	(ISO 41011:2024) - Fulfilment of the physical, mental, social and cognitive needs and expectations of a worker related to their work. Note 1: Well-being at work can also contribute to the quality of life outside of work. Note 2: Well-being at work relates to all aspects of working life, including work organisation, social factors at work , workplaces, equipment and hazardous tasks.

Table 2.4 Definitions of comfort in relation to different IEQ domains.

IEQ Domain	Definition
General	(ISO 6707-3:2022) – **Indoor environmental quality:** Measure of a building's internal environment in relation to the health, comfort and well-being of those who use space within it.
Thermal quality	(ISO 6707-3:2022) – **Indoor thermal comfort:** occupant satisfaction with the indoor thermal environment, described in terms of air temperature, vapour pressure and air velocity. (ISO 16813:2006) – **Thermal comfort:** condition of mind derived from satisfaction with the thermal environment.
Acoustic quality	(ISO 6707-3:2022) – **Indoor acoustic comfort:** occupant satisfaction with the indoor acoustic environment, described in terms of sound pressure level, reverberation and noise level. (ISO 16813:2006) **– Acoustic comfort:** reaction of occupants to the indoor acoustical environment, described in terms of sound pressure level and audibility.
Visual quality	(ISO 6707-3:2022) – **Indoor visual comfort:** occupant satisfaction with the indoor visual environment, described in terms of illumination level, glare, visibility, reflection and psychological and physiological content with natural and artificial illumination. (EN 12665:2024) – **Visual comfort**: subjective condition of visual well-being induced by the luminous environment.
Indoor air quality	(ISO 6707-3:2022) – **Indoor air quality:** quality of air inside a building, described in terms of odour, physical parameters, chemical and biological pollutants. Note 1 to entry: Indoor air quality is directly related to the ventilation rate, air distribution patterns and pollution sources. Note 2 to entry: Indoor air quality is important in ensuring human health, olfactory comfort and perceived comfort. (ANSI/ASHRAE 62.1-2022) – **Acceptable Indoor 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.

In a thermally comfortable environment, occupants will neither want to feel warmer nor cooler. Although mathematical thermal comfort models, which predict the average satisfaction of occupants based on a few environmental factors (air temperature, velocity, humidity, and mean radiant temperature) and personal parameters (activity level and clothing), have been in use for decades (Fanger, 1967; ISO 7730:2005), their reliability is limited by the omission of other critical psycho-physiological phenomena. Adaptive approaches have since been developed to account for an occupant's capacity to adjust to the thermal environment through behavioural adaptations (e.g., changing clothing), relaxation of expectations, and acclimatization to surrounding conditions. Given the limitations of established models and the challenges of collecting and interpreting subjective data, Kim et al. (2018), proposed a new personal comfort model paradigm aimed at predicting individual responses rather than the average response of a large population. Their framework leverages high-resolution longitudinal environmental data, physiological data from wearable devices, and machine learning methods to learn individuals' thermal preferences. In a field study examining the correlation between thermal satisfaction and the thermal and non-thermal conditions experienced by 779 occupants of open-plan offices, Crosby and Rysanek (2021) that factors such as gender, age, body mass index (BMI), lighting, CO_2 concentration, and noise influence thermal satisfaction, even under the same thermal conditions, underscoring the limitations of models that focus solely on thermal parameters. As confirmed by Koth and Kobas (2024), gender differences significantly impact thermoregulatory responses, further highlighting the importance of considering individual factors in comfort modeling.

Although influenced by different environmental factors, occupant health and well-being—achieved through physiological and psychological satisfaction—are central also to definitions of acoustic, visual, and olfactory comfort as outlined in building standards. A comfortable visual and acoustic environment is primarily associated with preventing discomfort or annoyance. To assess this, both the physical properties of light and sound, as they are emitted or enter the workspace from external sources, must be evaluated in conjunction with the characteristics of the workspace itself -at both room and workstation scales- and ultimately in relation to occupants’ work tasks. Similarly, while the term “comfort” is not commonly used in relation to IAQ, it is generally linked to the absence of discomfort from odours or sensory irritation.

In all domains, comfort can be defined as the absence of unpleasant sensations, creating a subjective state of well-being that varies from person to person. As previously discussed in section 2.1.2 (Figure 2.4), in an office environment, this includes the fulfilment of physical, functional, and psychological needs (Vischer, 2007). While improving workers’ health and well-being remains a priority for policymakers and organisations, recent research is gradually uncovering the complex interactions of often overlooked and hard-to-quantify factors (e.g., exposure to natural materials, presence of windows; Douglas et al. 2022). This underscores the need for a holistic, human-centred approach that extends beyond traditional comfort metrics.

2.2.2. Activity and Productivity

The physical and functional characteristics of the work environment affect both the well-being and job performance of occupants. In her seminal work, Vischer (2007) describes this effect in terms of person-workspace fit: a problematic workspace (“poor fit”) drains energy from occupants, causing distractions and leading them to adopt coping behaviours; conversely, a supporting environment (“good fit”) enables workers to conserve their attention and energy for their tasks.

Focusing on the scope of this thesis, which addresses indoor workplaces where employees are primarily engaged in intellectual activities—commonly referred to as “knowledge workers” (Davenport, 2005) —the concepts of productivity and activity require clear definitions. As Veitch (2018) points out, while many industries define "productivity" in terms of output per unit of input, this concept does not easily apply to tertiary occupations. In these contexts, the focus is more on assessing the value added to the organisation's mission rather than simply measuring outputs, such as the number of typed characters or emails processed per unit of time.

At an organisational level, "productivity" reflects the balance between output value and input costs (Al Horr, Arif, Kaushik, et al., 2016), both of which are influenced by the quality of the work environment. Notably, quality and management system standards often overlook the work environment in their definitions of "worker," "productivity," and "activity." However, FM standards link activity to measurable outcomes (i.e., deliverables), though these connections are frequently not straightforward (Table 2.5).

Table 2.5 Standard definitions for "worker", "productivity", and "activity".

Term	Definition
Worker	Person performing work or work-related activities that are under the control of the organisation. (ISO 45001:2018)
Productivity	Ability to generate, create, enhance or deliver products, services and knowledge. (ISO 10014:2021)
	Ratio of work product to work effort. (ISO/IEC/IEEE 24765:2017)
Activity	Task or tasks that contribute to the completion of deliverables. (ISO 41011:2024) Deliverable: Measurable and verifiable outcome, result or item to be produced within a specific timeframe to complete a project or part of a project. (ISO 41011:2024)

In office settings, control over the environment and adequate workspace-activity fit (i.e., services, equipment, and environmental conditions that support the activity), are considered key to perceived productivity (Leaman & Bordass, 1999). Depending on the type of task (e.g., analytical, creative, decision-making, coordination) and its complexity, as well as subjective characteristics (e.g., introversion-extroversion, gender, age) individuals perform best under diverse environmental conditions (Zaki et al., 2018). For instance, a subdued environment may be preferred for demanding tasks, while exposure to more external stimuli can support the execution of menial tasks. In this context, maintaining employees' arousal levels at an optimal point—neither bored nor stressed—ensures emotional and psychological well-being and leads to better performance (Figure 2.6).

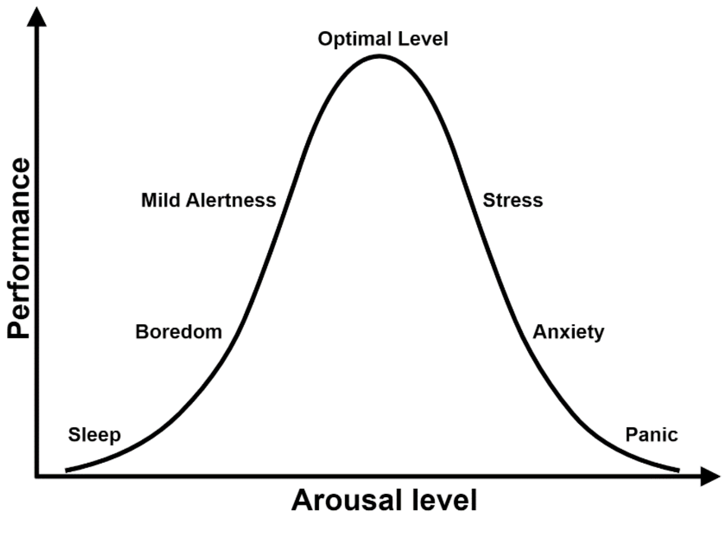

Figure 2.6 The relationship between performance and arousal, edited from Klados et al. (2014).

Conversely, neglecting the importance of a supportive and engaging work environment harms both the organisation's bottom line and employees' psychological health. According to the UK Centre for Mental Health (2011), environmental and organisational factors must be considered to avoid “presenteeism”—a condition where employees are physically present but not fully engaged, leading to reduced performance. In the UK alone, presenteeism is estimated to cost £15 billion annually in lost productivity.

The significance of this issue has driven numerous studies investigating factors that influence employee productivity. In their review, Al Horr, Arif, Kaushik, et al. (2016), identified four key areas—personal, social, organisational, and environmental— although the interrelationships between these areas remain unclear. Focusing on person-workspace fit, Veitch (2018) emphasizes the impact of spatial density (m^2 per person), social density (number of occupants per office), and the emotional responses related to space occupation on achieving a state of "flow" (Csikszentmihalyi, 1990). Flow describes effortless attention and focus, which in a work context can lead to peak performance and is influenced by both the physical workspace and employees’ perceptions.

To address the limitations of traditional work stress research, which often focuses only on psychological factors, Vischer (2007) proposed a theoretical model that infers the component related to the workspace from the number and frequency of coping behaviours adopted by occupants. Both physical workspace factors and occupant characteristics significantly impact productivity. For example, office layout (i.e., open-plan vs. enclosed) heavily influences control over unwanted interactions and interruptions (Kim & de Dear, 2013). Additionally, factors related to conventional IEQ domains—such as thermal, acoustic, air, and visual quality (Z. Deng et al., 2024; Liu et al., 2022) —as well as employee characteristics, including gender and age (Haynes et al., 2017), also play critical roles.

2.2.3. Occupant-centric building management

As emphasized by Donkers et al. (2021), literature shows clearly that a gap between designed, measured, and perceived building performance exists. Although the limitations of building-centric design and operation approaches in delivering high-quality indoor environments have long been recognized—and the user is now acknowledged as the most critical component of the building ecosystem (Agee et al., 2020)—it is only in recent times that the increasing digitization of the construction industry has provided the technical tools to support a long-awaited paradigm shift toward occupant-centric approaches. Evidence suggests that buildings often fail to meet the needs and expectations of their occupants when they are treated as “average” passive recipients, with operations based solely on monitoring physical parameters to provide “ideal” environmental conditions (O’Brien et al., 2020). Initially used to describe research focused on integrating occupancy and occupant behaviour into building design and operation to enhance energy performance and comfort (International Energy Agency, 2018), “occupant-centric” approaches are now shifting the paradigm of the FM discourse, with academia and industry joining forces to develop conceptual and technical solutions that enable a deeper understanding of occupants’ requirements for the optimisation of indoor environments and well-being (Heimar Andersen et al., 2024; Upasani et al., 2024).

This ambitious goal presents two main challenges: first, the collection of sufficiently reliable data on both the occupants and environmental conditions, and second, the meaningful integration of this data to gain actionable insights for improving the occupant-environment fit.

In recent smart building applications, indoor environmental states are commonly monitored through the deployment of sensors, which are integrated into networks and connected to building management systems. These sensors collect data that is used to infer occupant comfort based on expected satisfaction ranges, triggering adjustments to building systems (e.g., HVAC, lighting) according to predefined rules that often overlook the occupants' real-time experiences. However, the low spatial and temporal resolution of the collected data (i.e., sensor density and measurement frequency), along with the inability to account for the mutual interaction of various factors on individual perceptions, pose significant limitations in reliably predicting occupant satisfaction.

Occupants are the best source of information about their comfort needs and their feedback is crucial for assessing facility performance (Ergen et al., 2021). As a result, the concept of using "humans-as-a-sensor" (Jayathissa et al., 2020) is gaining traction in applications that aim to reverse the traditional approach to IEQ assessment, shifting the focus to evaluating occupant conditions. Evidence shows that occupants' verbalised perceptions and responses to IEQ surveys are reliable for assessing environmental conditions (J. Park et al., 2016) and should be integrated more actively into the development of tailored thresholds for specific facilities and use cases (Sadick et al., 2020).

Occupant experiences can be assessed either directly—through subjective survey responses or objective individual data such as facial expressions and physiological parameters—or indirectly, by observing coping mechanisms (Al Horr, Arif, Kaushik, et al., 2016). Traditionally, Post-Occupancy Evaluation (POE) surveys have been used to collect occupant feedback (Vischer & Wifi, 2017), but these suffer from critical limitations: low frequency (e.g. administered only once or a few times per year), lack of contextual information (e.g. generalized responses); asynchronous data collection, and recall biases (Ergen et al., 2021). To address these shortcomings, building researchers have adopted the Ecological Momentary Assessment (EMA) method, originally developed in clinical psychology by Shiffman et al. (2008). This method involves the repeated sampling of subjects' current experiences in real time (momentary), within their actual environment (ecological), by administering surveys and measuring physiological parameters through wearable devices and sensors. While this approach avoids the recall bias associated with traditional surveys, it requires minimally invasive survey designs and that do not disrupt subjects' workflows, as disruptions can lead to survey fatigue, resulting in incomplete or inaccurate responses.

Intille et al. (2016), in a field study, observed that simple micro-surveys administered via smartwatches achieved significantly higher compliance rates, completion rates, and quicker response times compared to longer surveys delivered through smartphone interfaces, making this approach particularly suitable for the continuous human-computer interactions required by the EMA method. Moreover, Jayathissa et al. (2019) developed an open-source clock-face application, Cozie[6], collecting human comfort data via consumer smartwatches, which proved effective for intensive longitudinal comfort model investigations (Jayathissa et al., 2020). Donkers et al. (2021) proposed a system which collects occupant feedback and physiological parameters to be semantically integrated with building data, enabling the creation of occupant-centred Digital Twins.

[6] https://github.com/cozie-app - Accessed 05/05/2025.

However, despite the increasing adoption of the EMA method for occupant subjective and objective data collection, which is enabling the transition to occupant-centric management, the reliability of survey feedback and the significance of physiological measurements must always be carefully considered. While advancements in wearable sensors are allowing for more sophisticated observations of physical indicators that correlate well with comfort domains (e.g., electrodermal activity and skin temperature related to thermal comfort, Moon et al. 2024) and overall well-being (D'Ascenzi et al., 2023), psycho-social phenomena unrelated to the actual environmental conditions may negatively influence individuals' satisfaction as captured in POE surveys over extended periods (e.g., "honeymoon-hangover" effect, Xiong et al. 2024).

Moreover, while this thesis does not address the serious privacy concerns associated with continuous non-invasive monitoring approaches, advancements in sensor technology have enabled significant progress in the indirect observation of occupant conditions. Ma et al. (2022) demonstrated the feasibility of a system using a low-resolution infrared camera to monitor office workers' sitting postures and facial expressions, assess psycho-physical comfort, and provide health recommendations (e.g., suggesting breaks). In a controlled experiment, Du et al. (2024) explored the potential of using facial expression recognition and physiological monitoring to predict dissatisfaction with IEQ factors (e.g., IAQ and noise during cognitive tasks), achieving an accuracy of 0.71, highlighting both the promise and challenges of these methods. In an extensive review of vision-based occupant information systems, Choi et al. (2021) proposed a five-tier taxonomy for their application in occupant-centric control (i.e., presence, count, position, behaviour, and psychological state), and discussed adoptable privacy-preserving techniques.

Once occupant data relevant to a specific managerial use case is obtained, monitoring the corresponding contextual physical parameters through environmental sensors is key to assessing the occupant-environment fit. Ideally, the immediate conditions surrounding each occupant should be sampled continuously to maintain a perfect correlation with their subjective data. While Parkinson et al. (2019) introduced a desk-level multi-IEQ parameter monitoring station, it remains impractical in real-world applications for sensor to be deployed at such a high-resolution to consider every relevant micro-climate variation in a building (M. M. Abdelrahman et al., 2022). The deployment of IEQ sensor must therefore be carefully planned to achieve adequate resolution of environmental properties while minimizing economic and energy costs. In this regard, Yuan et al. (2024) developed and tested an optimisation method for the deployment of indoor temperature sensors in large spaces, emphasizing the need for trade-offs in multi-objective optimisation depending on the operational scenario. Similarly, Hobson et al. (2023) conducted a simulation-based study to determine the minimum CO_2 sensor grid density needed for effective demand-controlled ventilation, demonstrating that efficient ventilation control can be maintained while reducing sensor installation and maintenance costs.

Despite increasing research is supporting the development of occupant-centric approaches, these rely on high-volume data on both occupant and environmental conditions for which numerous challenges remain in translating these solutions into practical applications.

2.3. Enabling occupant-centric building management

In the previous sections, we discussed the factors characterizing an indoor workplace with reference to its three main components: the physical environment, the occupants, and their work activities. This section examines the current conceptual and technical solutions that enable the monitoring and operation of facilities with an occupant-centric approach. First, the contemporary Digital Twin (DT) paradigm applied to building management is explored. Then, the role of Semantic Web technologies in organising and integrating building and occupant-generated data to extract actionable insights is discussed.

2.3.1. Digital Twins for occupant-centric building management

Although the terminology has evolved, the core idea that a digital informational construct about a physical system, a "twin", could be created as an entity of its own and linked with the physical system originated in the manufacturing industry in the early 2000s (Grieves, 2005). This concept involved a virtual system that reflects relevant information about a physical system and maintains a connection throughout its entire lifecycle—covering design, production, operation, and disposal phases—to support product lifecycle management (PLM) use cases. According to Tao et al. (2019), despite the increased sophistication introduced over time, the three fundamental elements—a physical artifact, its digital counterpart, and the connection between them—remain central to how DTs are understood today.

Accounting for the structural delay in the reception of innovations typical of the construction industry, the concept of "Digital Twin" was introduced more recently in the AECO sector. The increasing adoption of ICT, along with the spread of the BIM method and technologies, has driven the ongoing digital transformation of the industry, leading stakeholders to recognize the benefits of digital representation, simulation, and optimisation of physical assets and processes in the built environment during the entire lifecycle (M. Shahzad et al., 2022). However, despite numerous frameworks, definitions, and implementations proposed for various purposes, there remains no consensus on a unified DT definition for the AECO sector, either in academia or practice (M. Abdelrahman et al., 2024). Without attempting to resolve this open issue, this section explores the key aspects of the current DT paradigm for the built environment and its implementation attempts for occupant-centric building management.

Several international standards have recently incorporated definitions of DT into their vocabularies (Table 2.6), all of which revolve around three core concepts: a digital representation of a physical entity, a certain degree of synchronization or information exchange between the digital and physical entities, and the purposeful application of these capabilities. In the AECO sector, DTs are typically intended as digital representations of built assets based on BIM models produced during design and construction, and used to support their operation and maintenance (Borrmann et al., 2018). Recognizing the need for a more comprehensive definition that accounts for the industry's fragmented and complex nature, Sacks et al. (2020) build on the existing concepts of BIM, automated data acquisition, and artificial intelligence to introduce the notion of Digital Twin Construction (DTC). Their proposed DTC information system workflow includes information stores, processing functions, and monitoring technologies, structured around three concentric control workflow cycles. This approach aims to move beyond viewing DT as a simple extension of BIM tools, instead positioning DTs a means to ensure reliable, real-time information for decision-making throughout the lifecycle of built assets.

Table 2.6 Definitions of "Digital Twin" across different international standards.

Domain	Digital Twin definition
Building	(ISO 6707-4:2021) – Digital representation of a physical facility that receives information from the facility and sends actuation information to the facility.
Manufacturing	(ISO 23247-1:2021) – Fit for purpose digital representation of an observable manufacturing element with synchronization between the element and its digital representation.
IoT	(ISO/IEC 20924:2024) – Digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization. Note1: Digital twin has some or all of the capabilities of connection, integration, analysis, simulation, visualization, optimisation, collaboration, etc. Note2: Digital twin can provide an integrated view throughout the life cycle of the target entity.

In their seminal work, Boje et al. (2022) provide a comprehensive analysis of the current DT paradigm for the built environment, considering different scales and domain-specific applications. Rather than offering a rigid definition, they present the DT as a broad paradigm under which a variety of technologies and approaches can fit. Drawing inspiration from the simplicity and effectiveness of the maturity-ability framework used for BIM, they propose a comparable three-level schema for developing DT systems of built assets, emphasizing that not all capabilities are required or need to be implemented in practice immediately (Figure 2.7). The first level focuses on sensing and monitoring capabilities, followed by intelligent semantic platforms at level two, where ontologies and semantic web technologies become essential in transforming static systems into dynamic, web-based environments. This transition enables the coherent integration and sharing of heterogeneous models and knowledge. The third and final level envisions the integration of AI capabilities, enhancing interaction with communities and stakeholders and expanding the DT's utility by offering more advanced services.

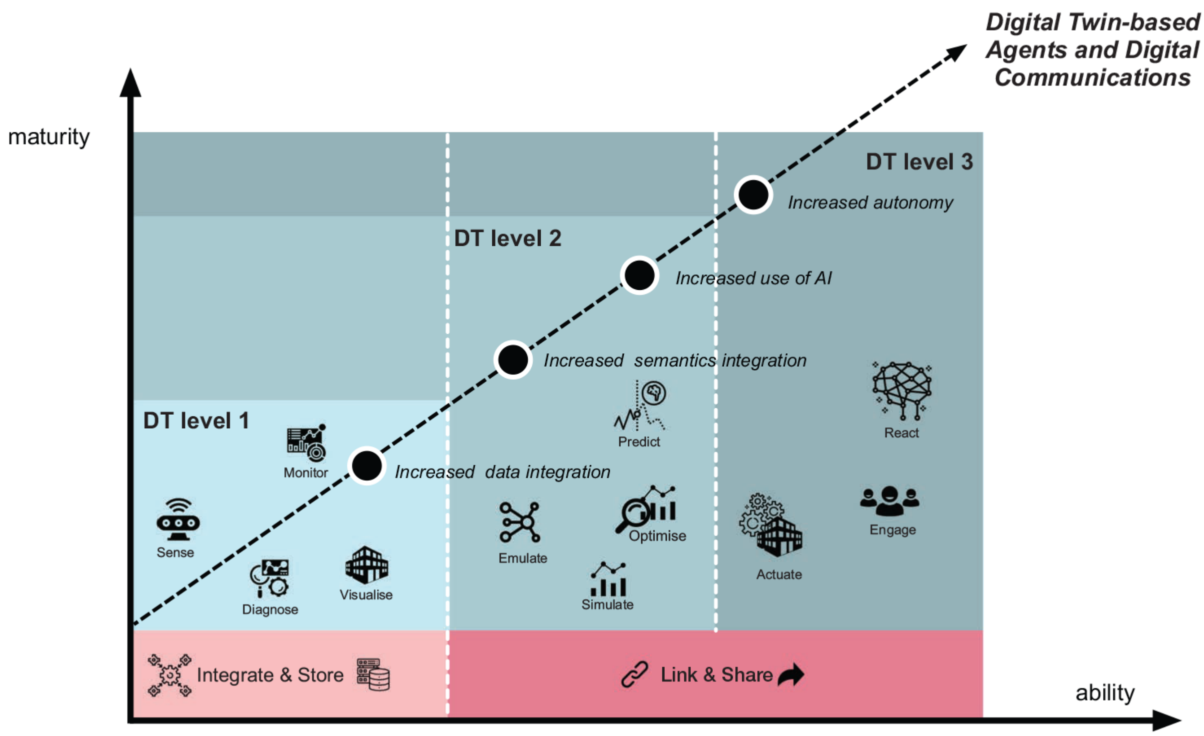

Figure 2.7 Digital Twins levels based on perceived abilities from Boje et al. (2022).

In this context, Kosse, Hagedorn, et al. (2024) argue that while domain-specific DT implementations are becoming increasingly common, the full benefits of a pervasively digitalized built environment can only be realized through ensuring interoperability and interconnectivity between DTs by standardizing their creation, management, and deployment. Building on Boje et al. (2021), who identified modularity as a key requirement for deploying standardized and interoperable DTs, Kosse, Hagedorn, et al. (2024) examine the modularity of current DT approaches in the built environment. They define four areas of DT modularity—technical, process-oriented, spatial, and life cycle-oriented—and identify standardized information containers as a viable way to implement modular DTs. In comparing the capabilities of the Asset Administration Shell (AAS) (IEC 63278-1:2023), used in Industry 4.0, and the Information Container for linked Document Delivery (ICDD) (ISO 21597-1:2020), developed for the AECO sector, they highlight their potential for modular approaches. The recent cooperation agreement between buildingSMART International (bSI) and the Industrial Digital Twin Association (IDTA, 2024) reflects a growing interest among stakeholders in aligning AECO and Industry 4.0 technologies and standards to achieve open digital interoperability in the built environment.

Pushing the modularity concept further, Hagedorn et al. (2024) propose enabling DT by coupling multiple ICDDs within a System-of-Systems (SoS) approach, where independent systems or subsystems interconnect to achieve common goals beyond what individual systems can accomplish independently. Analysing the structure and capabilities of the ICDD container, which is not a DT itself, they argue that it can serve as a crucial part of an SoS, integrating static document-based data (e.g., BIM) with dynamic time-series data from heterogeneous sources. As showed also by Zhang (2024), this integration positions the ICDD as the backbone of a DT. Furthermore, the ICDD's intrinsic capability for storing and managing semantic data offers a foundation for developing intelligent DT platforms where knowledge can be processed and shared among various services and stakeholders, extending beyond mere integration of monitored data (Al-Sadoon et al., 2024; Polter and Scherer, 2023).

Currently, DT implementations are being proposed to address significant challenges across various domains of the AECO sector, with applications tailored to specific use cases and life-cycle phases, particularly to support facility management of existing complex assets, improving energy efficiency and indoor conditions (M. Deng et al., 2021; Halmetoja, 2022). However, most of the proposed solutions are often limited to 3D visualization of space conditions, primarily assisting in monitoring asset performance based solely on IEQ sensor data (Opoku et al., 2024). Nevertheless, as discussed earlier (§2.2), the long-anticipated shift from building-centric to occupant-centric operation of the built environment requires fully leveraging the DT paradigm to integrate user-generated data and profile occupant needs and behaviours, thereby informing the management of human-centred spaces with optimised functions, services, and indoor conditions (Zaki et al., 2018).

In this regard, considering the possibility of predicting occupant environmental preferences, M. M. Abdelrahman et al. (2022) demonstrated that DTs can facilitate the adoption of personal thermal comfort models by integrating subjective thermal comfort feedback, indoor localization, and spatial context from BIM into machine learning models. To address the challenge of impractically positioning IEQ sensors at a high enough resolution to capture all conditions characterizing the typical heterogeneity of indoor spaces, they incorporated a vector-based spatial model, Build2Vec, into their framework. This model combines spatial data and subjective comfort feedback collected through a smartwatch-based EMA approach into a knowledge graph structure, which is then used to predict occupant thermal preferences. Their test implementation showed significant improvements in comfort prediction (up to +28%) compared to traditional models, demonstrating the feasibility of DTs in supporting occupant-centric building management approaches, moving beyond simple monitoring to prediction and optimisation.

Focusing on the management of indoor workplaces, understanding and clustering worker environmental preferences offers significant benefits in terms of space optimisation and energy use by grouping occupants with similar preferences or needs related to their activities. Limiting their focus to workplaces that adopt activity-based workspaces (ABW)—where workers can choose different spaces to do their work and activities on a day-to-day basis—Sood et al. (2020) occupant preferences through real-time environmental feedback on thermal, visual, and acoustic comfort, matching them with suitable, environmentally comfortable, and spatially efficient flexible workspaces. The feasibility of this approach was tested in a case study involving two office buildings over a one-month data collection period. By integrating environmental sensor data with worker feedback, they were able to segment workers into specific types, paving the way for the development of a recommendation engine that will be integrated into the platform to assist workers in finding available workspaces that best meet their immediate needs.

While the discussed cases promise to transform existing facilities into intelligent assets that can be managed more efficiently to improve occupant well-being and productivity, ultimately benefiting organisations, Xu et al. (2019) argue that the current “smart building” discourse has been too limited in scope. They propose a more ambitious concept of “cognitive facility management,” envisioning facilities equipped with cognitive capabilities akin to those of humans—such as perceiving, learning, and acting. Alongside this working definition, they present an eight-layer system architecture and a demonstrative scenario to illustrate its potential implementation. Although examples of systems approaching this vision remain limited and in the early stages of development, the full realization of the DT paradigm would inherently enable such advancements. Facilities would not only improve occupant conditions but also understand their behaviours and preferences, learn from feedback, differentiate between individual users and needs, and serve them as an experienced manager, capable of perception, learning, and action.

2.3.2. Making sense of complexity: Semantic Web technologies and occupant-building data integration

A wide variety of reference architectures and technical implementations can be found in the literature to realize DT systems for domain-specific use cases. These approaches aim to create a virtual representation of a target built asset and establish information exchange between the physical and digital environments. This transition involves moving from the static paradigm of BIM data to a dynamic representation, incorporating both static and dynamic data from heterogeneous sources (e.g., sensors, IoT devices, web services, user feedback). As argued by Boje et al. (2022), numerous promising applications have demonstrated that Semantic Web technologies, along with the adoption of a Linked Data (LD) approach, provide a feasible solution for this purpose, enabling DTs to go beyond mere monitoring capabilities and leverage formal data interpretation, thereby realizing Semantic Digital Twins (SDTs).

SDTs employ building information within a formal semantic structure, which can be enriched by linking it with heterogeneous data represented by ontologies (Boje et al., 2020; Eneyew et al., 2022; Mavrokapnidis et al., 2021). Karabulut et al. (2024) conducted a systematic literature review on the role of ontologies in SDTs, emphasizing their importance in enabling the representation of domain knowledge and fostering interoperability across various domains. This view is further supported by Mikołajczyk et al. (2023), whose work focuses on ontological representations in construction-phase SDTs as part of a joint research project involving various stakeholders in Europe.

As a technological foundation for SDTs, the Semantic Web extends the World Wide Web by adding structured, machine-readable data and enhancing resource integration through metadata and ontologies (Hitzler et al., 2010). Ontologies, as defined in computer science, refer to a formal and explicit description of concepts used to capture knowledge about a domain of interest, including its features, attributes, restrictions, and relationships (Horridge, 2011; Noy & McGuinnes, 2001). They enable the exchange of conceptualizations and foster both human and machine understanding within a contextual framework (Hitzler et al., 2010). Linked Data complements the concept of the Semantic Web by establishing a globally interconnected network of accessible data using Uniform Resource Identifiers (URIs) and HTTP protocols as described in the Linked Data fundamentals by Berners-Lee (2006). LD represents a subset of the Semantic Web technology stack and employs Resource Description Framework (RDF)[7] and RDF Schema (RDFS)[8] (Cyganiak et al., 2014; Schneider et al., 2012) for structured representation in a graph-based triple pattern consisting of *subject-predicate-object* statements (Figure 2.8).

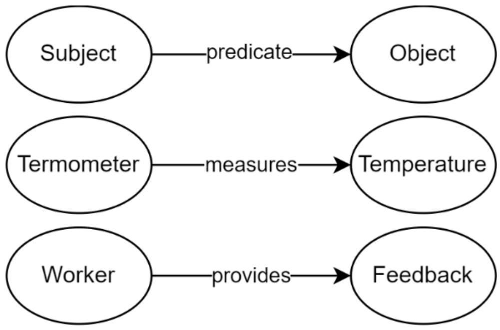

Figure 2.8 RDF graph triple structure and samples.

In an RDF graph, subjects and objects represent nodes, while predicates represent edges. Networks of such entities, uniquely identified using International Resource Identifiers (IRIs), which extend URIs by allowing the use of a wider range of Unicode characters, can be modeled to connect resources and ultimately describe domain knowledge. Using the SPARQL[9] query language, sophisticated searches and data retrieval across linked datasets stored as RDF graphs, also referred to as knowledge graphs, are enabled, allowing for filtering, aggregation, and

[7] https://www.w3.org/TR/rdf11-concepts/ - Accessed 05/05/2025.
[8] https://www.w3.org/TR/rdf11-schema/ - Accessed 05/05/2025.
[9] https://www.w3.org/TR/sparql11-query/ - Accessed 05/05/2025.

sorting. The schema of a knowledge graph is provided in the formalization of ontologies using Web Ontology Language (OWL)[10], which encodes knowledge in ontologies, while RDF graphs contain instance data.

Among other industries, the potential of the Web of Data and LD technologies has also been recognized in the AECO sector (Pauwels et al., 2017). The translation of the Industry Foundation Classes (IFC) open data standard into an OWL ontology, known as ifcOWL[11] (Beetz et al., 2005; Pauwels & Terkaj, 2016), gave impulse to Web-based building information access and exchange. However, fully mirroring the IFC schema has made ifcOWL unnecessarily complex, non-modular, and difficult to extend, hence hindering its application. To address these limitations and drive the standardization of building data representation and exchange on the Web, which is essential for advancing the industry toward interconnected data ecosystems, the buildingSMART Linked Building Data (LBD) Working Group and the W3C Linked Building Data Community Group[12] were subsequently established. These groups have since promoted the development of an ecosystem of smaller, modular, and extensible LBD ontologies that, while interfaceable with IFC, do not rely heavily on it but cover similar concepts. A primary example is the Building Topology Ontology (BOT)[13] (Rasmussen et al., 2017), which defines foundational terms such as “Building”, “Space”, and “Element” and serves as a backbone for spatially describing a building while aligning other domain-specific concepts. Comprehensive overviews of LBD approaches and available ontologies for the built environment are provided by Pauwels et al. (2022) and Farghaly et al. (2023).

Relevant applications have demonstrated the feasibility and benefits of using occupant-aware SDTs to enhance facility management. Donkers, Yang, Vries, et al. (2021) proposed a method that integrates building topology, static properties, and dynamic properties with occupant-perceived building performance using a dedicated ontology, the Building Performance Ontology (BOP)[14]. Building on these results, Donkers et al. (2022a) developed a cross-domain SDT that combined building information, sensor data, weather data, and occupant information and feedback. This implementation featured an algorithm for identifying conditions affecting occupant experience, with findings subsequently incorporated into the system knowledge base, illustrating the potential for supporting occupant-centric decision-making with SDTs. Addressing the inadequate consideration of occupants in the current DT models, Sobhkhiz & El-Diraby (2022) demonstrated the feasibility of integrating building information and occupant-generated data (i.e., work orders) using an LBD approach. Petri et al. (2023) adopted a similar method to develop a performance assessment and management application for industrial buildings, further underscoring the versatility of SDTs.

As highlighted in section 2.3.1, SDT standardization remains a distant goal, with ongoing research gradually addressing diverse use cases, pointing out the need for a modular and flexible approach to SDT deployment. Kosse, Hagedorn, and König (2024) argue that a standardized container environment can be employed as a system capable of connecting to multiple other systems, thus supporting a modular DT structure. Expanding on this, Hagedorn et al. (2024)

[10] https://www.w3.org/OWL/ - Accessed 05/05/2025.
[11] https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2_TC1/OWL# - Accessed 05/05/2025.
[12] https://www.w3.org/community/lbd/ - Accessed 05/05/2025.
[13] https://w3c-lbd-cg.github.io/bot/ - Accessed 05/05/2025.
[14] https://w3id.org/bop - Accessed 05/05/2025.

propose a scalable system-of-systems approach using the Information Container of Linked Document Delivery (ICDD), where compatibility is ensured through adherence to ISO 21597-1:2020. This approach is further advanced into a service-oriented SDT by Kosse, Betker, et al. (2024) and Kosse, Hagedorn, Maibaum, et al. (2024), integrating services into the system-of-systems framework. Service-oriented architectures are similarly explored in the works of Ramonell et al. (2023) and Chamari et al. (2023). The application of ICDD containers as a foundation for SDT deployment is shown in Polter and Scherer (2022) and Zinke et al. (2023). With ICDD supporting the LD approach, it is readily adaptable for communication via established web standards. Moreover, the ontological layer of ICDD allows for enhancing containerized data with formal semantics. Senthilvel and Beetz (2021) further illustrate the potential for nesting and interlinking ICDD containers, enabling a scalable system-of-systems approach for SDTs (Hagedorn et al., 2024).

The literature discussed suggests that while SDTs are technologically capable of advancing the DT paradigm by effectively integrating heterogeneous data into actionable knowledge to support occupant-centric facility management and operations, a robust semantic description of concepts and knowledge across diverse domains in usable ontologies is essential. In their seminal work, Hong et al. formalized energy-related human behaviour in buildings using the four key concepts of Drivers-Needs-Actions-Systems (DNAS framework), aiming to enhance indoor environments while reducing energy consumption (Hong, D'Oca, Taylor-Lange, et al., 2015; Hong, D'Oca, Turner, et al., 2015). Their approach is notable for its focus on the psycho-physiological conditions of occupants distinguishing between an "inside world" of cognitive processes and the "outside world" of the building environment—both of which require careful consideration.

To address gaps in occupant experience modeling in indoor spaces and facilitate reasoning about comfort, Qiu, Schneider, Kauppinen, Rudolph, and Steiger (2018) proposed the Human Comfort in Building (HBC) ontology. While this ontology's capabilities were evaluated in office building use cases, it offers limited workspace representation and does not account for worker activities. Moreover, recognizing occupant behaviour as a significant source of uncertainty in building energy simulation outcomes—and thus in actual operational performance—Chávez-Feria et al. (2020) presented the Occupancy Profile (OP)[15] ontology, a semantic model based on obXML allowing representation of occupant behaviours and actions within building spaces (Hong, D'Oca, Taylor-Lange, et al., 2015).

Given the critical importance of effectively collecting and contextually interpreting both building- and occupant-generated data, further efforts have been directed toward formalizing occupant feedback and its relation to building properties monitored by sensors. Donkers et al., (2022d) introduced the Occupant Feedback Ontology (OFO)[16] to directly integrate feedback with linked building data, demonstrating its potential within an SDT implementation. With a different approach, Ergen et al. (2021) proposed a semantic formalization of occupant feedback in office buildings for integration with BIM data. This schema adopts a problem-oriented approach in which occupants provide feedback at specific building locations, concerning problem sources associated with building spaces or elements. Such an approach

[15] https://bimerr.iot.linkeddata.es/def/occupancy-profile/ - Accessed 05/05/2025.

[16] https://alexdonkers.github.io/ofo/ - Accessed 05/05/2025.

aligns with traditional facility management practices, prioritizing reactive issue resolution over proactive optimisation of indoor spaces to accommodate occupant needs and enhance comfort.

Despite the discussed contributions, a formal knowledge representation capturing occupant conditions in indoor workplaces and enabling monitoring and reasoning capabilities for occupant-centric workplace management purposes is still missing.

2.4. Research gaps

Guided by the defined research questions (§1.2), we first explored the disciplinary scope and factors characterizing the complex ecosystem of indoor workplaces (§2.1, RQ1, RQ3). Subsequently, a focus on the primary actors and pivotal objects of our research—the workers—led to an investigation of well-being, comfort, and productivity dimensions within a work environment, along with the acknowledgement of a necessary paradigm shift from building-centric to occupant-centric perspectives to achieve healthier, more sustainable, and supportive, built environments (§2.2, RQ2, RQ3). Finally, we reviewed state-of-the-art methodological and technological solutions for creating a purposeful virtual representation of the workplace system. This included approaches for collecting, integrating, and analysing heterogeneous data from both the building and its occupants to understand their mutual influences and inform improvement actions (§2.3, RQ3, RQ4, RQ5).

Based on these insights, we identified the following two main research gaps, which the present study aims to address in pursuit of effective solutions:

- *Lack of formal conceptualizations and established methodologies for effectively capturing the worker-activity-workplace fit to enable improvement actions.* Although various methodologies have been investigated to assess occupant conditions within indoor environments for diverse purposes, a widely accepted approach remains lacking. Despite the substantial knowledge on tangible and intangible factors shaping indoor workplaces, predicting worker experiences based on generalized models remains challenging due to the complex, non-linear interactions between objective physical properties and subjective personal factors. Progress has been made in understanding workplace ecology, yet traditional, building-centric management approaches often fall short of meeting occupant expectations, mainly due to limitations in capturing environmental conditions with sufficient temporal and spatial resolution and the inaccuracy of generalized models in forecasting worker comfort or satisfaction. This limitation underscores the need for a formalized, human-centred framework that integrates insights from diverse disciplinary perspectives. Addressing this gap calls for a semantic characterization of the workplace knowledge domain, recognizing cross-correlations among various IEQ factors, and considering a wide range of physical, psychological, social, and organisational factors influencing occupant well-being and productivity. Practically, collecting the necessary subjective worker data requires a shift beyond conventional POE methods toward a more frequent sampling strategy—ideally leveraging emerging technologies to facilitate EMA-based, real-time data collection that accurately captures workers' conditions, perceptions, and preferences.

- *Lack of a dedicated Digital Twin framework and implementation for occupant-centric management of indoor workplaces*. Recent conceptual frameworks and technical implementations have highlighted the potential benefits of DT systems in enhancing the performance and management of existing facilities, particularly by including occupants in the feedback loop. Advances in real-time sensing of physical environments and occupants (e.g., IoT, sensors, wearable and mobile devices), along with methods and tools for accurately describing building information (e.g., BIM) and for formalizing and exchanging domain-specific knowledge (e.g., Semantic Web, Linked Data), are enabling the development of SDTs with knowledge integration and reasoning capabilities. These advances hold promise for a more predictive and adaptive management of the built environment, aligning facility operations more closely with user needs. However, a comprehensive framework and implementation specifically designed to integrate and process both objective building-generated data and subjective occupant-generated data for occupant-centric workplace management is still absent. Achieving effective interoperability and scalability remains challenging, particularly in the vertical and horizontal integration of interconnected systems. In this regard, modular architectures could offer greater flexibility in accommodating evolving use cases and diverse technical implementations, meeting the heterogeneous requirements of diverse organisations.

Together, these two gaps underscore critical opportunities for advancing occupant-centric workplace management through improved data integration and contextual understanding of worker conditions and experiences.

This thesis aims to address these gaps by offering a feasible and effective solution for integrating and contextualizing building- and occupant-generated data, enabling occupant-centric workplace management strategies that enhance worker well-being and productivity. To achieve this, a high-level framework for a Workplace Semantic Digital Twin was developed, followed by its prototypical implementation and evaluation, demonstrating the feasibility of using SDTs to foster occupant-centric approaches that promote worker well-being and productivity in indoor workplace environments.

3

Framework and Methodology

Building on the findings from the literature and aiming to address the identified research gaps, this chapter begins by presenting the research framework of the Workplace Semantic Digital Twin, which is central to this thesis (§3.1). Next, the five research questions guiding the study are introduced and contextualized within the research workflow (§3.2). Specific sections are dedicated to detailing the methodology used to address each key step of the workflow.

True architecture exists only where
man stands in the center.

- Alvar Aalto

3.1. Workplace Semantic Digital Twin framework

To address the identified research gaps and the formulated research questions, this thesis aims at integrating the *Digital Twin paradigm* with an *Occupant-centric approach* for workplace environments. The objective is to develop a system that supports workplace management decision-making, hence enhancing worker well-being and productivity, and optimising workplace environmental conditions and functional organisation. Figure 3.1 illustrates the conceptual framework developed to guide this research, serving as a foundation for addressing the research questions. The framework consists of three sections linked in a continuous cycle of information exchange and actions aimed at the improvement of the worker conditions.

The *physical workplace* is the complex system characterized by dynamic interactions between workers and their environment. This thesis focuses on indoor workplaces, specifically office buildings occupied by *knowledge workers* primarily engaged in intellectual activities (Davenport, 2005). This section of the framework is pivotal, as it serves both as source of information and the object of management decisions and interventions.

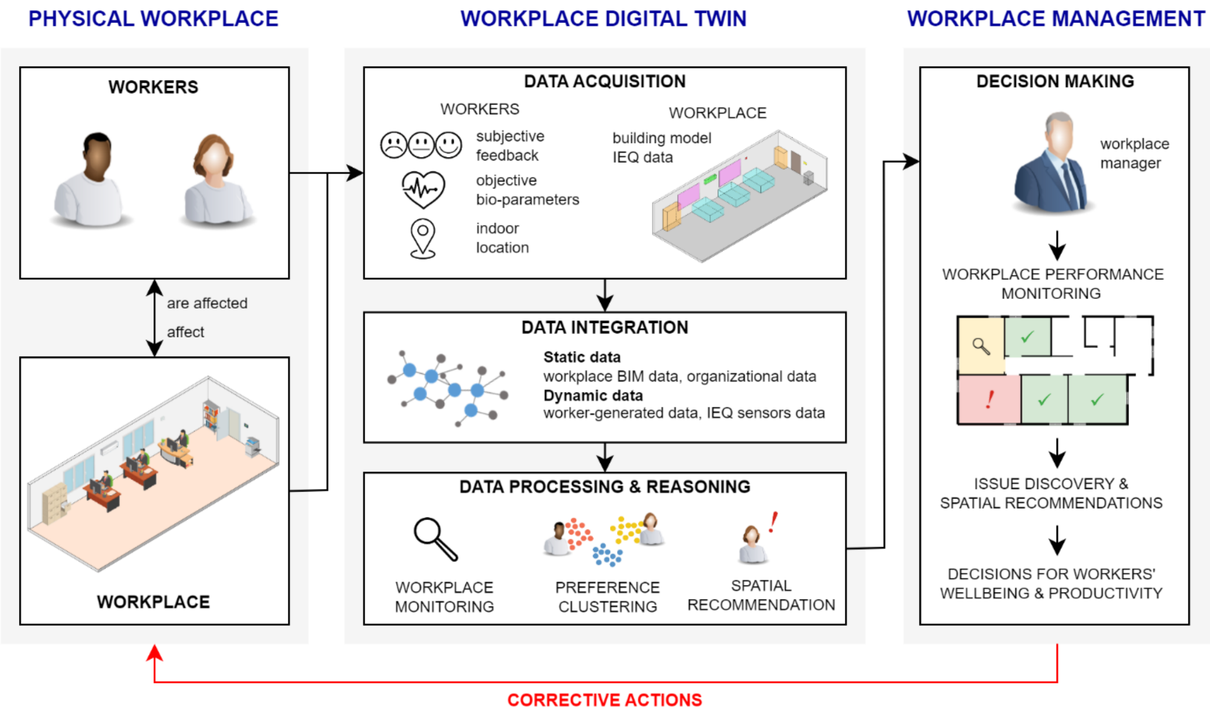

Figure 3.1 Semantic Digital Twin framework for occupant-centric workplace management.

Moving to the centre of the framework, the *Workplace Digital Twin* consists in the digital representation of this physical system, including its components and the dynamic evolution of their properties and relationships. This concept refers to a system that collects heterogeneous data from the physical workplace (*data acquisition*), integrates them into a coherent structure (*data integration*), and provides computational tools (*data processing and reasoning*) to support workplace management decision-making. The data required to realize and constantly update the workplace digital counterpart are categorized into two main groups: *worker data* and *workplace data*.

Worker data includes the information needed to describe the worker experience in the workplace. This includes both “static” data, such as employment details and demographics, typically stored in organisational databases or human resource management systems, and “dynamic” data, which capture the workers’ changing objective and subjective conditions over time. This research focuses on dynamic data, as it is essential for a granular understanding of workplace operational conditions from an occupant-centric perspective. Objective data includes worker location within the workplace, which is always necessary for workplace data correlation, and physiological parameters (e.g., heart rate), when dedicated wearables or mobile devices are implemented. Subjective data encompasses workers’ perceptions, both inward -self-assessed personal conditions (e.g., concentration level) - and outward - satisfaction with the surrounding environment (e.g., preference).

Workplace data pertains to the geometrical, functional, and physical properties of the building’s indoor environments that are occupied by workers. These include “static” data, such as the building’s 3D geometry, the properties of its components and systems (e.g., sensors and actuators), and functional properties like room identifiers, furniture, and equipment configuration, which change infrequently based on organisational needs. This information can be effectively stored within BIM models, which also include the topological relationships among spaces and components, facilitating the linking of other heterogeneous data. To leverage the integration of building and worker data, real-time 'dynamic' data on the operational properties of the workplace and indoor environmental quality (IEQ) conditions must be continuously collected. Depending on managerial requirements, sensors can be installed at various locations to capture this data at sufficient resolution.

Beyond data collection, the second challenge in realizing the Workplace Digital Twin lies in data integration. To transform this diverse data into actionable knowledge about the workplace, relationships between pieces of information must be established and organised into a meaningful formal structure that is both machine-readable and interpretable by humans. This structured knowledge enables the application of data processing and reasoning algorithms, which form the basis of services and functions that support decision-making.

The Workplace Digital Twin offers a granular understanding of workplace performance in relation to the specific needs and expectations of its employees, beyond the basic compliance with general comfort thresholds typical of building-centric approaches that overlook occupant feedback. Managers can use it to monitor real-time and historical workplace conditions, analyse workers feedback, and detect hidden issues or causes of dissatisfaction. Furthermore, proactive management strategies can be implemented by applying clustering algorithms to worker preferences and corresponding environmental conditions. Based on identified worker profiles, the system can recommend optimal workspace allocation to better align with individual preferences. Ultimately, the Digital Twin provides workplace managers with access to knowledge and actionable insights, enabling them to make better-informed decisions that impact the physical workplace.

While recent industry and academic trends define a Digital Twin as involving automatic and real-time information exchange between the physical and digital components, this thesis aligns with the concept of mutual interaction underlying that definition while emphasizing the crucial role of human decision-making. In this framework, the exchange of information and actions between the two system components is mediated by the workplace manager, who interprets the insights provided by the Digital Twin. Although a high level of automation is foreseen to enhance the value derived from the system, the manager, as a human agent, remains responsible for making decisions that significantly impact employee well-being and productivity - decisions that cannot be delegated to automated systems alone.

The following section describes the challenges encountered and the methodology adopted in developing the Workplace Digital Twin at the core of the discussed framework.

3.2. Research workflow and methodology

As illustrated in Figure 3.2, five research questions (RQs) were formulated to guide this study in the realization of the conceptualized Workplace Semantic Digital Twin:

RQ1: *What are the key factors that characterize an indoor workplace environment?*

RQ2: *What are the key factors that affect worker well-being and productivity in an indoor workplace environment?*

RQ3: *What methods or tools can be used to collect data on worker and workplace environmental factors?*

RQ4: *How can worker data and building environmental data be integrated to provide actionable workplace knowledge?*

RQ5: *How can integrated worker-building knowledge be applied to enhance workplace management and decision-making?*

The first two research questions (RQ1 and RQ2) focus on characterizing the complex nature of indoor workplaces by identifying key factors relevant to describe both the environment and the occupant experience over time. Although the concept of a "workplace" may seem straightforward, defining it in a way that extends beyond common interpretations and is not confined solely to building science posed a challenge. A multidisciplinary approach, which also considered human and social domains, was required due to our occupant-centric perspective. For this reason, the literature related to Facility Management was reviewed and the "workplace" standard definition provided by the ISO 41011:2024 was adopted, which informed the specification of its knowledge into three primary domains: building (physical environment), worker (occupant and agent), and activity (work).

In addition, a review of studies related to building comfort—specifically within workplace environments—highlighted key areas (e.g., spatial organisation, thermal quality) and factors (e.g., social density, air temperature) that characterize the quality of indoor workplaces. Concepts related to worker comfort, satisfaction, and activity were also examined to understand the physical, psychological, functional, and social dimensions that influence worker well-being and productivity.

While defining a comprehensive taxonomy of these factors is beyond the scope of this thesis, this exploration shaped the structure and sources of workplace knowledge domains. For example, the impact of spatial and physical characteristics of the environment on workers' perceptions suggested the opportunity to leverage BIM data. Similarly, the need to gather and interpret workers' individual experiences necessitated the investigation of methods for collecting and monitoring worker data alongside key environmental properties.

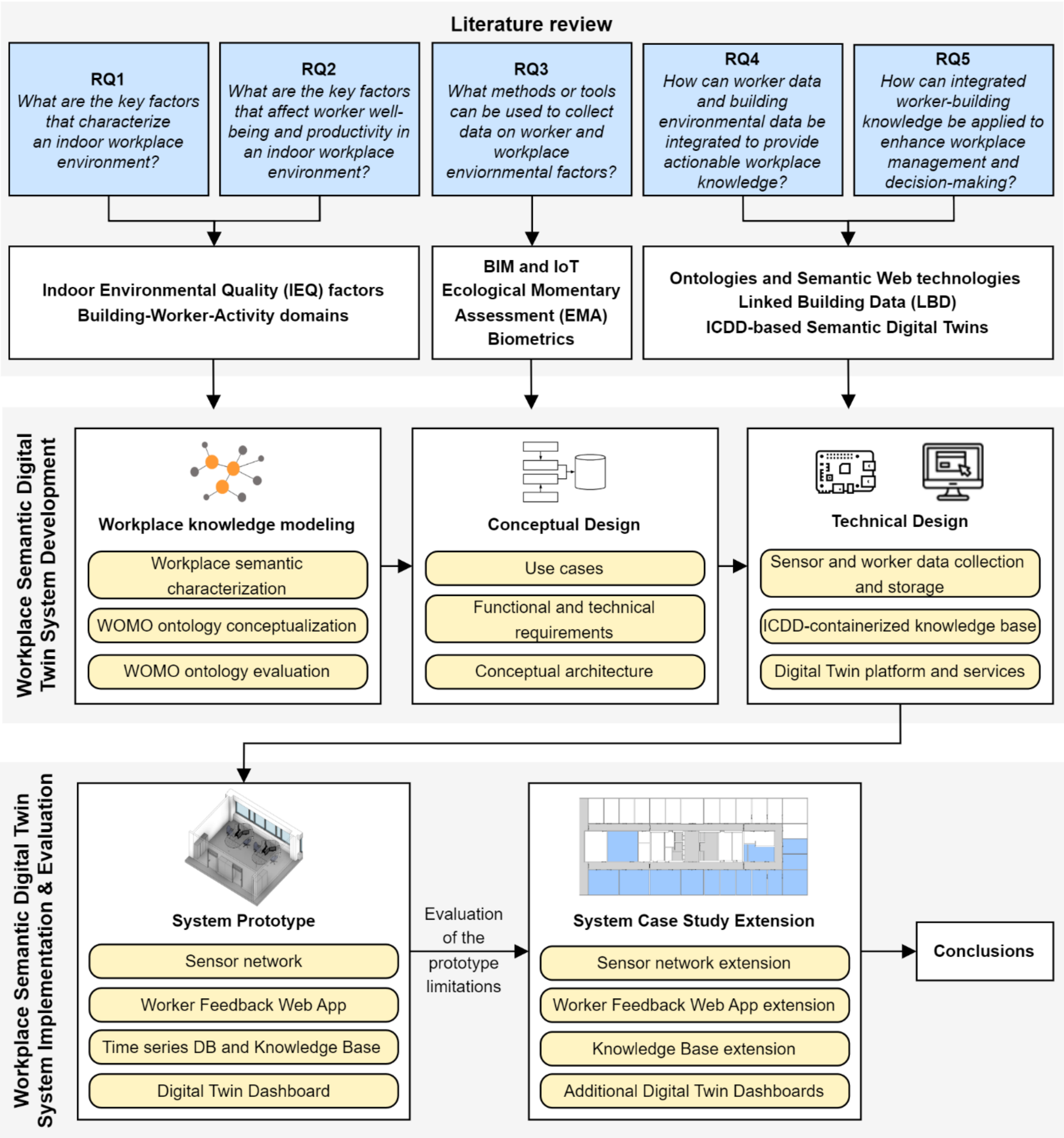

Figure 3.2 Research workflow and methodology.

Following the identification of factors characterizing the workplace environment and their influence on workers' experience and perceptions, RQ3 explored methods and technical solutions for gathering such heterogeneous information. Numerous studies and applications have confirmed that integrating BIM with IoT and sensor technologies offers a viable and effective solution for monitoring and representing the physical and operational aspects of an indoor workplace. However, capturing the experience of the occupants presents challenges beyond the building science domain and requires a multidisciplinary perspective that includes human and social sciences.

While a wide range of environmental and worker-related conditions can be reliably measured through sensors, wearables, and mobile devices, correlating this data with worker well-being and productivity remains difficult to generalize. The influence of individual physiological and psychological factors, along with the social dimension of workplace environments involving continuous direct and indirect interaction among employees is acknowledged and requires the collection and interpretation of workers subjective data.

This study reviewed findings from diverse methods. Indirect methods, such as monitoring coping mechanisms, collecting physiological data, and using computer vision techniques, provide only partial information and have significant limitations. For example, tracking window-opening patterns might indicate actions to improve an unsatisfactory office environment, but it would remain unclear whether the issue was air quality or thermal comfort, as well as the impact on occupants' satisfaction. Despite the growing consumer wearable market (e.g., smartwatch) providing more affordable and unobtrusive devices to monitor physiological conditions (e.g., heart rate), reliable models to correlate this data with specific psychological states are still lacking, while processing and storing such sensitive health-related information presents privacy concerns. Moreover, facial and posture recognition techniques have shown promising results in monitoring workers' moods, sensations, and activities. However, beyond research purposes, privacy concerns related to continuous video monitoring present critical barriers to real-world application.

For these reasons, direct methods, particularly the use of established post-occupancy evaluation (POE) approaches via questionnaire surveys, have been identified as the primary means of gathering workers' data. Specifically, the need to interpret workers' subjective feedback in relation to contextual environmental conditions has led to the adoption of the ecological momentary assessment (EMA) method. Frequently used in other domains (e.g., clinical psychology), the EMA method utilizes short surveys, usually graded with Likert scale questions, timely administered to the monitored participants in their current environment, making it suitable for the semi-quantitative analysis of occupant experiences.

Regardless of the specific methodology adopted, the collection and processing of data describing workers' personal conditions and experiences over time and space remain central to an occupant-centric approach to workplace management. However, this reliance on personal data raises critical ethical concerns, particularly regarding privacy, consent, and the potential misuse of sensitive information. Ensuring the ethical collection, storage, and processing of such data is essential for both the legitimacy and acceptability of occupant-centric systems.

In this study, all personal data used during the implementation of the system prototype (see section 6.3) were collected following informed consent from case study participants, with clear communication regarding data usage, storage duration, and anonymity measures. Nevertheless, beyond compliance with standard consent procedures, broader ethical considerations—including data ownership, long-term privacy risks, and the potential for unintended surveillance—must be acknowledged. These concerns highlight the need for stringent data governance frameworks that ensure transparency, grant users control over their personal data, and mitigate the risk of workplace monitoring being perceived as intrusive.

In the European Union (EU), several regulations and frameworks address these ethical concerns. The General Data Protection Regulation (EPCEU, 2016) establishes principles of fairness, transparency, data minimization, and purpose limitation to govern the processing of personal data. The more recent Data Governance Act (EPCEU, 2022) poses conditions for the re-use of data held by public sector bodies while ensuring respect for individuals' rights and fostering trust. Furthermore, with the introduction of the Artificial Intelligence Act (EPCEU, 2024), the EU has placed a particular focus on ensuring that AI systems used within its jurisdiction are safe, transparent, and aligned with fundamental rights, especially concerning the processing of personal data.

A detailed examination of these aspects falls beyond the scope of this thesis but remains a crucial focus for future research, as ethical data management represents a fundamental requirement for the deployment of the proposed system in real-world applications.

The final two research questions address the major conceptual and technical challenges in developing a system to support workplace management decision-making: integrating heterogeneous workplace and worker data (e.g., static/dynamic, objective/subjective) and extracting insights to align workplace conditions with occupants' specific needs and preferences. To address RQ4, we investigated data integration and knowledge representation in the AECO sector, identifying ontologies and semantic web technologies as effective open solutions to overcome the limitations of proprietary BIM-based building monitoring platforms.

In knowledge engineering, an "ontology" is a formal, machine-readable data representation that describes knowledge within specific domains, providing a vocabulary for key concepts and their relationships. Domain knowledge, serialized in subject-predicate-object triples according to the Resource Description Framework (RDF)[17] standard, can be interchanged on the web and stored in directed graphs known as knowledge graphs. The Linked Building Data (LBD) Community Group[18], a recognized community of scholars and professionals, develops and shares open resources, such as ontologies and tools, to promote these principles within the construction sector, fostering the integration of building information with data from diverse sources and thereby improving information management throughout the building lifecycle.

In this thesis, an LBD approach is adopted to develop the Occupant-centric Workplace Management Ontology (WOMO) to address the identified lack of suitable data models for the semantic integration of building and worker data. Workplace knowledge is organised into a modular structure that includes the definition of original concepts, properties, and relationships, which were integrated with those of established ontologies (e.g., BOT, SSN/SOSA) specialized in describing the building domain. It is important to note that the developed ontology does not aim to exhaustively capture the full complexity of specific sub-domains; rather, it provides a flexible framework that can be further enriched by integrating specialized ontologies or through additional investigations in future work. This approach ensures flexibility to extend the workplace knowledge description both vertically, by detailing the concepts within a specific domain, and horizontally, by being open to the integration of additional ontologies to adapt to evolving use cases and future requirements.

However, the development of the ontology alone could not resolve the remaining technical challenges related to creating and managing the system's semantic knowledge base. For this

[17] https://www.w3.org/RDF/ - Accessed 05/05/2025.
[18] https://www.w3.org/community/lbd/ - Accessed 05/05/2025.

reason, a particular type of information container, the Information Container for Linked Document Delivery (ICDD) defined in the standard ISO 21597-1 (2020), was chosen for its ability to store and semantically interlink both documents (e.g., IFC models, spreadsheets) and their contents according to predefined ontologies.

Finally, RQ5 focuses on extracting value from the insights obtained by semantically integrating workplace and workers knowledge. Specifically, the decision to store and manage the workplace knowledge base using an ICDD-container-based approach was supported by the adoption of a dedicated web platform previously developed at the Chair of Computing in Engineering at Ruhr University Bochum[19] (Hagedorn, 2022). The platform's capacity to store, query, process, and visualize semantic construction data was extensively tested and validated through various previous case studies, including the rule-based semantic validation of linked building models (Hagedorn & König, 2021), infrastructure asset management (Hagedorn, Liu, et al., 2023), and ontology-driven linking and validation of heterogeneous data (Hagedorn, Senthilvel, et al., 2023).

Building on the successful application of this platform in these contexts, further developments have facilitated the definition of Semantic Digital Twin architectures based on a System-of-Systems approach (Hagedorn et al., 2024) which aims to enable the forthcoming Industry 4.0 paradigm in the construction sector (Kosse, Betker, et al., 2024). The Workplace Semantic Digital Twin architecture, which will be discussed later in this thesis, relies on the adoption and customization of the mentioned ICDD platform to suit occupant-centric workplace management use cases identified in this research.

3.2.1. Workplace Knowledge Modeling

Addressing the challenge posed by the semantic integration of highly heterogeneous worker and workplace data (e.g., BIM, IEQ sensors, occupant subjective feedback and objective measurements) is central to the proposed Workplace Digital Twin framework. This integration must take into account the specific requirements of the adopted data acquisition and processing strategies. Therefore, an ontological approach was chosen to formalize knowledge related to occupant-centric workplace management use cases, given its flexibility, scalability, and support for semantic reasoning. Considering the identified lack of suitable data models for our purpose, workplace knowledge was modelled into the Occupant-centric Workplace Management Ontology (WOMO), described in Chapter 4, proceeding through the following three steps:

1) *Workplace semantic characterization*: The literature review highlighted the challenges involved in the characterization of the complex human-building ecosystem constituted by a "workplace". As a preliminary step toward its conceptualization, a coherent semantic definition of its constituent domains was necessary. To achieve this, the standard definition of "workplace" from the Facility Management discipline (ISO 41011:2024) was selected for its effectiveness. This definition was broken down and further specified as the intersection of three principal knowledge domains: building (physical location), human (occupant), and activity (work).
2) *WOMO ontology conceptualization:* While the application of knowledge engineering to the AECO sector is relatively recent, a common ground in ontology modeling principles

[19] RUB ICDD Platform - https://icdd.vm.rub.de/ui - Accessed 05/05/2025.

can be observed across the different methodologies developed over time. In this thesis, the ontology development followed a structured approach, drawing on both long-established framework, such as METHONTOLOGY (Fernandez, Gómez-Pérez, & Juristo, 1997) and more recent approaches, such as the Linked Open Terms (LOT) methodology (Poveda-Villalón, Fernández-Izquierdo, Fernández-López, & García-Castro, 2022). The first step involved defining the scope and purpose of the ontology, along with identifying target use cases, supported by practical examples. This was followed by determining the functional requirements, specifying the capabilities needed for the ontology to address these use cases, and considering its integration with the intended system. Next, a set of competency questions in natural language was formulated to guide and validate the ontology's development. Additionally, the ontology's relationship with established data schemas (e.g., IFC) was considered, alongside its integration with existing ontologies used in LBD applications. Specifically, two ontologies were reused to represent the building and sensor domains relevant to the physical workplace: the Building Topology Ontology (BOT)[20], and the Semantic Sensor Network ontology (SSN)[21]. To ensure flexibility for future iterations and additional use cases, the ontology was structured into four conceptual modules representing the three main workplace knowledge domains—workspace (spatial), worker (human), and activity (work)—along with an additional feedback module, which is crucial for integrating data across these domains. As will be further detailed in Chapter 4, this modular structure supports the ontology's adaptability. Finally, for the formalization of the WOMO ontology's concepts and relationships, the Web Ontology Language (OWL[22]) was chosen due to its widespread adoption within the W3C's Semantic Web technology stack, including RDF[23], RDFS[24], SPARQL[25].

3) *WOMO ontology evaluation:* Before deployment and integration within the intended system, the ontology's capabilities were evaluated by querying the specified competency questions on a demonstrative dataset. Additionally, potential future extensions of the ontology and its integration with other specialized ontologies are discussed to guide further developments (see section 4.8).

3.2.2. System development

Complementary to modeling the workplace knowledge into an ontological structure serving the semantic integration of building and worker data, the conceptual and technical aspects of the remaining system components were developed to address the data collection and processing capabilities within the Workplace Semantic Digital Twin framework according to the workflow shown in Figure 3.3.

The system's conceptual design began with the identification of three main use case areas, derived from the framework's overarching goal and aligned with the WOMO ontology: workplace performance assessment, workplace issue discovery, and worker preference

[20] https://w3c-lbd-cg.github.io/bot/ - Accessed 05/05/2025.
[21] https://www.w3.org/TR/vocab-ssn/ - Accessed 05/05/2025.
[22] https://www.w3.org/OWL/ - Accessed 05/05/2025.
[23] https://www.w3.org/TR/rdf11-concepts/ - Accessed 05/05/2025.
[24] https://www.w3.org/TR/rdf11-schema/ - Accessed 05/05/2025.
[25] https://www.w3.org/TR/sparql11-query/ - Accessed 05/05/2025.

clustering and recommendation. These use cases informed the conceptualization of the WSDT system's requirements, which were distinguished into *functional* and *technical* requirements, adapting the paradigm proposed by Boje et al. (2022) for DTs for the built environment.

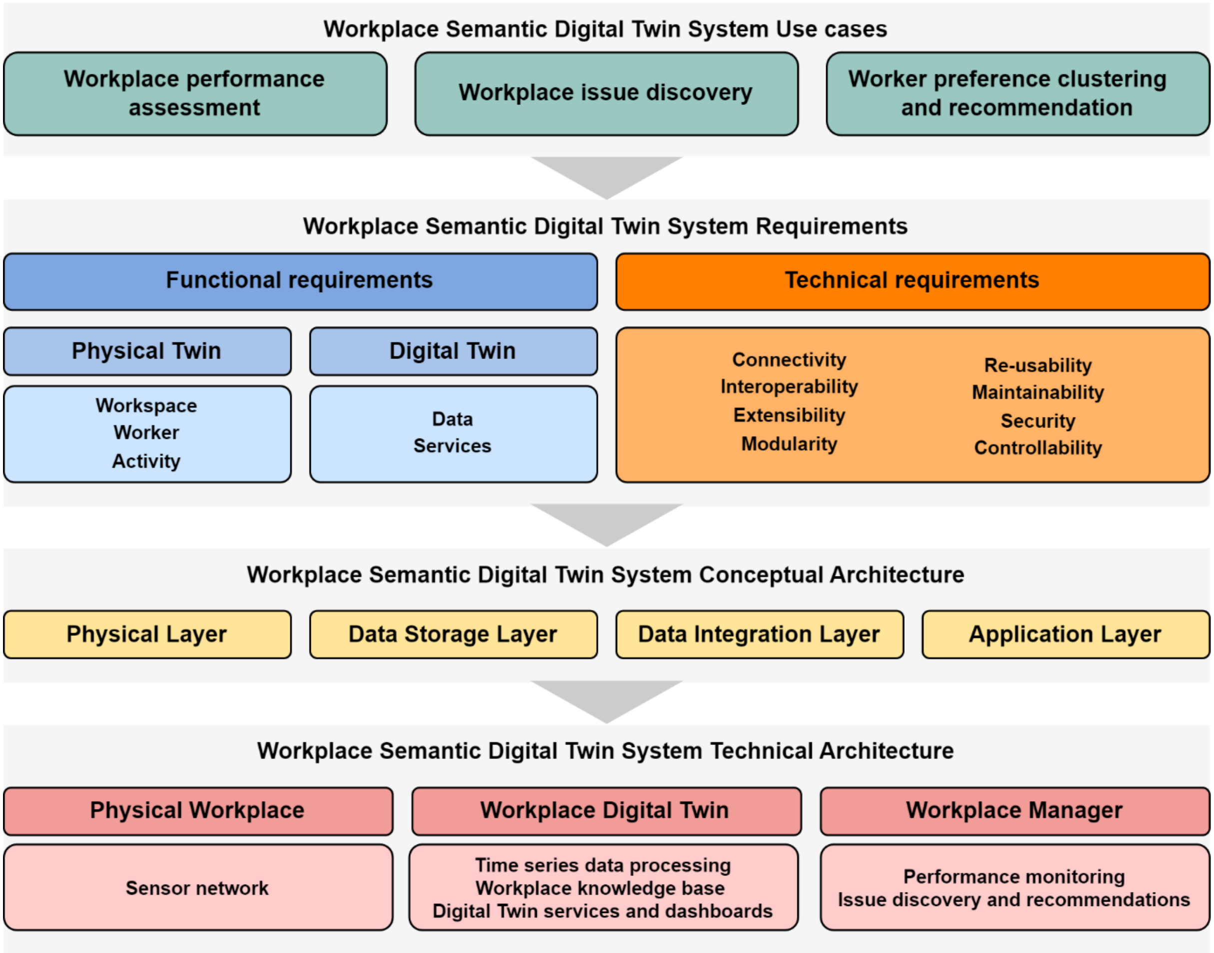

Figure 3.3 Workplace Semantic Digital Twin system development stack.

Functional requirements refer to the system's ability to collect and exchange data between the physical workplace and its digital counterpart, as well as to support core functions that address the identified use cases. This includes the system's sensing and monitoring capabilities, which supply data to be stored, processed, and visualized in order to enable decision-support services for managers. On the other hand, technical requirements pertain to the technological solutions necessary for deploying and maintaining the system's functions effectively.

Building on the identified use cases and requirements, the conceptual architecture of the WSDT system is structure into a four-layer schema that encompasses the physical workplace, data storage, data integration, and the data processing services to support workplace management and decision-making applications. The physical layer integrates conventional IEQ monitoring approaches with the collection of both objective worker properties (i.e., location, physiological data) and subjective feedback regarding their momentary preferences and perceived conditions. The data storage layer addresses challenges related to storing heterogeneous workplace data, ranging from static building and organisational information to time series data streamed by sensors and monitoring devices. The data integration layer focuses on interlinking and extracting valuable information from the stored data, ultimately supplying the processing and visualization services designed to support workplace managers in their decision-making.

This high-level schema concludes the system's conceptualization and guides both the technical architecture and system implementation discussed in this thesis, while also providing a flexible framework for different implementations and future developments. Starting with the monitoring of physical workplace conditions, suitable sensor network technology and infrastructure were selected from the literature based on feasibility criteria relevant to real-world applications. These criteria prioritized mature and commercially available solutions, considering factors such as device cost, reliability for smart-building applications, flexibility and scalability of deployment, and minimal intrusiveness to existing building systems or resources.

For the software infrastructure and data management strategies supporting the Digital Twin system, two major aspects were addressed: the integration of static workplace information with dynamic sensor observations and occupant feedback, and the implementation of data processing and visualization services to support workplace management use cases. For the former, distinct solutions were adopted for handling time-series data and workplace semantic knowledge. Commercial time-series database platforms were considered to handle the incoming IEQ sensor data and occupant feedback, leveraging their ability to gather, store, and process data from various sources. To enable worker data collection, a single-page survey web application was developed, allowing workers to provide momentary feedback on their preferences and perceived conditions via browser from their workstations. Meanwhile, the workplace knowledge base was constructed using the WOMO ontology by integrating heterogeneous data within ICDD containers, which were then linked to the time-series database to supply dynamic information on demand. For this purpose, the previously mentioned RUB ICDD platform[26] (Hagedorn, 2022) was chosen for its proven capabilities in semantic data processing and visualization. The platform's services were tailored and presented through dedicated dashboard interfaces to support workplace management use cases effectively.

3.2.3. System implementation and evaluation

To evaluate the suitability of the developed WSDT conceptual and technical architecture in achieving the goals of the Workplace Digital Twin framework, the system was implemented in two iterative phases, as shown in Figure 3.4. In the first phase, a minimal viable prototype was deployed, incorporating sensor network installation, worker feedback collection, dynamic data gathering through a time series database, the construction of the workplace knowledge base using an ICDD-container-based solution, and the development of customized ICDD platform services integrated within Digital Twin dashboards for a specific use case (see Chapter 6). This initial implementation was carried out in a shared office room at the Chair of Computing in Engineering at the Ruhr University Bochum, involving four employees over a one-week data collection period. The prototype was evaluated, and the issues encountered were discussed in the context of the system's current limitations.

Building on the lessons learned, the second phase focused on scaling up the prototype to extend its application to the entire Computing in Engineering department (see Chapter 7). In

[26] RUB ICDD Platform - https://icdd.vm.rub.de/ui - Accessed 05/05/2025.

this extension, the sensor network was expanded, and the configuration of the time series database and knowledge base was reorganized—transitioning from a single ICDD container for the prototype room to a multi-container solution suitable for multiple workspaces. Additionally, at a conceptual level, further survey items for the worker feedback application and enhanced Digital Twin dashboard functionalities were developed to address a broader set of use cases. The full implementation of these conceptual enhancements is deferred to future work.

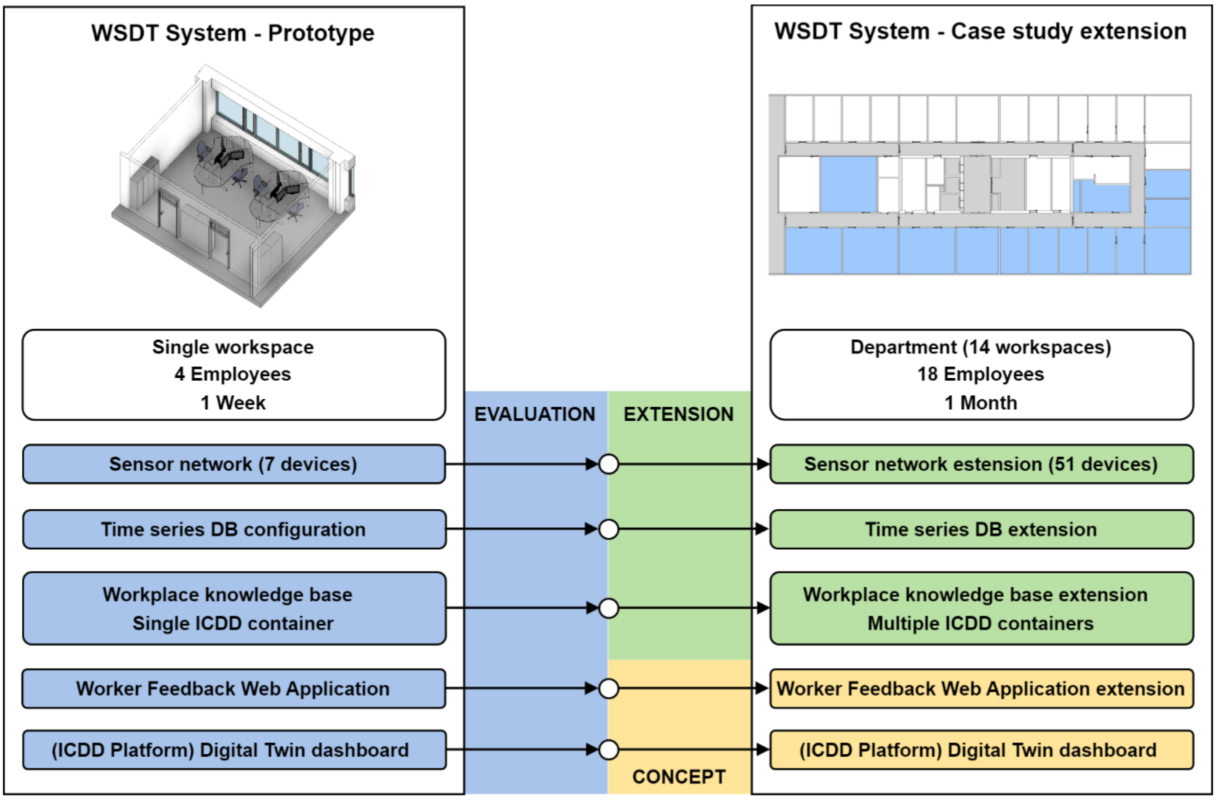

Figure 3.4 Workplace Semantic Digital Twin system implementations: prototype and case study extension.

Given the limitations observed in the prototype system, a comprehensive evaluation campaign of the extended system at a department scale is a major priority for future developments. Such an evaluation should not only examine the technical robustness and performance of the system but also assess its usability and overall perceived value. In particular, it will be critical to evaluate how the system is received by both workers and workplace managers, ensuring that technology meets practical needs and enhances decision-making in a real-world setting.

4

Occupant-centric Workplace Management Ontology

This chapter introduces the development of an ontology aimed at representing the semantic structure of heterogeneous workplace data. The first section offers a detailed characterization of workplace domains, establishing the foundational concepts and relationships (§4.1). Following this, the ontology requirements specification is outlined, including the scope and purpose (§4.2), use cases (§4.3), functional requirements (§4.4), and competency questions (§4.5) that guide the ontology's design. An overview of the ontology's structure and its modularization is then provided (§4.6). Subsequent sections delve into the specific modules of the ontology: the workspace module, the worker module, the activity module, and the feedback module. Each module is discussed in terms of its role and significance within the overall framework. Additionally, the ontology capabilities and data patterns are evaluated with a demonstrative dataset (§4.7). Finally, the integration of the ontology with other systems and datasets is explored, highlighting the ontology's adaptability and potential for extension (§4.8).

I liked the idea that a piece of information is really defined only by what it's related to, and how it's related. There really is little else to meaning. The structure is everything.

-Tim Berners-Lee (1999)

4.1. Workplace semantic characterization

"Ontology" has many definitions in the knowledge-engineering literature. In this dissertation, drawing from Noy & McGuinnes (2001) and Horridge (2011), the term "ontology" refers to a formal and explicit description of concepts used to capture knowledge about a domain of interest, along with its features, attributes, restrictions, and relationships.

Our domain of interest is the "workplace". The definition of "workplace" varies depending on the disciplinary perspective and intended purposes. Therefore, to develop the ontology presented in this chapter, it was necessary to choose a specific definition to establish a coherent semantic foundation for this complex physical system. To align with the scope of this research, the comprehensive, acknowledged, yet flexible definition of "workplace" (a),

"physical location where work is performed" (a)

adopted in the standard ISO 41011:2024 Facility Management – Vocabulary (ISO 41011:2024) was chosen and further specified.

This definition is broken down into three semantic domains (Figure 4.1): the spatial domain (*where*); the functional domain (*what*); and the operational domain (*who*). The set of functions and activities that characterize the day-to-day routine of the workplaces within our scope can be effectively captured by the term "work". Meanwhile, additional constraints are needed for the spatial and operational domains. Specifically, the physical location where work is performed is limited to an indoor building environment, and only human occupants are considered as agents. Therefore, the definition adopted for our purposes becomes:

*"**building location** where work is performed **by the occupants**"* (b).

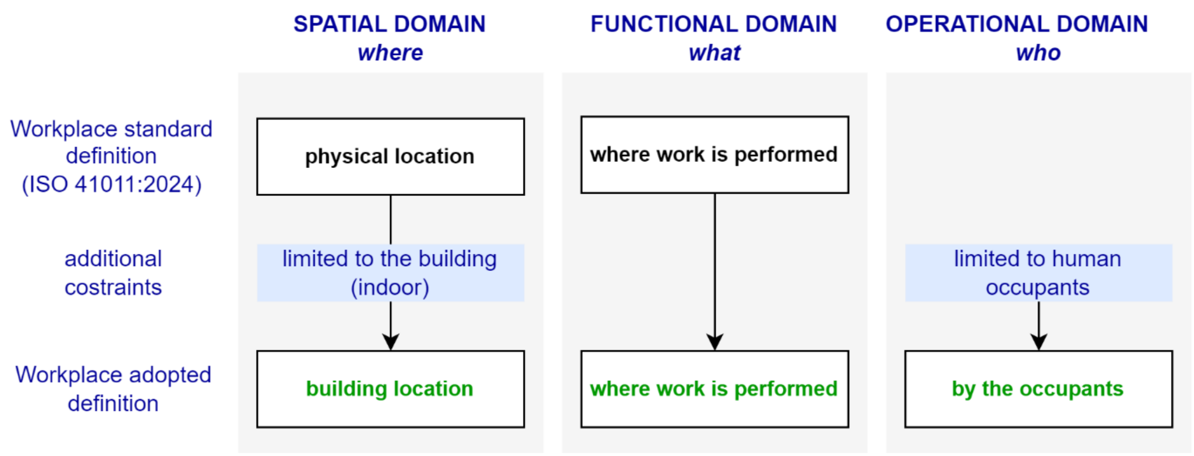

Figure 4.1 Workplace definition specification.

As shown in (Figure 4.2), this represents the semantic intersection of three domains - *building*, *human*, and *activity* – which can be specified as follows:

- *Building domain* – Building elements and spaces with their physical and conceptual characteristics (e.g., window geometry and materials; measured noise level in a space; space type and function).

- *Human domain* – Human individuals temporarily occupying a certain building space and performing work or a work-related activity.
- *Activity domain* – Activities or tasks performed by occupants as part of their working routine, including all supporting activities carried out within the workplace (e.g., lunch and breaks).

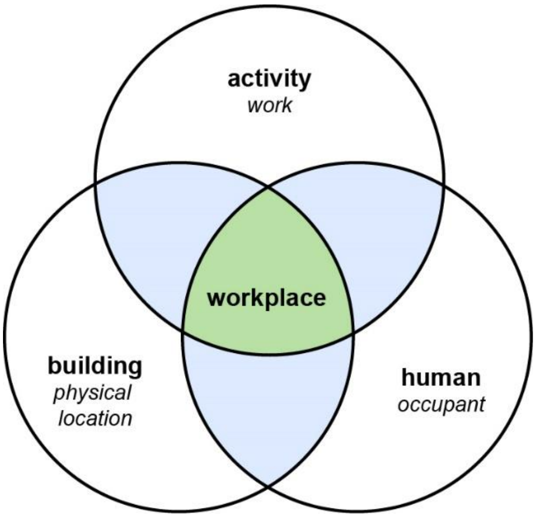

Figure 4.2 Workplace knowledge domains (Venn diagram).

With reference to the light blue areas shown above, it is worth noting that any intersection of just two of the cited domains falls outside our field of interest. In this study, the following are not considered: non-working occupants and temporary building users (human + building); outdoor workplaces (human + activity); and indoor spaces where work is carried out mainly by machines or systems, with human intervention being episodic and not continuous (building + activity).

4.2. Scope and purpose

In the previous paragraph, a high-level workplace definition was provided, encompassing all possible configurations of indoor workplaces, from factories to tertiary activities. As discussed in section 3.1, this dissertation focuses on a subset of workplaces: *offices* where *knowledge workers* (Davenport, 2005) carry out office work. These workers' daily routines are characterized by intellectual tasks and social interactions, with negligible physical strain. Adopting an occupant-centric perspective, Table 4.1 reports the elements included and excluded in the scope of the ontology for each domain within this ecosystem. Social activities, breaks, and support spaces are also considered due to their significant role in workers' well-being and productivity.

Following the domain specifications, the ontology's purpose aligns with the research framework's overarching goal: to support managers' decisions by providing insights derived from the timely correlation of subjective and objective workers' data and workplace conditions. As discussed in the following paragraph, this goal is further broken down into three main use cases, each aimed at improving the decision-making process through our data-driven approach.

Table 4.1 Specification of the scope of the ontology domains.

Domain / Scope	Office (workplace)		
	Building (spaces)	**Activity**	**Occupant**
In	• **Workspaces** Single office, shared office, conference room, open space area, laboratory, etc. • **Support spaces** Kitchen, entrance, common spaces, etc.	• **Work** All work-related activities carried out by the workers as part of their job: solo work, group work, meetings, etc. • **Break** Breaks, lunch, social interactions, etc.	• **Workers** Occupants who spend the main part of their work time within the workplace, usually having an allocated workspace and/or workstation; knowledge workers.
Out	• **Technical or service spaces** All spaces with only episodic worker presence: restrooms, server room, closets, etc.	• **Transfer** From one workspace to another: corridors, stairs, elevators, are considered as workplace elements, but not as recipients for the activities of interest.	• **Auxiliary staff** Cleaning, repair, maintenance, etc. • **Building users** All occupants who temporarily visit the workplace: public, customers, users, etc.

4.3. Use cases

The ontology is designed to inform the decision-making process and provide actionable insights for the day-to-day activities of workplace managers in relation to three main use cases: *workplace performance assessment*, *workplace issue discovery*, and *worker preference clustering and recommendation* (Figure 4.3). As discussed below, these use cases require an incremental level of correlation between worker- and building-generated data.

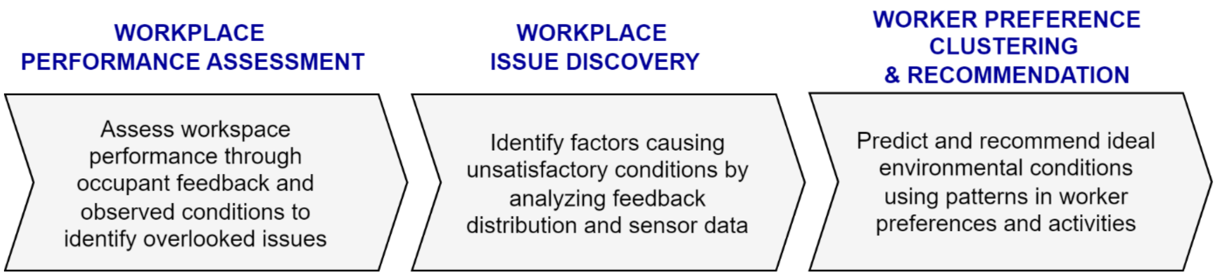

Figure 4.3 Ontology use cases.

4.3.1. Workplace performance assessment

Workplace performance assessment involves quantifying a workplace's ability to meet the needs of workers and the requirements of the organisation's core business. This requires correlating worker and workspace conditions across various spatial or organisational scales, collecting indoor environmental properties (e.g., air temperature, occupancy count) via sensors, and integrating this data with worker objective (e.g., location, physiological parameters) and subjective information (e.g., feedback). The workplace performance assessment use case is divided into three specific areas:

- *Environmental comfort* – This area focuses on monitoring and evaluating workplace performance based on worker satisfaction with indoor environmental quality. By analysing trends in worker preferences and correlating them with observed physical properties, suboptimal environments can be identified, leading to corrective actions to improve workspace conditions.

- *Activity support* – This area assesses workplace performance in terms of workspace usage and its alignment with designated functions and activities. By examining the distribution of activity types and social interactions, potential issues can be identified, informing organisational actions to enhance activity support.
- *Worker support* – This area evaluates workplace performance based on worker self-assessed conditions such as productivity and concentration. By analysing the distribution of worker conditions in relation to their activities and contextual environmental properties, underperforming workspaces can be identified, guiding corrective actions.

Examples of these specific areas are provided in the following Table 4.2.

Table 4.2 Examples for use case: 1 - Workplace performance assessment.

Workplace performance assessment - Environmental comfort ***Satisfaction with acoustic quality***	
Goal	**Assessing workers' satisfaction with the acoustic quality of a workspace.**
Required data	Worker feedback time and location (workspace). Worker momentary preference (feedback) about the perceived acoustic quality of a workspace.
Data processing	Feedback data is queried and visualized based on: - spatial criteria (specific workspace or group of workspaces); - temporal criteria (specific time frame).
Result	Overview of the workplace performance in terms of perceived acoustic quality of the monitored workspaces.
Corrective actions	- further analyse available data (see "Workplace issue discovery use case"); - remove or mitigate known sources of noise (e.g., change noisy piece of equipment); - change the workspace characteristics, configuration, and/or designated activities; - change workers' allocation (workspace or workstation).
Workplace performance assessment – Environmental comfort ***Preferred thermal conditions***	
Goal	**Assessing which thermal conditions correspond to workers' preferences.**
Required data	Worker feedback time and location (workspace). Worker momentary preference (feedback) about the perceived thermal quality of a workspace. Sensor observations of workspace environmental properties correlated with thermal comfort (e.g., air temperature, relative humidity, etc).
Data processing	Worker feedback about thermal quality preference is queried and visualized in relation to: - spatial criteria (specific workspace or group of workspaces); - temporal criteria (specific time frame); - values of workspace observable properties such as air temperature, relative humidity, etc.
Result	Overview of the mean values of workspace environmental properties corresponding to satisfactory or unsatisfactory conditions.
Corrective actions	- further analyse available data (see "Workplace issue discovery use case"); - compare the mean values of observable properties (e.g., air temperature) for satisfactory and unsatisfactory conditions for the same workspace or for different workspaces and adjust HVAC systems' set points accordingly; - change the workspace characteristics, configuration, and/or allocated activities; - change workers' allocation to a workspace or workstation that meets their preferences.
Workplace performance assessment – Activity support ***Workspace usage***	
Goal	**Assessing workspace usage.**
Required data	Worker feedback time and location (workspace). Worker momentary activity and social interaction.
Data processing	Activity data is queried and visualized based on: - spatial criteria (specific workspace or group of workspaces); - temporal criteria (specific time frame).
Result	Overview of the workplace performance in terms of workspace usage and its alignment with designated functions and activities.
Corrective actions	- evaluate the compatibility of inhomogeneous activities carried out in the same workspace using data related to self-assessed worker conditions (e.g., productivity); - adapt workspace configuration and equipment to support the reported activities and functions; - allocate workers to workspaces which better suit their activities and social interactions.

Table 4.2 Examples for use case: 1 - Workplace performance assessment (continued).

Workplace performance assessment – Worker support ***Worker self-assessed productivity evaluation***	
Goal	**Evaluating workers' self-assessed productivity over time and location.**
Required data	Worker feedback time and location (workspace). Worker momentary self-assessed productivity.
Data processing	Feedback data is queried and visualized based on: - spatial criteria (specific workspace or group of workspaces); - temporal criteria (specific time frame).
Result	Overview of the workplace performance in terms of worker self-assessed productivity.
Corrective actions	- further analyse available data (see "Workplace issue discovery use case"); - analyse self-assessed productivity with correlated data (e.g., time of the day, worker physiological parameters, activities); - allocate workers to workspaces that better suit their activities and social interactions.
Workplace performance assessment – Worker support ***Workspace-worker fit for productivity evaluation***	
Goal	**Evaluation of workers' self-assessed productivity in relation to workspace properties over time.**
Required data	Worker feedback time and location (workspace). Worker momentary self-assessed productivity. Sensor observations of workspace environmental properties correlated with worker productivity, such as thermal factors, acoustic factors, visual factors, IAQ factors.
Data processing	Feedback data is queried and visualized based on: - spatial criteria (specific workspace or group of workspaces); - temporal criteria (specific time frame). - values of workspace observable properties such as temperature, noise level, CO_2 concentration, etc.
Result	Overview of the mean values of workspace environmental properties corresponding to reported ratings of workers' self-assessed productivity.
Corrective actions	- further analyse available data (see "Workplace issue discovery use case"); - remove or mitigate identified sources of disruption of workers' self-assed productivity (e.g., improving fresh air change rate); - change the workspace characteristics, configuration, and/or designated activities to support workers' needs; - change workers' allocation (workspace or workstation).

In light of the adopted occupant-centric perspective, this use case in its different areas can be conducted independently of the workspace environmental property collection. This makes it suitable for sensitive contexts (e.g., historical buildings, restrained environments) where the permanent deployment and maintenance of IEQ sensors may be limited or not feasible. In such cases, analysing the distribution of occupants' feedback is sufficient to raise awareness of overlooked unsatisfactory conditions. However, more valuable insights can be gained by semantically integrating occupants' feedback with contextual workspace conditions.

An example is provided in Table 4.2 – *Satisfaction for acoustic quality*, where the assessment of perceived acoustic quality throughout the workplace relies solely on workers' feedback. Conversely, Table 4.2 – *Preferred thermal conditions* illustrates an assessment of thermal quality enriched with observed correlated properties values corresponding to perceived satisfactory or unsatisfactory conditions (e.g., air temperature), allowing workplace managers to make further considerations. In this regard, the collection and integration of workers' physiological data (e.g., heart rate variability) should be enabled as they provide valuable and objective indicators for assessing the psycho-physiological conditions of the occupants.

Furthermore, the ontology should enable the monitoring and evaluation of workplace parameters and conditions even in the absence of worker-generated data (i.e., feedback, physiological parameters, activities). This includes typical IEQ monitoring use cases, which are excluded because they are not related to the feedback of the actual workers, such as maintaining IEQ indicators within predetermined acceptability ranges (e.g., air temperature within setpoints), and monitoring workplace parameters essential for efficient operations, such as occupancy count for workspace utilization rates.

4.3.2. Workplace issue discovery

Assessing workplace performance as perceived by employees is a fundamental and necessary step toward achieving worker well-being and satisfaction through the continuous improvement of workplace conditions. However, while the distribution of worker feedback highlights suboptimal situations and its correlation with observed workspace properties provides crucial information on satisfactory and unsatisfactory conditions, understanding the underlying issues and taking appropriate actions is not a trivial task. This is where workplace issue discovery becomes essential.

Workplace issue discovery involves identifying and understanding the underlying factors contributing to unsatisfactory workplace conditions. Unlike simple correlations that can be misleading, this use case focuses on discerning patterns and trends that indicate potential problems within the workspace. For example (Table 4.3), observing a widespread "Prefer warmer" feedback among workers in the same workspace may indicate a general issue with its thermal conditions, potentially confirmed by sensor data showing an HVAC malfunction. Conversely, if only a few workers express dissatisfaction, whereas the majority reports satisfaction with the environment, the problem might be more localized, such as a leaking window near a specific workstation, or a mismatch between the environment and individual worker preferences.

Table 4.3 Examples for use case: 2 - Workplace issue discovery.

Workplace issue discovery ***Identifying causes of reported thermal discomfort***	
Goal	**Identify sources of thermal discomfort reported by workers.**
Required data	Worker feedback time and location (workspace) and preference for thermal quality. Sensor observations of workspace environmental properties correlated with thermal comfort (e.g., air temperature, relative humidity, window opening, etc).
Data processing	- query and visualize feedback based on spatial and temporal criteria; - correlate feedback with sensor data (e.g., temperature, humidity, HVAC terminal functioning); - analyse the distribution of feedback among workers.
Result	Identify specific areas or conditions leading to thermal discomfort for workers.
Corrective actions	- fix malfunctioning HVAC system terminals; - adjust workspace configuration or provide personal comfort devices (e.g., fans). - reallocate affected workers to more comfortable workspaces or workstations.
Workplace issue discovery ***Identifying causes of reported low levels of concentration***	
Goal	**Identify sources of low levels of concentration reported by workers.**
Required data	Worker feedback time and location (workspace), momentary self-assessed concentration, and activity. Sensor observations of workspace environmental properties (e.g., temperature, noise level, CO_2, etc).
Data processing	- query and visualize feedback based on spatial and temporal criteria; - correlate feedback with sensor data; - analyse feedback in relation to nearby activities.
Result	Identify patterns indicating low concentration linked to the occurrence of specific distracting conditions (e.g., uncomfortable temperatures) or activities (e.g., noisy meeting).
Corrective actions	- mitigate identified distracting conditions (e.g., improve thermal quality, reschedule activities; provide earphones, etc). - reconfigure workspace layout to keep conflicting activities separated; - reallocate affected workers to a more suitable workspace or workstation.

This use case extends beyond the simple correlation between worker feedback and sensor data by encompassing a comprehensive analysis of the distribution of critical inputs. This includes examining the relationship of these inputs to the employee population (e.g., whether feedback is evenly distributed or concentrated among a few individuals), spatial distribution (e.g., whether feedback is evenly spread across different workspaces or concentrated in specific areas), temporal patterns (e.g., identifying time-based trends in unsatisfactory conditions), and their concurrence with other factors such as the activities being performed (e.g., unsatisfactory conditions arising when a particular activity is conducted in a workspace). This enhanced level of data integration and analysis enables managers to precisely identify issues and implement corrective measures effectively.

4.3.3. Worker preference clustering and recommendation

Building on the insights gained from workplace performance assessment and workplace issue discovery, the third use case focuses on worker preference clustering and recommendation. This use case aims to enhance workplace conditions by identifying patterns in worker preferences and providing personalized recommendations to optimise individual and collective workspace satisfaction.

Worker preference clustering involves analysing worker feedback to identify groups of employees with similar preferences and needs. By clustering workers based on their feedback on environmental conditions, activities, and workspace features, managers can better understand the diverse needs of their employees in relation to both their specific tasks and workspaces. This analysis can lead to personalized recommendations for workspace adjustments, resource allocation, and environmental settings that serve these identified clusters.

For instance (Table 4.4), if a cluster of workers consistently prefers a warmer workspace, adjustments can be made to the HVAC system in their designated area. Similarly, if another cluster reports higher productivity in quieter environments, soundproofing measures or designated quiet zones can be implemented. By proactively addressing these preferences, organisations can significantly enhance worker satisfaction and productivity. Moreover, this use case can also be extended to recommending suitable workspaces for employees based on their preferences and the feedback from similar workers.

Table 4.4 Examples for use case: 3 – Worker preference clustering and recommendation.

Worker preference clustering and recommendation ***Thermal environment preference clustering***	
Goal	**Identify clusters of workers with similar preferences for thermal environment and recommend suitable workspaces.**
Required data	Worker feedback time and location (workspace) and preference for thermal quality. Sensor observations of workspace environmental properties correlated with thermal comfort (e.g., air temperature, relative humidity, window opening, etc).
Data processing	- cluster workers based on their feedback for thermal preference; - correlate clusters with sensor data (e.g., temperature, humidity); - identify workspaces that meet the preferred thermal conditions of each cluster.
Result	Identify groups of workers with similar thermal preferences and provide recommendations for suitable conditions or workspaces.
Corrective actions	- adjust HVAC settings in designated areas suitable for each cluster; - allocate workers to workspaces that match their thermal preferences; - provide personal devices to increase comfort for workers with specific needs; - (for employees) receive personalized suggestions for HVAC system adjustments or workspace with suitable conditions.

Table 4.4 Examples for use case: 3 – Worker preference clustering and recommendation (continued).

Worker preference clustering and recommendation ***Acoustic environment preference for productivity***	
Goal	**Identify clusters of workers with similar preferences for the acoustic environment in relation to their self-assessed productivity and recommend suitable workspaces.**
Required data	Worker feedback time and location (workspace), momentary preference for workspace acoustic quality, self-assessed productivity, and activity. Sensor observations of workspace environmental properties (e.g., noise level).
Data processing	- cluster workers based on their feedback for acoustic preference and productivity; - correlate clusters with sensor data (e.g., noise levels); - identify workspaces that meet the preferred acoustic conditions of each cluster.
Result	Identify groups of workers with similar acoustic preferences in relation to their productivity and provide recommendation for suitable conditions or workspaces.
Corrective actions	- implement personal or collective soundproofing measures in designated areas for each cluster; - allocate workers to quiet zones or areas with noise levels which are appropriate for their preferences; - schedule activities to minimize disruption for workers with sensitive task; - (for employees) receive personalized suggestions for workspace with suitable conditions.

Unlike the first two use cases, worker preference clustering and recommendation represents a proactive approach to workplace management. By anticipating worker preferences before issues arise, organisations can prevent dissatisfaction and maintain a high level of worker well-being. However, this proactive approach requires continuous data acquisition, raising important issues related to data privacy. It is crucial to address these concerns by either anonymizing the data to protect employee identities or obtaining explicit authorization from employees to process their data. Ensuring compliance with data protection regulations and maintaining transparency with employees about data privacy and usage are essential steps in implementing this use case effectively.

4.4. Functional requirements

The use cases identified in the previous section represent progressive milestones to be achieved in the ontology development process and serve to inform the expansion of the ontology's capabilities and the system implementing it throughout its various iterations. While the ultimate goal of this research is to comprehensively address all identified use cases, at the current stage, the dissertation primarily focuses on the first two: *workplace performance assessment* and *workplace issue discovery*. From these foundational use cases, the ontology functional requirements, which are essential for its implementation and development, are outlined in this section. Specific competency questions will then be extrapolated from these requirements (§4.5) and addressed in the ontology evaluation carried out with a demonstrative data set as specified in section 4.7.

1) *Worker temporary assessment* – The ontology must enable the detailed description of each worker's temporary conditions, encompassing both observed (objective) and perceived (subjective) states. Objective data might include information such as indoor location at varying resolutions (e.g., workspace, workstation, indoor coordinates), physiological parameters (e.g., heart rate), and current activities (e.g., attending a meeting). Subjective data should differentiate between worker perceptions directed outwards (e.g., environmental preferences) and inwards (e.g., feelings). Additionally, to enrich the worker description and support managerial considerations, static or quasi-static properties should be incorporated, such as demographic details and organisational roles.

2) *Spatiotemporal variability of data* - The ontology must facilitate the collection and spatiotemporal correlation of heterogeneous data generated by both sensors and workers. This includes data streams related to workspaces (e.g., occupancy counts), elements (e.g., equipment status), and workers (e.g., heart rate variability), as well as temporary feedback provided by workers (e.g., environmental preferences, self-perceived conditions).

3) *Integration of objective and subjective data* - The ontology should accommodate various system deployments and management needs, ensuring flexibility in objective and subjective data collection while maintaining accuracy and enabling their unambiguous correlations. For sensor data, essential information should include the value, unit of measure, position, and time of each data point, along with relevant metadata (e.g., frequency, precision). Subjective data should be collected through brief surveys administered to workers, using customizable yet consistent rating scales (e.g., Likert method). Additional metadata about the feedback, such as the generation type (e.g., scheduled, voluntary) and response type (e.g., responded, postponed), should also be captured to enable further analysis of the intrusiveness of the survey method adopted and thus the reliability of the data collected.

4) *Activity temporary assessment* – To fully understand worker data and monitor workspace usage, it is crucial to capture the characteristics of activities being performed when data is collected. This includes specifying the activity category (e.g., work, break), type (e.g., solo work, meeting), and social interaction type (e.g., solo, one-on-one, group).

5) *Representation of workspace spatial, functional and environmental properties* – The ontology should comprehensively represent the functional and physical environment occupied by the workers at the time their feedback is generated. This includes all the spaces and elements (e.g., walls, windows, desks, lamps) within a workplace, along with their dynamic environmental and functional properties. It should also capture the topological relationships among these spaces and elements (e.g., containment, adjacency) and the periodic sensor observations. Additionally, static properties of workspaces or elements that serve management purposes (e.g., room occupancy profiles) should be addressed.

4.5. Competency questions

Following the definition of the domain (§4.1), scope and purpose (§4.2), use cases (§4.3), and related functional requirements (§4.4), this section specifies the ontology requirements through a set of *competency questions* (CQs). As emphasized by Bezerra et al., (2013), competency questions play a crucial role in the ontology development life cycle. These questions are stated and answered in natural language, ensuring that the ontology can respond to them correctly and exhaustively. Given the identified scenarios (use cases) related to the workplace knowledge domain, CQs reflects the workplace manager demands and support ontology development in two primary ways:

- Identifying the main workplace concepts and relationships to create the ontology vocabulary, and;
- Providing a straightforward method to assess the satisfaction of the ontology requirements in terms of knowledge retrieval and entailment on its axioms.

For the designated user, the workplace manager, 14 competency questions have been defined for the identified use cases (Table 4.5). The evaluation of the ontology's capabilities and the data patterns necessary to address these CQs has been conducted using a demonstrative dataset, as reported in section 4.7.

Table 4.5 Competency questions.

Use case	Competency question	
1. Workplace performance assessment	**1 – Environmental comfort**	
	CQ1	**How has workspace A been perceived for thermal quality in the last week?** *Assess a workspace's performance from the workers' perspective regarding an environmental property over time, to identify suboptimal situations.*
	CQ2	**Which has been the preferred air temperature in workspace A in the last week?** *Identify a range of environmental properties that have been satisfying for workers over time, to use as a baseline reference for the workspace or for improving other underperforming workspaces.*
	CQ3	**Which workspaces are underperforming for thermal comfort and how (too cold, too warm)?** *Determine which workspaces fail to meet workers' preferences and in which way, to inform corrective actions accordingly.*
	2 – Activity support	
	CQ4	**How is workspace A typically utilized?** *Understand the activities and social interactions taking place in different workspaces over time, to ensure they are effectively supported and do not conflict with each other.*
	CQ5	**In workspace A, for which activities the workers are most/least satisfied with the environment?** *Identify if certain types of activities are associated with higher or lower worker satisfaction levels with the environment, helping to determine if the workspace effectively supports those activities.*
	CQ6	**Which are the preferred workspace conditions for a specific activity?** *Determine the optimal environmental conditions and workspace settings that enhance worker satisfaction during specific activities.*
	3 – Worker support	
	CQ7	**How do workers' self-assessed productivity levels vary between different workspaces within the workplace over time?** *Track and compare changes in workers' self-assessed condition levels across different workspaces over time to identify high-performing and underperforming areas.*
	CQ8	**How do workspace environmental conditions correlate with workers' collected physiological parameters?** *Explore the relationship between environmental conditions and workers' physiological parameters to gain insights into factors affecting workers' well-being and performance.*
	CQ9	**How do workspace environmental conditions correlate with workers' reported conditions (e.g., concentration)?** *Examine the relationship between environmental conditions and workers' self-reported states to identify conditions that enhance or hinder perceived well-being.*
2. Workplace issue discovery	**CQ10**	**How is negative feedback for workspace A environmental conditions distributed over time, worker population, location, and activity?** *Analyse the distribution of negative feedback regarding environmental conditions in relation to other factors to identify generalised or concentrated issues.*
	CQ11	**Are similar environmental conditions perceived as satisfying in a workspace and unsatisfying in another?** *Compare satisfaction for similar environmental conditions across different workspaces to understand whether context-dependent or personal factors affect satisfaction.*
3. Worker preference clustering & recommendation	**CQ12**	**Which workspace environmental conditions are preferred by a worker over time and depending on the activity?** *Identify and track a worker's preferred environmental conditions for various activities over time for profiling purposes and to provide personalized recommendations for optimal workspace allocation.*
	CQ13	**Under which worker cluster can a worker be profiled depending on its historical preferences?** *Classify a worker into a preference cluster using their historical feedback.*
	CQ14	**Which workspace suits the needs and preferences of a worker or worker profile best?** *Recommend the most suitable workspace for a worker or a worker profile based on their preferences and needs to enhance worker satisfaction, well-being, and productivity.*

4.6. Ontology overview

The Occupant-centric Workplace Management (WOMO) ontology presented in this dissertation has been developed to describe knowledge related to office environments and to enable the development of a workplace Digital Twin system centred on the occupant experience. Building and worker-generated data, semantically integrated according to the proposed ontology, are made accessible through the system and provide workplace managers with actionable insights to improve workers' satisfaction, well-being, and productivity.

The ontology digitally represents a physical workplace ecosystem, comprising indoor building spaces with all necessary components, systems, and equipment, and its occupants, under the following underlying assumptions:

- At any time during the workday[27], every worker is located in a building space (i.e., workspace) where they perform some activity, while having a subjective experience of the surrounding environment (outward perception) and of their personal conditions (inward perception), and being involved (or not) in a type of social interaction.
- Objective worker and workplace conditions, both physical and functional (e.g., worker location, occupancy, IEQ properties) can be observed in a quasi-continuous fashion and with adequate accuracy through the deployment of dedicated sensors.
- Worker's physiological parameters can be collected by direct and automatic observation through the adoption of wearable or mobile devices (e.g., smartwatch, smartphone).
- Workers' psychological experience (subjective perceptions) and activities are assessed multiple times during the workday directly in the work environment in accordance with the EMA method, collecting workers' feedback through the timely administration of micro-surveys.

With reference to the last assumption, despite several studies having explored the implementation of computer vision, wearables, sensors, and machine learning approaches for the detection and recognition of human activities and psychological conditions (Choi et al., 2021; Moon et al., 2024), their limitations in terms of accuracy and privacy concerns due to continuous worker monitoring oriented this dissertation towards considering an acknowledged survey-based approach.

As shown in Figure 4.4, the proposed ontology is organised into four conceptual modules corresponding to the three main identified workplace knowledge domains – *Worker, Workspace, Activity* – with the addition of the classes and properties describing the feedback. As further detailed in §4.6.4, the feedback concept links the collected worker and activity data and locates them in space and time, enabling their integration and interpretation with building and sensor data. This modularization aims to facilitate the ontology development, integration with other specialized ontologies, and its future extension (see §4.7.2). In particular, the workspace module, describing the static and dynamic aspect of the physical environment, largely reuses concepts and properties of two existing ontologies, renowned for their effectiveness in Linked Building Data applications: the Building Topology Ontology (Rasmussen et al., 2021), as a lightweight alternative to ifcOWL for the translation of information stored in workplace BIM

[27] With *workday* is assumed here the period of time spent by a worker at the workplace.

models, and the Semantic Sensor Network ontology (Haller et al., 2017) for the description of relevant sensor data and metadata.

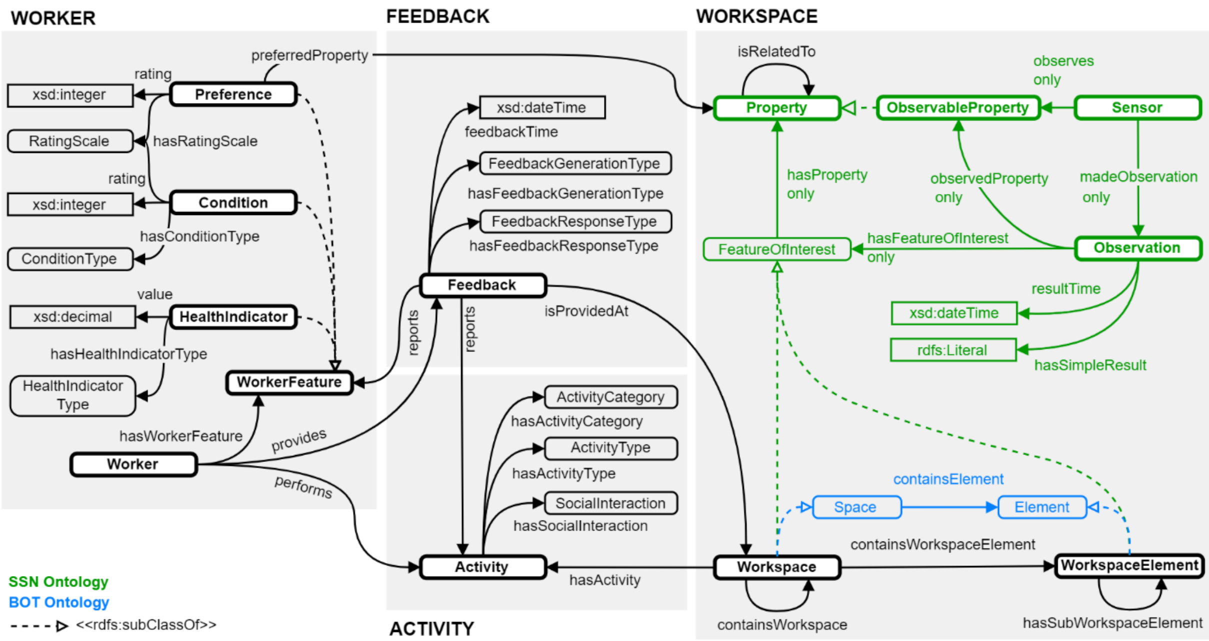

Figure 4.4 WOMO Ontology overview (first published in Bruttini et al., 2022).

In the following paragraphs (§4.6.1-4.6.4) the classes and properties characterizing each ontology module are described and contextualised in their operational scenario. Classes and properties will be highlighted using the `Courier New` font and the suggested prefixes `womo`, `bot`, and `ssn/sosa` will be used for their namespaces. The current version of the WOMO ontology is publicly available along with its documentation at https://w3id.org/womo#. The documentation of the ontology classes and properties is also provided in Appendix A.

4.6.1. Workspace module

The *workspace module* encompasses the concepts and relationships necessary for the topological representation of the workplace and the description of its properties over time (Figure 4.5). The scale at which the workplace is considered can vary significantly depending on the use case and the resolution of the sensor deployment. Therefore, the ontology must provide flexibility and granularity in modeling and retrieving the related knowledge. Each physically and functionally identifiable portion of space within the workplace belongs to the module's core class `womo:Workspace` (sub class of `bot:Space`). This class applies to entire departments, individual rooms (e.g., shared offices), parts of rooms (e.g., areas within an open-plan office), and even single workstations, which are the minimal spatial units where work is performed. The mutual spatial relationship between workspaces is modelled through the object property `womo:hasWorkspace` (sub property of `bot:hasSpace`).

Similarly, each physical element within the workspace, being a building component, a sensor, or a piece of furniture or equipment belongs to the `womo:WorkspaceElement` (sub class of `bot:Element`) and can be described in composition with other elements through the `womo:hasSubWorkspaceElement` property (sub property of `bot:hasElement`). Workspace element that are completely contained within a workspace can be described through the property womo:containsWorkspaceElement (sub property of bot:contains-Element), while for adjacency and intersection relationships the corresponding BOT properties are maintained.

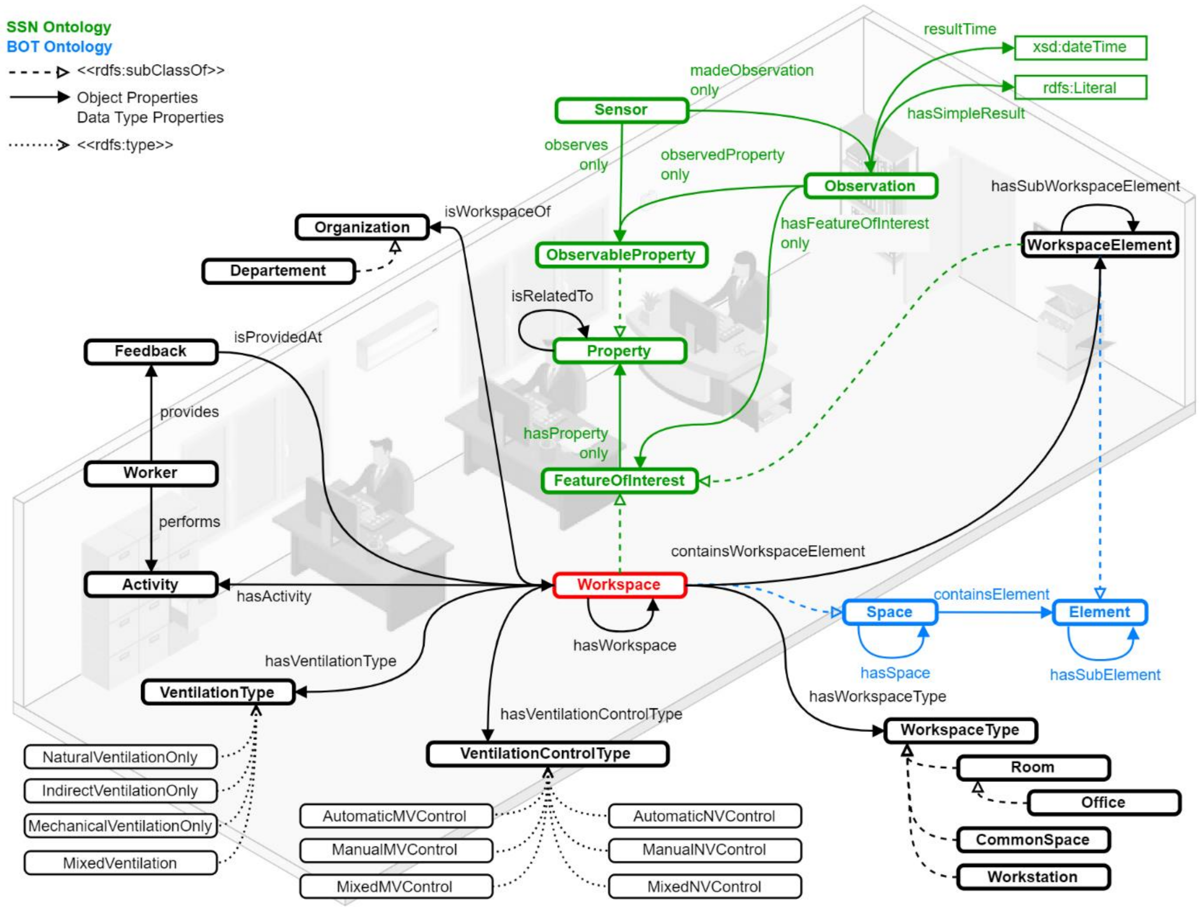

Figure 4.5 WOMO Ontology – Workspace module overview.

Workspace allocation and functional characterization are enabled by linking to instantiated members of womo:Organisation (e.g., company, department) and womo:Workspace-Type classes. For the latter, three sub classes have been defined: womo:Room for spaces mainly dedicated to work activities; womo:CommonSpace for spaces dedicated mainly to social interactions and breaks; womo:Workstation indicating the minimal spatial unit where the employees carry out their tasks.

As emerged from the literature reviewed in Chapter 2, lighting, heating, ventilation, and air conditioning systems, along with their operational strategies, play a crucial role in workspace environmental quality and occupant satisfaction. Regarding the characterization of workspace ventilation, the womo:VentilationType and womo:VentilationControlType classes are provided with a predefined set of enumerated members. These members encompass both natural and mechanical configurations, as well as automatic and manual control strategies.

The relation of workspaces and workspace elements with the timely observations of their objective properties is addressed defining their instances as members of the sosa:FeatureOfInterest class and adopting the semantics provided by the Semantic

Sensor Network ontology (SSN). For this purpose, in the ontology (see Figure 4.6) the four general IEQ concepts are defined as instances of ssn:Property (womo:AirQuality, womo:AcousticQuality, womo:VisualQuality, womo:ThermalQuality), and some of the related measurable parameters as instances of its sub class sosa:ObservableProperty (womo:CO2Concentration, womo:AirTemperature, womo:Illuminance, womo:NoiseLevel, womo:OccupancyRatio, womo:RelativeHumidity, womo:OccupancyCount). For instance, this approach allows an occupant to provide feedback on general workspace properties, such as thermal quality, while an installed thermometer and humidity sensor (sosa:Sensor) provides periodic measurements (sosa:Observation) of known time and value (sosa:resultTime; xsd:dateTime; sosa:hasSimpleResult; rdfs:Literal). To establish a meaningful link between properties at this two different level of abstraction, and thus between feedback and sensor observations, the womo:isRelatedTo object property is defined.

Concludingly, direct linking between instances of womo:Activity and womo:Feedback classes (womo:hasActivity, womo:isProvidedAt) enables fast retrieval of information characterizing the worker use of the space and their experience. On the other hand, worker and workspace concepts are kept decoupled to keep the spatio-temporal contextualization of occupants' information to the feedback entities and avoid redundancy.

Further details about concepts and relationships from the BOT[28] and SSN[29] ontologies reused in this work can be found in their public specifications. In this regard, it bears mentioning that the first step in the semantic data integration at the basis of the workplace digital twin system proposed in this thesis consist in mapping and converting workplace BIM models' entities provided in IFC to BOT classes and properties. Additionally, to model and detail the deployed sensor network, the semantics of the SSN ontology shall also be fully exploited.

4.6.2. Worker module

The *worker module* focuses on describing the experiences of the individual employees (womo:Worker) within the monitored workspaces over time (Figure 4.6). To achieve this, both the objective conditions and subjective perceptions of the occupants are captured through voluntary feedback (womo:Feedback) and reported as instances of the womo:WorkerFeature class.

Worker features are further specified in three sub classes: womo:HealthIndicator for objective observations of worker physiological parameters; womo:Preference for worker subjective perceptions of the surrounding environment; and womo:Condition for worker self-assessed internal conditions.

Health indicator instances describe data points that are automatically collected through wearables and mobile devices (e.g., smartwatches, smartphones) and linked to a measured value (xsd:decimal) and type (womo:HealthIndicatorType). The ontology includes two predefined members of this class, womo:HeartRate and womo:DailyStepCount,

[28] https://w3c-lbd-cg.github.io/bot/ - Accessed 05/05/2025.
[29] https://www.w3.org/TR/vocab-ssn/ - Accessed 05/05/2025.

which can serve as proxies for occupants' metabolic rate and fitness habits. Additional parameters that are effective in the representation of workers' physiological and psychological experience could be considered as health indicator types, such as sleep quality history for concentration and productivity, heart rate variability (HRV) for stress, and electrodermal activity (EDA) for psychological arousal. However, the need for more sophisticated and intrusive monitoring devices, and the extension of the observation time outside work hours represent critical shortcomings that should be considered case by case.

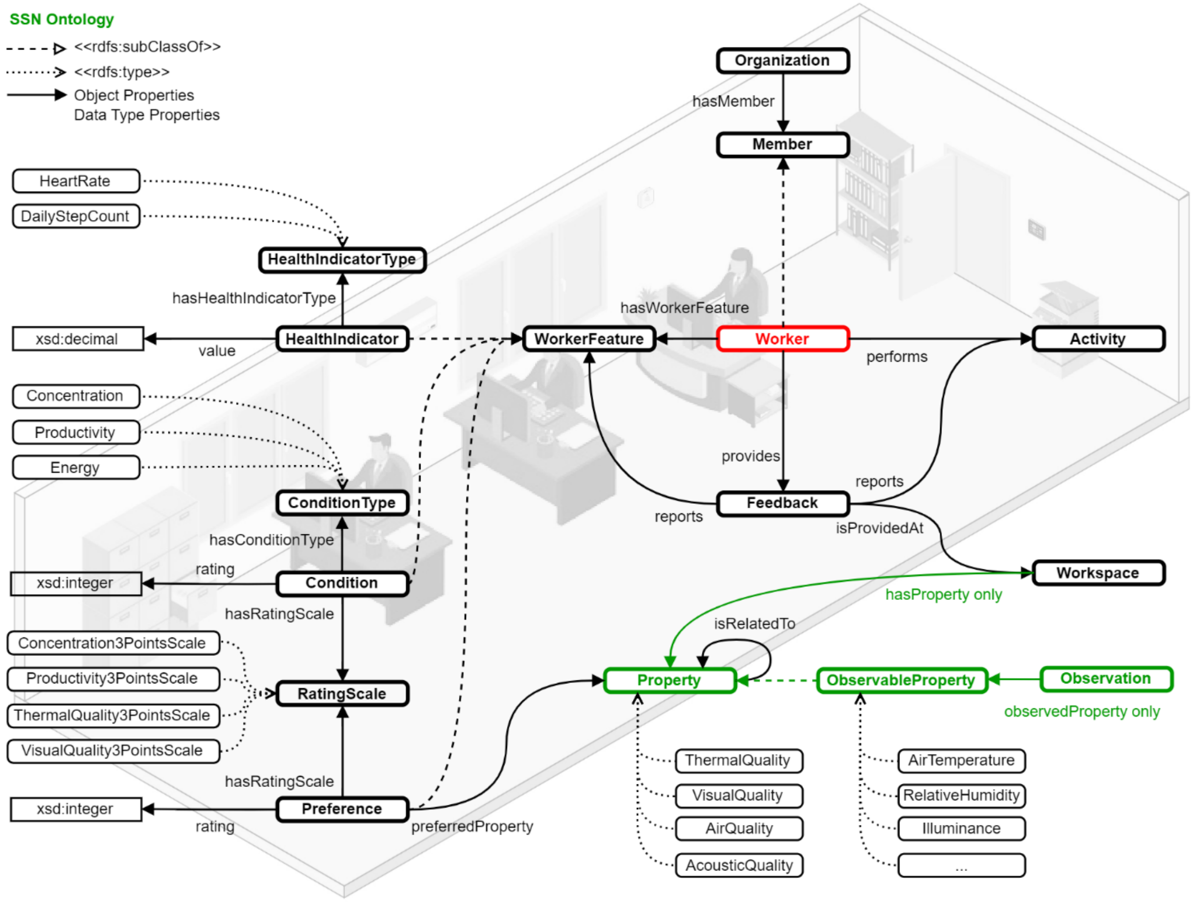

Figure 4.6 WOMO Ontology – Worker module overview.

Conditions describe the worker's self-assessed personal conditions at the time and location of the provided feedback, and are specified by linking to a specific member of the `womo:ConditionType` class. The ontology provides three instantiated condition types, `womo:Concentration`, `womo:Productivity`, and `womo:Energy` to support the evaluation of worker-workspace fitness. However, depending on the use case, additional perceived conditions should be considered for surveying (e.g., satisfaction, motivation, stress, etc). Each condition is expressed with a numerical rating (`xsd:integer`) and is related to a predetermined scale (`womo:RatingScale`). For the enumerated worker conditions, three-points rating scales are instantiated based on the acknowledged psychrometric Likert-scale method (e.g., `womo:Concentration3PointsScale`).

Complimentarily to conditions, preferences are modelled to capture workers' subjective perceptions towards the surrounding environment. For this reason, the object property `womo:preferredProperty` is modelled to link preference instances to a general ssn:Property or specific sosa:ObservableProperty of a workspace or workspace element. For example, depending on the use case requirements and survey design, workers can express a preference for the womo:ThermalQuality of their workspace, as well as for one or more of its measured properties, like womo:AirTemperature and womo:RelativeHumidity. The mutual relationship among different properties and observable properties and the interpretation of the related preferences is ensured with the introduction of the reflexive object property womo:isRelatedTo, which enhances the property semantics and the ontology granularity. Similarly to conditions, each preference includes a numerical rating (xsd:integer) and is interpreted with a predetermined rating scale (e.g., womo:VisualQuality3PointsScale).

Besides these individual features, the characterization of the workers' experience within the occupied workspace is completed through the specification of the activity they are performing (womo:Activity, womo:performs, see section 4.6.3).

Workers' temporary status, comprising of the described features and activity, is collected through voluntary feedback at discrete points in time and space (see section 4.6.4). Therefore, their spatio-temporal information (i.e., timestamp, workspace) is univocally attached to the corresponding instance of the womo:Feedback class.

For additional worker data and demographics, which are not currently considered in the ontology but could be relevant for organisational purposes (e.g., age, gender, contract, role, etc), the classes womo:Member and womo:Organisation are introduced. These classes are intended as pivots for the semantic enrichment of the worker's and organisation's description to be explored in future developments, also reusing existing ontologies (see section 4.8).

4.6.3. Activity module

The *activity module* addresses the description of the workers' daily routines, allowing an understanding of how workspaces are used and how well they meet workers' needs and expectations (Figure 4.7). Through temporary surveys, workers report their current activities, which are recorded as members of the module's core class womo:Activity, and are contextualized in space and time through properties attached to the corresponding womo:Feedback instance.

Activities are specified by linking them to instances of three related classes: womo:ActivityCategory, womo:ActivityType, and womo:SocialInteraction. The classification strategy adopted in this research acknowledges the significant role of break time in maintaining a healthy and productive workday. Therefore, it distinguishes between two activity categories, womo:Work and womo:Break, which must be specified for each recorded activity instance (womo:hasActivityCategory). Additional details are provided by linking to one of the predefined activity types (e.g., womo:WorkCall, womo:BreakCoffee, etc). Depending on the use case and organisational characteristics of the workplace, alternative categories and types can be introduced (e.g., brainstorming, meeting, experiment). Moreover, the social interaction of the worker, or the lack thereof, during the reported activity is captured by linking to one of the enumerated types (i.e., womo:Solo, womo:Pair, womo:SmallGroup, womo:Group).

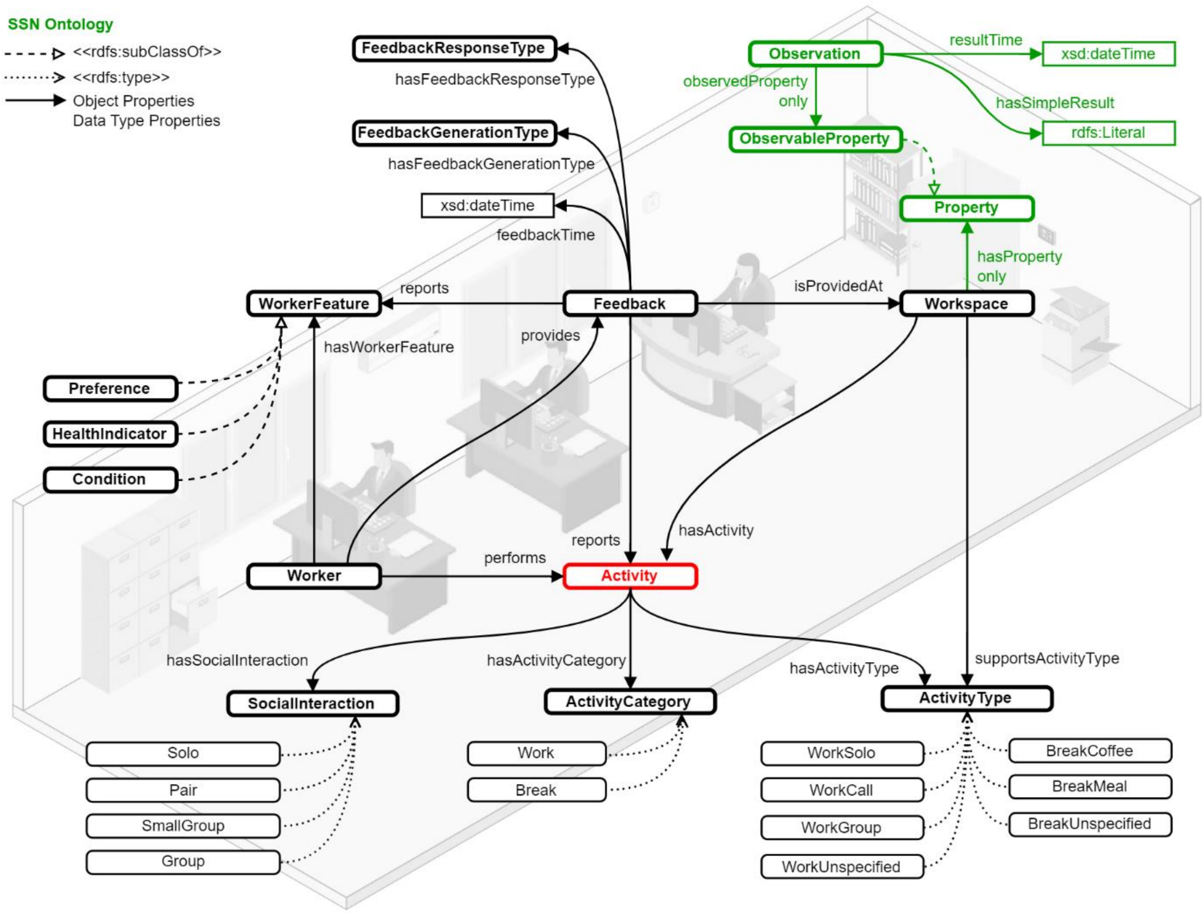

Figure 4.7 WOMO Ontology – Activity module overview.

The link between activity and feedback (`womo:reports`) enables the correlation of the activity information with worker features and workspace conditions, ultimately providing a snapshot of the worker-activity-workspace dynamics at a given moment.

Further correlations between activities and other concepts are beyond the scope of this dissertation and are not covered in this version of the ontology. However, the integration with conceptual project management entities (e.g., phases, tasks, outcomes, schedules) or physical workplace entities, such as pieces of equipment (`womo:WorkspaceElements`) required for or used during the activity, should be further investigated for specific use cases. A brief discussion on these perspectives and an overview on existing ontologies suitable for this purpose is provided in section 4.8.

4.6.4. Feedback module

The *feedback module* describes the pivotal concept of "feedback", which enables the spatio-temporal integration of worker, activity, and workspace knowledge defined in the ontology (Figure 4.8). According to the EMA method, the assessment of workers' conditions is carried out through the collection of their physiological parameters (e.g., heart rate) and perceptions (e.g., thermal preference) at discrete moments and locations within the workplace. Each time a worker (`womo:Worker`) voluntarily provides (`womo:provides`) and allows for the collection of these data, an instance of the module's core class `womo:Feedback` is generated.

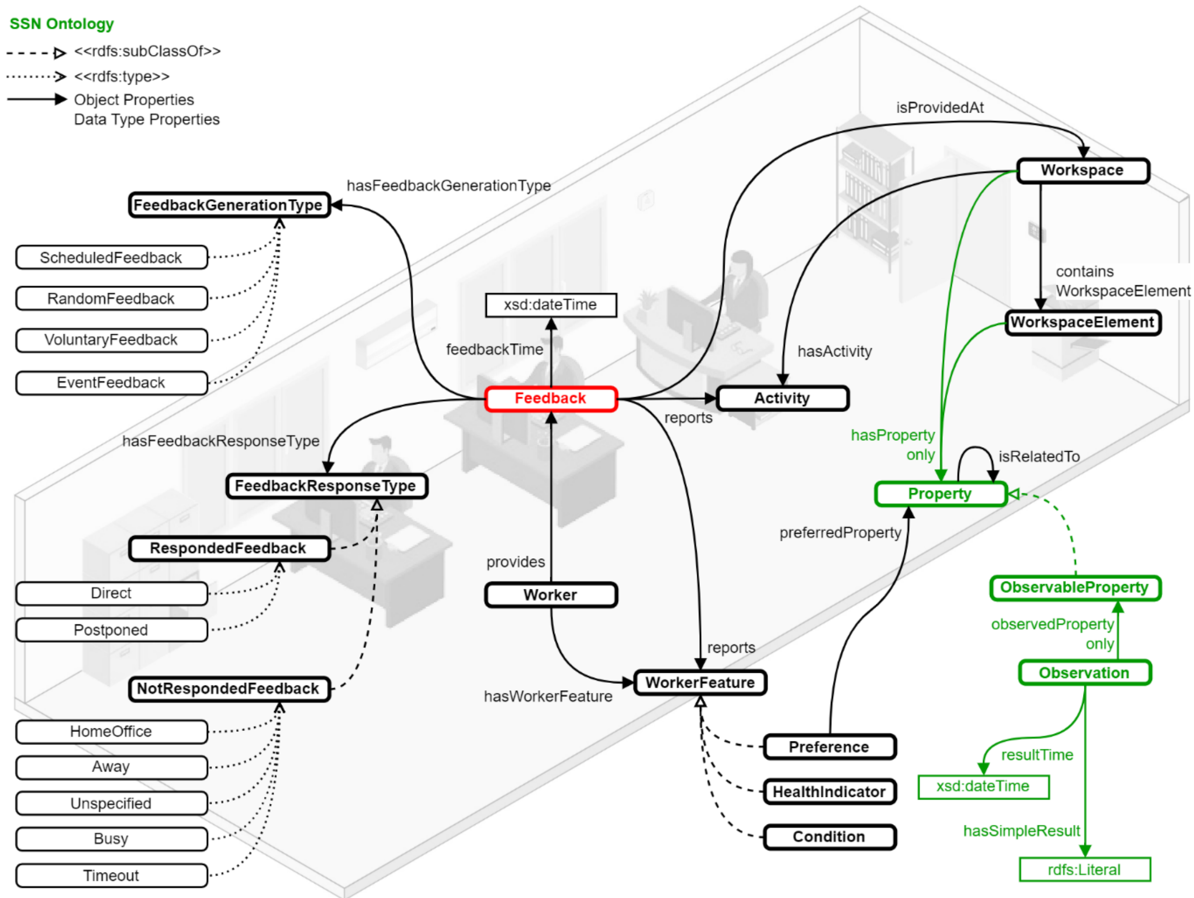

Figure 4.8 WOMO Ontology – Feedback module overview.

A `womo:Feedback` instance is always linked to a timestamp (`womo:feedbackTime`, `xsd:dateTime`) and a location (`womo:isProvidedAt`, `womo:Workspace`) to enable the integration and correlation of the collected worker data with the values of the environmental properties observed by sensors (`sosa:Observation`, `sosa:resultTime`; `xsd:date-Time`; `sosa:hasSimpleResult`; `rdfs:Literal`). At feedback generation, worker activities (`womo:Activity`), preferences, conditions, and health indicators (subclasses of `womo:WorkerFeature`) along with the related data are linked through the object property `womo:reports`.

Moreover, the ontology provides additional classes describing the feedback process to enable the assessment of the data collection strategy and the meta-analysis of the workers' responses (`womo:FeedbackGenerationType`, `womo:FeedbackResponseType`). Except for physiological parameters, which are automatically observed with wearable devices (e.g., smartwatch), the collection of preferences, conditions, and activities requires workers' responses to a short survey. These can be provided either spontaneously (`womo:VoluntaryFeedback`) or on request using different methods (e.g., smartwatch app, smartphone app, web form, polling station). Feedback requests can be generated according to a predefined schedule (`womo:ScheduledFeedback`), randomized (`womo:RandomFeedback`), or triggered by events (`womo:EventFeedback`) registered by the system (e.g., exceeded a workspace's set social density). In turn, the worker's reaction to a feedback request notification is recorded, enabling the analysis of the distribution of responded and not responded surveys. This highlights the occurrence of survey fatigue and supports the adoption of less intrusive surveys. In particular, useful insights can be obtained by knowing that a feedback request arrived when a worker was working at home or at a different location than the monitored workplace, or that it was declined simply because they were too busy or started to respond but couldn't complete the survey within a given time window.

The possibility to introduce further semantics to describe the feedback and the integration with existing ontologies dealing with the description of feedback collection is provided in section 4.8.

4.7. Ontology evaluation

The evaluation of the proposed ontology was conducted by generating and querying a test dataset for a demonstrative use case. The test scenario involves monitoring a single workspace, specifically a shared office, over two work weeks (10 workdays). Regarding environmental properties, a single sensor (thermometer) is assumed to be deployed to measure the workspace air temperature, with hourly mean values considered between 9:00 and 18:00. Three workers are assumed to share the office during the data collection period, providing feedback five times per day. This feedback includes their current activity and social interaction, preference regarding the current thermal environment, and perceived productivity. Additionally, the workers are assumed to wear smartwatches to record their heart rate values with each feedback. The test scenario and dataset characteristics are detailed in Figure 4.9 and Table 4.6, while Figure 4.10 illustrates a sample extract of the dataset to visualize the evaluated data patterns. The ontology's capability to capture knowledge related to the workplace ecosystem and describe its relationship with the occupant workers was tested using the competency questions listed for the identified use cases in the previous Table 4.5.

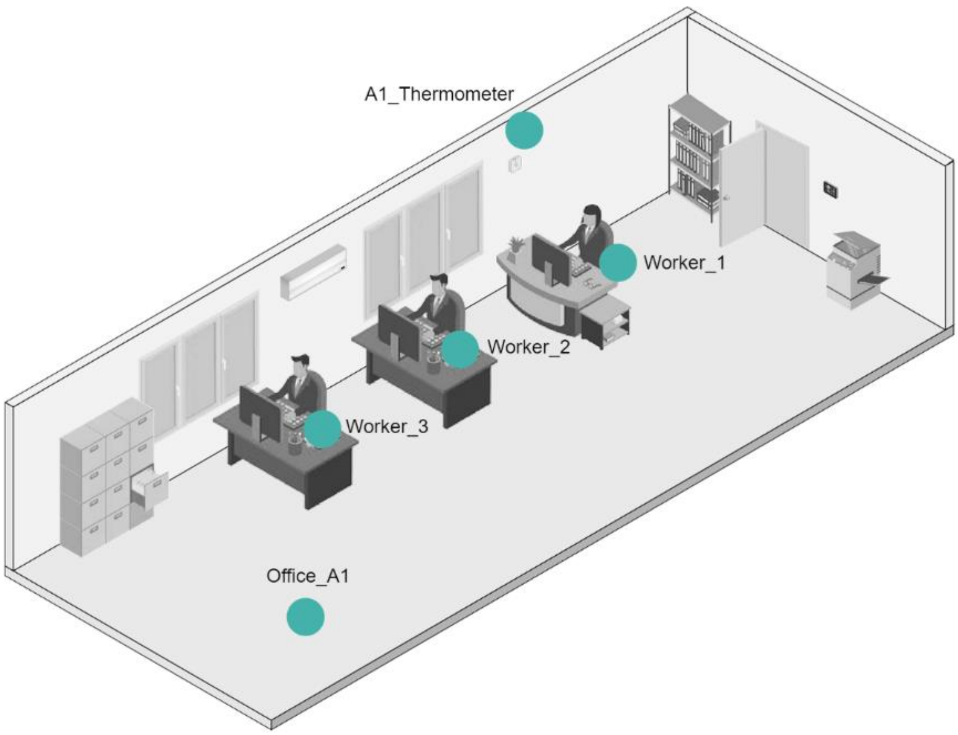

Figure 4.9 Physical representation of the test scenario.

Table 4.6 Test dataset characteristics.

Class	Individuals
`womo:Activity`	`ACT_0001,...,ACT_0150` *1 activity per feedback*
`womo:ActivityCategory`	`Break, Work`
`womo:ActivityType`	`BreakCoffee, BreakMeal, BreakUnspecified,WorkCall, WorkGroup, WorkSolo, WorkUnspecified`
`womo:Condition`	`CDT_0001,...,CDT_0150` *1 condition per feedback*
`womo:ConditionType`	`Productivity`
`womo:Feedback`	`FBK_0001,...,FBK_0150` *5 Feedback per worker per day for 2 work weeks (10 work days)*
`womo:HealthIndicator`	`HI_0001,...,HI_0150` *1 health indicator per feedback*
`womo:HealthIndicatorType`	`HeartRate`
`sosa:ObservableProperty`	`A1_AirTemperature` *Air temperature in Office A1 (observed by A1_Thermometer)*
`sosa:Observation`	`OBS_0001,...,OBS:0090` *9 observations per day, 9:00-18:00 hourly mean values, 2 work weeks (10 days)*
`womo:Preference`	`PRF_0001,...,PRF_0150` *1 preference per feedback (expressed regarding the experienced thermal quality)*
`ssn:Property`	`A1_ThermalQuality` *Perceived thermal quality in Office A1 (and related to A1_AirTemperature)*
`womo:RatingScale`	`ThermalQUality_3Points, Productivity_3Points` *Prefer cooler (-1), No change/OK (0), Prefer warmer (+1)* *Not productive (-1), Normal (0), Very productive (+1)*
`sosa:Sensor`	`A1_Thermometer` *Measuring the air temperature (observable property) in Office_A1*
`womo:SocialInteraction`	`Group, SmallGroup, Solo, Pair`
`womo:Worker`	`Worker_1, Worker_2, Worker_3`
`womo:Workspace`	`Office_A1`

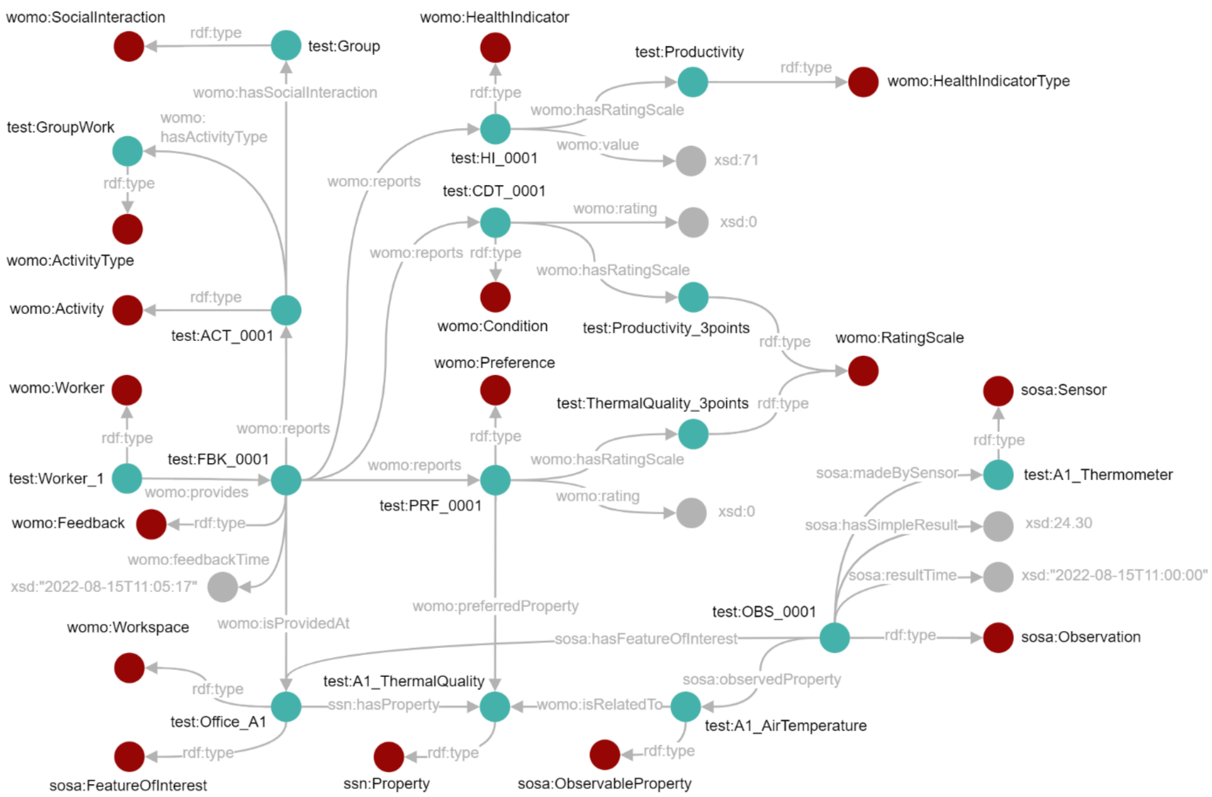

Figure 4.10 Sample entities and data patterns for the test scenario.

4.7.1. Workplace performance assessment

For this use case, the ontology should enable the evaluation of the objective environmental conditions in workspaces over time, as observed by sensors, and capture how workers utilize and experience them. Three areas of workplace performance assessment have been defined: environmental comfort, activity support, and worker support.

Environmental comfort

To assess the workplace performance for environmental comfort, workplace managers need to evaluate how occupants perceive certain properties of the workspace (CQ1), identify conditions that align with their preferences (CQ2), and determine the satisfaction levels across different workspaces over time (CQ3). CQ1 is addressed by querying workers' thermal quality preferences over a specific period. For CQ2, preferences with a neutral rating (0 = No change/OK) are filtered, and observations of the air temperature property timely close to these preferences are retrieved to determine the average value perceived as satisfying. With similar datasets for multiple workspaces, preferences can be queried by workspace and rating to compare performance across the whole workplace (CQ3).

Activity support

An overview of workspace utilization, including activity categories and types of social interactions, can be obtained by querying reported activities (CQ4). Additionally, by linking worker satisfaction with an environmental property (e.g., thermal quality) during a specific activity, it is possible to assess the extent to which a workspace supports or hinders that activity (CQ5). Integrating sensor observations for the related environmental property provides insights into conditions perceived as satisfying during certain activities (CQ6). For instance, evaluating the average value of observations corresponding to a "no change" preference expressed during group work activities can lead to statements such as: "In office A1, an air temperature of 24.30 °C is satisfying during group work activities." Workplace managers could leverage this knowledge to ensure comfortable conditions and improve other underperforming workspaces.

Worker support

The final area of workplace performance assessment considers how workspace conditions impact worker well-being and productivity. This is achieved by correlating observed environmental conditions with worker self-assessed conditions and measured physiological parameters. Querying instances of reported worker conditions, such as self-assessed productivity, allows for comparisons of different workspace performances (CQ7). By linking the corresponding feedback instances (workspace, timestamp), the values of workspace environmental properties observed by sensors in proximity to the reported conditions can be retrieved, facilitating a correlation between workspace conditions and worker well-being and productivity (CQ9). Furthermore, a similar correlation can be established with observed worker health indicators to explore the impact of the environment on worker health conditions (CQ8).

4.7.2. Workplace issue discovery

This use case focuses on leveraging semantic relationships among defined concepts to gain a granular understanding of potential root causes leading to underperforming workspaces. When a significant number or share of negative feedback (e.g., preferences for a cooler or warmer environment) is reported for a workspace property (e.g., thermal quality), workplace managers can analyse its distribution and correlation to other concepts through linked feedback instances (CQ10). For example, querying the workers who provided these preferences may highlight issues specific to certain employees or reveal a source of discomfort affecting most workers. Concentrations of negative feedback at particular times (e.g., hour of the day, day of the week) or during certain activities could indicate concurrent factors that hinder worker satisfaction. A further assessment can be conducted by querying worker preferences in other workspace for similar environmental conditions (CQ11). This comparison could reveal widespread issues affecting the entire workplace or issues specific to certain employees or workspaces.

4.7.3. Worker preference clustering and recommendation

The ontology's ability to link workers instances to their reported preferences, activities, self-assessed conditions, and measured health indicators through the feedback class, as well as to contextual observed workspace environmental conditions over space (workspace) and time (feedback timestamp), enables responses to the competency questions defined for this use case. CQ12 can be addressed by querying the preferences expressed by a specific worker, along with their reported activities and temporally close sensor observations. With sufficient historical data on workers' preferences and conditions, clustering algorithms can be applied to define worker profiles, classify employees (CQ13), and proactively recommend workspace conditions that suit workers' needs and expectations (CQ14).

4.8. Ontology integration and extension

This section discusses the integration of concepts from existing vocabularies into the WOMO ontology, along with opportunities for its further extension and specialization through additional ontologies (see Table 4.7). The discussion encompasses the identified conceptual modules—Workspace, Worker, Activity, and Feedback—and concludes with considerations related to standing limitations and directions for further investigation.

Workspace

The workspace module addresses the knowledge related to both static and dynamic aspects characterizing the worker's context from physical, functional, and organisational perspectives. BIM data, serialized according to the IFC schema, provides the foundation for representing various workspaces, their aggregation, and associated characteristics along with those of the included elements. However, a direct semantic translation of the IFC schema would introduce unnecessary complexity when linking other WOMO concepts and properties. Therefore, the core concepts of building space (`bot:Space`) and element (`bot:Element`) have been integrated from the lightweight BOT ontology, which has been employed to derive the concepts of `womo:Workspace` and `womo:WorkspaceElement`, allowing the use of BOT properties to describe their topological relationships.

To characterize the physical properties of these spaces and elements, as well as the semantic representation of the sensor network used for this purpose, classes and properties from the SSN ontology have been adopted. This ontology enables a comprehensive description of a sensor network, including sensors, observations, features of interest, components, observed properties, and associated procedures. SSN also includes SOSA (Sensor, Observation, Sample, and

Actuator), a lightweight, self-contained core ontology that provides elementary classes and properties for flexible application across domains. The recognized utility of SSN and SOSA across diverse applications—from large-scale scientific monitoring to social sensing—made them a suitable choice for integration within the WOMO ontology.

Table 4.7 List of existing ontologies reused (green) or considered for extension.

	Ontology	Workspace	Worker	Feedback	Activity
bop	**Building Performance Ontology** Integrates topological building information with static and dynamic properties, to create a homogeneous data environment used by complex building performance assessments. (Donkers, Yang, De Vries, et al., 2021)	×			
bot	**Building Topology Ontology** [Reused] Describes topological structure and relationships of the spatial entities and physical elements composing a building. It is reused for the workplace topological structure. (Rasmussen et al., 2021)	×			
brick	**BRICK schema** Describes the physical, logical and virtual assets in buildings and the relationships between them. Brick includes terms and concepts in and around buildings, a set of relationships for linking and composing concepts together, and a flexible data model for its integration with existing tools and databases. (The Brick Consortium, 2024)	×			
ofo	**Occupant Feedback Ontology** Describes passive and active occupant feedback and enables integration of this feedback with linked building data. (Donkers et al., 2022b)		×	×	
op	**Occupancy Profile ontology** Describes occupant behaviour in buildings and its energy impact, aiming to refine energy profiles and create realistic simulation scenarios. This ontology captures occupant interactions with building systems affecting thermal comfort needs. (Chávez-Feria, Poveda-Villalón, et al., 2020)	×	×	×	×
org	**The Organisation Ontology** Describes organisational structures and aims at supporting linked data publishing of organisational information across a number of domains. (Reynolds, 2014)	×	×		
prov	**PROV Ontology** Enables representing and interchanging of provenance information generated in different systems and under different contexts. It can also be specialized to create new classes and properties to model provenance information for different applications and domains. (Lebo et al., 2013)	×	×	×	×
rec	**RealEstateCore ontology** A comprehensive framework designed for the real estate industry to standardize the way data is structured, shared, and processed across smart building systems. It provides a common language for describing real estate assets, including buildings, spaces, equipment, and agents, making it easier to integrate data from various sources. (RealEstateCore Consortium, 2024)	×	×		
ssn sosa	**Semantic Sensor Network ontology** [Reused] Describes sensors and their observations, the involved procedures, the studied features of interest, the samples used to do so, and the observed properties, as well as actuators. It is reused for the sensor network deployed to monitor the environmental properties of the workplace and of its elements and their observations. (Haller et al., 2017)	×			
sur	**The Survey Ontology** Provides a novel conceptualization of surveys, enabling a structured modeling of both the survey structure and the collected answers.(Scandolari et al., 2021)		×	×	
tmo	**Task Model Ontology** Provides a representation of tasks for use in personal task management applications for knowledge workers.(Brunzel & Grebner, 2012),				×
vcard	**vCard Ontology** Describes people and organisations.(Iannella & McKinney, 2014)		×		

While BOT and SSN ontologies provide core concepts and properties for workspace description, further development iterations of WOMO should explore extending these capabilities through concepts from other ontologies specialized in building representation.

Additionally, vertical extensions could be incorporated to address key functional and organisational aspects relevant to workplace and facility management. Specifically, a detailed taxonomy of workspaces, categorized by function and organisational characteristics, and workspace elements could be integrated from the RealEstateCore (REC) ontology and the BRICK schema. For further relevant details, the Organisation Ontology (ORG) could be used to enhance descriptions of organisational structure in managed workspaces. Moreover, the Building Performance Ontology (BOP), developed to facilitate the integration of heterogeneous static and dynamic building data, should be considered to optimise sensor observation management and manage metadata for efficient storage and retrieval from linked databases.

To enhance WOMO's expressiveness, additional classes and properties for workspace descriptions could be drawn from more extensive frameworks such as the PROV ontology (e.g., organisation, location) and the Occupancy Profile (OP) ontology. Both of these ontologies provide reusable concepts and properties that are suitable across all four WOMO conceptual modules and, given their comprehensiveness, should be evaluated for integration across the entire ontology.

<u>Worker</u>

The worker module describes employees' subjective and objective conditions, including their location and current activities within the workplace, perception of the surrounding environment and preference for potential changes, self-assessed psycho-physical conditions, and parameters indicating their current health status. While at this development stage location is associated directly with a discrete spatial entity identified within the workplace, further extension should support expressing worker position in relative or absolute coordinates to accommodate advanced indoor tracking capabilities as they are implemented. Additionally, activities are decoupled from the worker module and addressed within a dedicated module.

In real-world management scenarios, the characterization of the worker's position within the organisational structure, along with conventional contact information, is essential. For this purpose, concepts and properties from the vCard, REC, and ORG ontologies could be integrated. Additionally, to support integration with ontologies focused on detailed characterization of occupants and their interaction with the environment through feedback instances (viewed as information transactions within the system), linking with suitable concepts from the Occupant Feedback (`ofo:Person`), Survey (`sur:Participant`), and PROV (`prov:Person`) ontologies should also be considered.

Future extensions of the WOMO ontology should remain open to the integrating frameworks that are closely related to workplace management, such as the behavioural modeling perspective adopted in the Occupancy Profile ontology for energy simulations. Moreover, advancements in knowledge mapping within the domains of physical and psychological health—currently under development for future smart healthcare applications (S. K. Shahzad et al., 2021)—could also become relevant for enhancing the Worker module's capability to interface with systems dedicated to the monitoring of health and well-being.

<u>Activity</u>

The activity module represents the activities workers perform at their current locations as reported through feedback instances. At this stage, only the category, type, and social interaction involved in each activity are defined attributes, with each activity connected via its corresponding feedback instance to the worker and a specific point in space and time within the workplace. Given the wide range of possible activity categories and types, a comprehensive taxonomy is not explicitly included and is instead left to be defined in each specific implementation.

However, linking activities with similar concepts in the Occupancy Profile (`op:Action`) and PROV (`prov:Activity`) ontologies could enable leveraging these semantics to provide a behavioural perspective on occupant-environment interactions, as well as the relation between the author and recipient of activities within the system. Additionally, attributes for describing the meta-characterization of activities (e.g., priority, progress), as defined in the Task Model Ontology, should be considered for future implementation.

Feedback

The feedback module addresses the knowledge associated with the informative objects linking workers to the observed or voluntarily provided information regarding their location (e.g., workspace), personal preferences, conditions, features, and activities at specific times. Metadata attributes defined for feedback include its generation type (e.g., random, scheduled) and response type, allowing for meta-analysis to identify trends related to the intrusiveness and effectiveness of the feedback collection system.

To distinguish passive and active feedback and facilitate integration with linked building data, future development of the WOMO ontology should consider integrating the specialized Occupant Feedback ontology by Donkers et al. (2022b). Likewise, the `op:Feedback` concept, central to the Occupancy Profile ontology, should be evaluated for potential incorporation into WOMO to strengthen feedback modeling. Additionally, the provenance information and relationships between agents and recipients of feedback could benefit from linking the feedback concept to `prov:Entity` concept in the PROV ontology. Finally, to enhance the expressiveness of worker survey responses—currently limited to the `womo:RatingScale` concept within the worker module—more comprehensive definitions from the Survey ontology, covering options for survey items other than Likert-scale ratings, could be incorporated.

Concludingly, while the current implementation of the WOMO ontology focuses on achieving robust modularity, scalability, and effective integration with established ontologies such as BOT and SSN—supporting use cases like workplace performance assessment—important areas remain for further development and investigation, particularly in addressing more advanced use cases. To support issue discovery and enable dynamic spatial recommendations, the ontology’s reasoning capabilities need to be thoroughly explored and validated through comprehensive testing. Moreover, the current version defines a limited, predefined set of environmental and worker feedback factors; expanding these descriptions to capture a broader spectrum of occupant experiences is a priority for future work and real-world implementation. Finally, as the ontology relies on structured data, additional strategies should be explored to address scenarios where data may be incomplete or inconsistently formatted. Addressing these aspects will be key to evolving WOMO into an even more robust and dynamic framework for occupant-centric workplace management.

5

Workplace Semantic Digital Twin Concept

In this chapter, the development of the Workplace Semantic Digital Twin (WSDT) system is detailed. To ensure the system addresses the research framework goals, the system use cases are first identified (§5.1). Then, the system requirements are specified, distinguishing between functional and technical requirements (§5.2), outlining the features the system must provide and the technical constraints it must operate within. Finally, the development of the system architecture is discussed, specifying its reference high-level framework (§5.3) and its technical implementation with a service-oriented design (§5.4).

The first 90 percent of the code accounts for the first 90 percent of the development time. The remaining 10 percent of the code accounts for the other 90 percent of the development time.

- Tom Cargill, Bell Labs (1985)

5.1. System use cases

The Workplace Semantic Digital Twin (WSDT) system proposed in this dissertation aims to enhance workers' well-being and productivity by offering actionable insights derived from the integration of their preferences and perceptions with the conditions of the contextual work environment. As discussed in relation to the WOMO ontology (§4.3), this overarching goal is pursued through the identification of three key use cases and operational scenarios where the WSDT system can support workplace managers decision-making (Table 5.1): *workplace performance assessment*, *workplace issue discovery*, and *worker preference clustering and recommendation*.

Table 5.1 Use cases of the Workplace Semantic Digital Twin.

Use case	Purpose	WSDT service
Workplace performance assessment	Evaluation of the extent to which a workplace supports (or hinders) its occupants' health, well-being, and productivity through the correlation of subjective feedback and objective indoor environmental conditions.	Workplace knowledge base deployment and maintenance. Heterogeneous data collection, semantic integration, processing, and visualization.
Workplace issue discovery	Evaluation of the distribution of unsatisfactory conditions and identification of latent issues that affect workers' needs.	
Worker preference clustering and recommendation	Learning and aggregating worker needs and preferences. Prediction of ideal conditions for worker groups or profiles. Recommendation of solution for underperforming spaces or occurred issues.	Recognition and evaluation of recurrent data patterns and correlations between occupant- and workspace-generated data.

Firstly, the system should facilitate the assessment of different facets of workplace performance by monitoring and storing real-time data on workspace and employee conditions and ongoing activities, as well as maintaining historical records. It should monitor and compare IEQ factors (e.g., thermal properties) and operational conditions (e.g., occupancy patterns) with predefined ranges, thus highlighting the occurrence of situations potentially uncomfortable or unsuitable for the assigned activities. The allocation of resources could be made more efficient by analysing and visualizing usage data, enabling the identification of misused or underutilized workspaces (e.g., shared office used for meetings, workspace with recurrent low occupancy). Additionally, the system should collect and contextualize occupants' subjective perceptions (e.g., feedback) and health indicators (e.g., heart rate) to incorporate user preferences and physiological states into the assessment of workspace performance across various building topological scales (e.g., workstation, room, department). Even without environmental sensor data, occupant-reported satisfaction alone can provide valuable insights into specific factors. For instance, repeated negative feedback on thermal quality can indicate an underperforming workspace, regardless of the availability of air temperature and relative humidity measurements. Furthermore, by correlating occupant feedback with environmental sensor data, workplace strategies tailored to occupants' preferred conditions can be implemented, such as organising workspaces based on different thermal environments and activity profiles.

Secondly, the system should enable the identification of root causes when occupants report unsatisfactory conditions for one or more workspaces, whether they fail to meet functional requirements or occupants' needs and preferences. By analysing the distribution of feedback and its timely correlation with observed workspace properties, hidden correlations can be uncovered. These insights can help workplace managers establish the underlying causal relationships of workers' negative perceptions and determine whether the issues can be addressed at the workspace or individual level. For instance, in shared workspaces, if negative feedback is concentrated spatially (e.g., in a specific workstation), temporally (e.g., within a limited time window), functionally (e.g., during specific activities), or originates primarily from a particular employee, the issue may be resolved through organisational actions. Conversely, for issues which are persistently shared by a variety of workers, interventions should focus on the improvement of workspace operation. This could involve rearranging the workstation layout, adjusting, replacing, or adding equipment and systems, or changing employee allocation and activity schedules.

Eventually, the system should implement clustering algorithms to recognize recurring data patterns, learn, and evaluate worker needs. By analysing data on workspace utilization, environmental conditions, system and equipment operation, and occupant feedback, the system should identify distinct worker profiles and the associated preferences. This information could then be used to predict optimal workspace conditions tailored to specific worker groups or profiles, fostering a personalized and productive work environment. The system should not only alert managers to uncomfortable or unproductive environmental conditions but also offer targeted recommendations to optimise workspaces, meeting the diverse needs and preferences of their occupants.

5.2. System requirements

This section specifies the requirements that the proposed WSDT must satisfy to address the discussed use cases. Drawing from the general DT paradigm presented by Boje et al., (2022), these requirements are divided into two groups – *functional requirements* and *technical requirements* – and drive the development of the system's conceptual (§5.3) and technical architecture (§5.4).

5.2.1. Functional requirements

The functional requirements outlined in Table 5.2 detail the capabilities that the system must offer to achieve effective and meaningful synchronization between the physical workplace and its digital counterpart, thereby supporting its core functions and use cases. The system's sensing and monitoring features should facilitate the continuous collection and contextual interpretation of diverse data streams that describe the physical environment (e.g., workspace), its occupants (e.g., workers), and their activities.

At this stage of development, the system does not include the capability to autonomously act upon any part of the work environment or its occupants in response to detected events (e.g., adjusting, activating, or deactivating physical components), unlike the approach taken by Boje et al. Its primary function is to support the workplace manager's decision-making process, enabling them to take necessary actions such as adjusting workspace spatial configurations, modifying operational parameters, reallocating resources, and reassigning activities and employees. In doing so, the WSDT system is currently intended to operate in integration with, rather than replacing, existing Building Management Systems (BMS).

5.2.2. Technical requirements

The effective deployment, maintenance, and future development of the WSDT functions depend on addressing both current and evolving technical challenges with appropriate solutions. For this purpose, the technical requirements listed in Table 5.3, developed elaborating the criteria outlined Boje et al., (2022) for the context of occupant-centric workplace management, have been identified to guide the system's implementation.

Table 5.2 Functional requirements of the Workplace Semantic Digital Twin (adapted from Boje et al., 2022).

System part		**Functional requirement**	**Description**
Physical twin	Workspace	Sense	Observe and measure in real-time using sensors objective properties affecting or characterizing the work environment and its physical components, e.g., internal air temperature, external air pollutant concentration, window opening status, HVAC operational conditions, occupancy count, etc.
		Monitor	Track, inform and issue warnings on observed workspace and workspace elements properties.
	Worker	Sense	Observe and measure in real-time via wearable devices and online polls worker objective and subjective properties, including but not limited to indoor location (i.e., workspace or coordinates), health indicators (e.g., heart rate), feedback (e.g., thermal preference, self-assessed productivity).
		Monitor	Track, inform and issue warnings on observed and reported worker conditions in the workspace context.
	Activity	Sense	Observe and measure in real-time the activities performed by and the social interactions occurring among workers via direct and/or indirect methods, e.g., activity recognition on camera footage, movement and metabolic rate inference from wearable devices, self-reported activity via micro-surveys.
		Monitor	Track, inform and issue warnings on observed and reported activities in the workspace context.
Digital twin	Data	Collect	Collect heterogeneous data in various formats, e.g., BIM, IoT, BMS, etc.
		Store	Store raw data, processed data and knowledge facts about the workplace.
		Integrate	Semantically integrate static and dynamic heterogeneous data in the workplace knowledge base.
		Link	Map the system resources and observed entities over the semantic web and interlink them with the stored static and incoming dynamic workplace data.
		Share	Share workplace data, facts and insights over IoT and semantic web protocols.
		Process	Enable semantic data processing, inference, validation and reasoning.
	Service	Emulate	Represent historical and real-time physical workplace properties and events, i.e., workspace-worker-activity.
		Diagnose	Monitor worker and workplace conditions. Assess workplace performance for objective indicators and subjective worker perceptions. Detect suboptimal workplace conditions and their actual or potential causes.
		Visualise	Support data understanding through graphical elements (e.g., diagrams, charts) and data tridimensional contextualization within the workplace model.
		Learn	Recognition and evaluation of recurrent data patterns and correlation in worker-workplace data. Aggregation of needs and preferences for worker groups or profiles.
		Predict	Predict the ideal workplace conditions for worker groups or profiles.
		Recommend	Apply optimisation methods and recommend resource allocation or spatial interventions to improve conditions of underperforming workspaces or solve occurred issues.

Given the increasing digitalization of the built environment and the growing availability of physical and virtual resources to be integrated into cyber-physical systems serving emerging use cases and evolving contexts, the WSDT system must be adaptable and scalable while preserving data, information, and knowledge for future use. For this purpose, this dissertation adopts the modular DT concept proposed by Kosse, Hagedorn and König (2024), and align with a system-of-system paradigm as suggested by Hagedorn et al. (2024).

Moreover, due to the sensitive nature of data related to workplace occupants, robust security measures are essential, including stringent access controls at all levels (e.g., employee, workplace manager). Additionally, the system should feature user-friendly interfaces that facilitate efficient interactions, allowing users to effectively utilize the system's services, data, and visualizations capabilities.

Table 5.3 Technical requirements of the Workplace Semantic Digital Twin (adapted from Boje et al., 2022).

Technical requirement	Description
Connectivity	System ability to connect with physical and virtual resources over the internet or other protocols, e.g., IoT devices and sensors, mobile devices, wearables, databases, etc.
Interoperability	System ability to exchange data with other systems internal and external to the building and the organisation, e.g., Building Automation and Management Systems (BASs, BMSs), Computerized Maintenance Management Systems (CMMSs), HR management systems, etc.
Extensibility	System ability to adjust to the evolution of current use cases, to support future different use cases (e.g., optimal workspace recommendation to the employees, etc), and to be extended to additional data sets (e.g., historical occupant health indicators such as sleep or step trends, etc).
Modularity	System architecture oriented to the composition of manageable components which can be analysed and optimised independently and with minimal impact on other components in case system requirements change or are extended.
Re-usability	System ability to re-use services, resources, captured and processed data, and extract insights for new applications or use cases.
Maintainability	System ability to allow easy maintenance as it develops and changes.
Security	System ability to ensure data privacy and security, particularly concerning sensitive organisational and occupant-generated data, e.g., environmental preferences, self-assessed conditions, timely location and activity, health indicators, etc.
Controllability	System ability to be configured and controlled by its end users.

5.3. System architecture

Deriving from the use cases and requirements specified above, this section outlines the high-level structure and key components which informed the following technological choices and strategy used for the system implementation (§5.4).

The conceptual architecture of the WSDT system provides a four-layered reference framework, illustrated in Figure 5.1, which connects the physical system (workplace) to its digital counterpart and end users (workplace manager). This architecture informs the current technical implementation and guides future developments by describing the components within each layer, their rationale, and mutual interactions.

At the bottom, the *physical layer* represents the workplace ecosystem, including all its elements and entities, their interactions, their physical and functional properties, and the integrated monitoring systems. Workplace environmental and operational properties (e.g., air temperature, window opening, occupancy) are observed in real-time by the deployed sensors. Workers' objective and subjective conditions (e.g., location, environmental preference), health indicators (e.g., heart rate), and activities are collected through momentary feedback, wearables, and mobile devices. All these collected data represent the dynamic conditions of the workplace and its occupants over time and are continuously transferred to the upper layer dedicated to data storage.

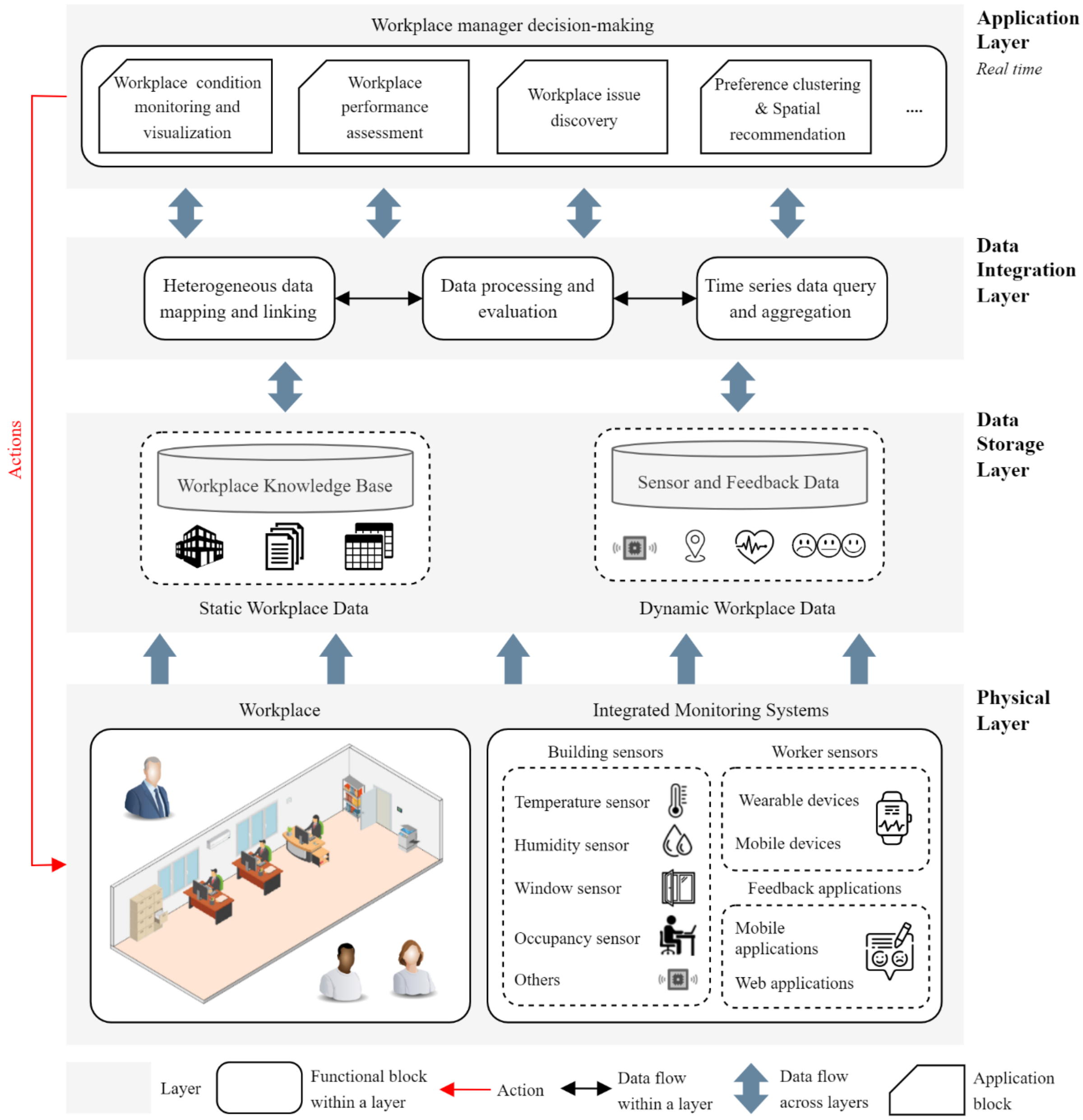

Figure 5.1 Conceptual architecture of the Workplace Semantic Digital Twin system.

The *data storage layer* serves two primary purposes: storing the static and dynamic workplace data. The former consists of building and organisational information, which is invariant or seldom changes over time. Such information can be highly heterogeneous and is usually scattered in structured or unstructured formats across different documents and databases. The translation of this information into a knowledge graph structure according to predefined ontologies and its semantic interlinking forms the static part of the workplace knowledge base. In this regard, although not limited to this, the system architecture heavily relies on the availability of a BIM model to derive the core topological, functional, and physical elements of the workplace and their relationships. On the other hand, the dynamic data comprise workplace observations and workers' feedback collected over time from various monitoring systems (e.g., sensors, wearables). These data are integrated and stored in a dedicated timeseries database to ensure efficient storing and a consistent timestamp assignment across heterogeneous sources.

Complementary to the storage layer, the *data integration layer* comprises the system's data processing and semantic integration capabilities. Here, different services enable the translation, mapping, and interlinking of the heterogeneous data forming the workplace knowledge base. Dynamic workplace observations are queried and added to the workplace graph in aggregated form (e.g., hourly mean values) and only depending on specific use case requirements, keeping the graph lean and leaving the bulk of the raw data stored in the time series database. Semantic reasoning capabilities are applied to evaluate the available data and infer knowledge according to the adopted ontologies and criteria. This layer provide access to the workplace knowledge base and time series database, bridging the two, and mediates the incoming requests from the top *application layer*.

This last layer provides the system's services which allow the end user, the workplace manager, to interact with the Digital Twin and be supported in the decision-making process for the identified use cases. These services should be designed to have user friendly interfaces (e.g., dashboards) and include functions for workplace condition monitoring and visualization, workplace performance assessment (i.e., building-worker-activity data correlation), issue discovery, and spatial recommendation.

Through the services in the application layer, workplace managers can access, visualize, and modify information contained in the workplace knowledge based, monitor workplace conditions, assess performance as perceived by employees, and ultimately obtain actionable insights and recommendations to enhance their well-being and productivity.

5.4. System implementation

This section concludes the discussion of the system development by detailing the system's technical architecture (Figure 5.2), including the components and functions that informed the practical system's implementation (Chapter 6-7), organised into three main areas:

- *Physical workplace*: This corresponds to the system's *physical layer* and includes the building's indoor environments (workspaces) and their occupants (workers). For each monitored workspace, environmental properties (e.g., CO_2 concentration) and operational properties (e.g., occupancy) are measured by the deployed sensor network. Workers' objective and subjective data (e.g., location, physiological parameters, preferences) are provided through momentary feedback and on a voluntary basis.
- *Workplace digital twin*: This includes the remaining layers of the system architecture. It encompasses data storage, integration, and processing functions for both time series and static workplace data, along with services that enable end-user interaction. Sensor observations and worker feedback are stored in a time series database, from which they are retrieved on-demand for processing and integration with static information (e.g., BIM) semantically stored in the workplace knowledge base. The ontological description of these heterogeneous concepts, properties, and relationships allows the implementation of specific services for semantic processing and data visualization (e.g., data query and inference, BIM viewer). Workplace managers can access and leverage the digital twin capabilities through user-friendly interfaces (dashboards) where these services are combined and orchestrated.

- *Workplace manager*: These are the system's end users, responsible for ensuring workplace conditions that foster employees' safety, well-being, and productivity, as well as achieving organisational goals. The system allows managers to monitor and assess the performance of various workspaces based on employee feedback and notifies them when IEQ parameters or operational conditions fall outside predetermined ranges. Additionally, managers are supported in their decision-making process by the system's services for identifying hidden issues and providing data-driven recommendations to improve workspace organisation and resource allocation.

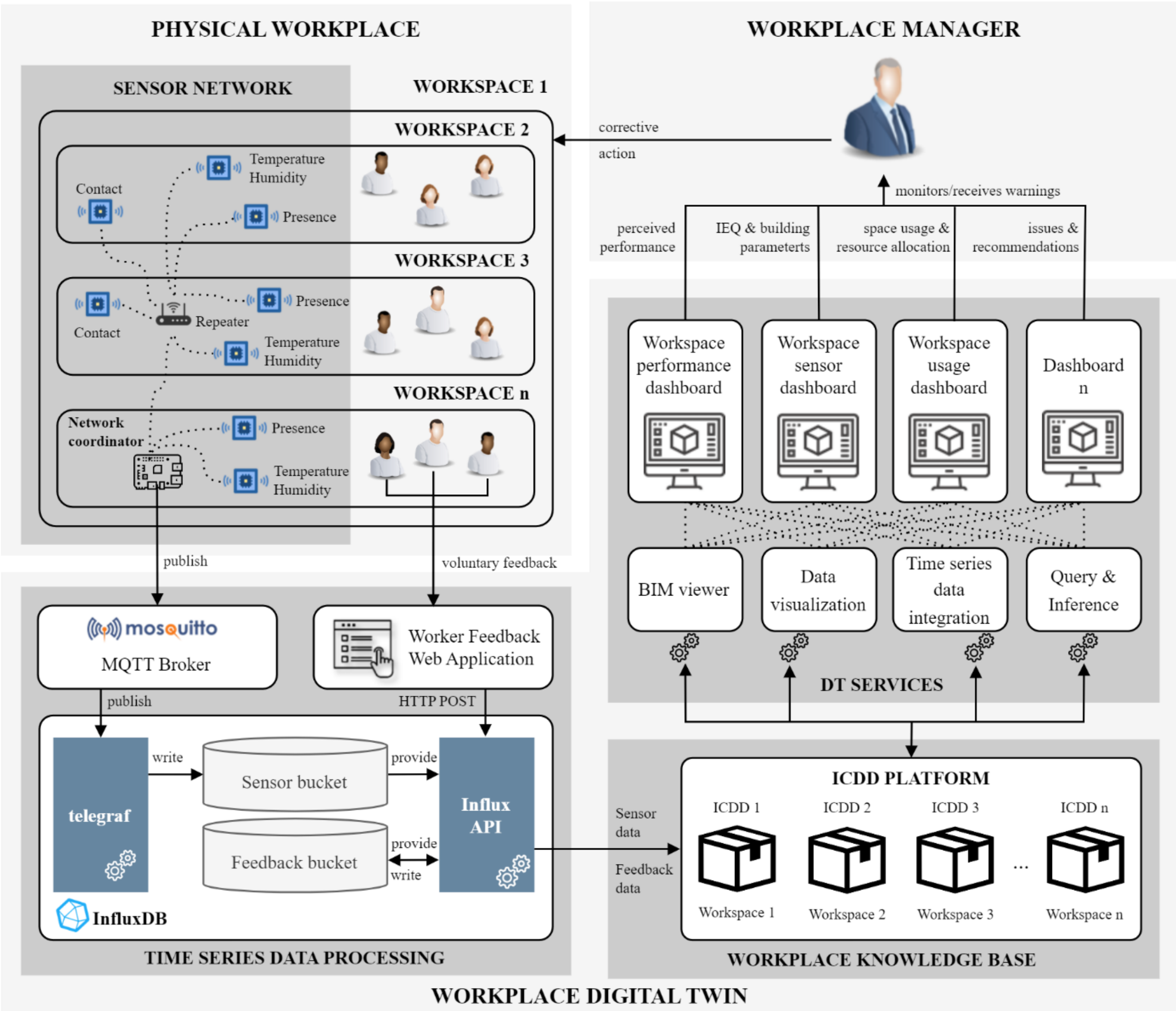

Figure 5.2 Technical architecture for the implementation of Workplace Semantic Digital Twin system.

The following paragraphs describe the hardware and software solutions adopted for the implementation of the system prototype (Chapter 6), tested on a single-workspace application, and its subsequent extension to a department-scale case study (Chapter 7).

5.4.1. Sensor network

In the last decade, the growing interest in IoT technologies for monitoring, managing, and automating the built environment has led to the proliferation of commercial solutions for various applications (e.g., smart-home, domotics, Industry 4.0). For the scope and purposes of this work, the choice of the most suitable technology and data communication protocol for the system sensor network was based on the following criteria:

- *structure and organisation* of the monitored spaces;
- *sensor* accuracy, installation type, and maintenance;
- *network* configuration, flexibility, and extendibility.

A workplace consists of a combination of several indoor building spaces (workspaces) with similar spatial, organisational, and functional properties hosting employees during their daily routines. The spatial resolution at which the workspace conditions need to be monitored varies with the use case requirements. Ideally, sensor deployment at the workstation level would allow the observation of the immediate worker's environment and more accurate correlations with their feedback (e.g., noise level and perceived disturbance). However, for certain workspace configurations and IEQ factors, room-level observations (e.g., air temperature and humidity) could still provide a sufficient understanding of workers' experienced conditions.

The system's targeted workplaces consist of office buildings of recent construction, with light vertical partitions (i.e., drywalls) and a regular, modular workspace distribution. These include private and shared office rooms, laboratories, and meeting rooms, with a gross floor area not exceeding approximately 50 m^2. Although integrating sensors already installed in the building should be considered for future developments, it is not included at this research stage. Based on these assumptions, a wireless network using the Zigbee[30] communication standard is chosen for the sensors' deployment. Zigbee compatible commercial sensors and devices are well-established in smart-home and smart-building applications due to their network reliability, ease of deployment and maintenance, and sufficient accuracy for consumer-level applications at a competitive cost compared with other solutions.

The Zigbee protocol supports mesh networking (Figure 5.3). In these networks, each device represents a node and is interconnected with other nodes so that multiple data transmission pathways can be established. All nodes must reach a unique network coordinator node that hosts the network gateway and provides configuration functions. Therefore, the coordinator node is power-supplied and must always be online to coordinate data transmission within the network and outside. All the other nodes connect to the network via the gateway. Since the gateway's signal range is limited, the mesh topology can be extended through power-supplied devices acting as repeaters (e.g., smart-plugs). Connections between nodes and the gateway, potentially routing through repeaters, are automatically optimised and dynamically reconfigured depending on the registered signal strength and mesh status. This provide flexibility and redundancy to the network, allowing for the addition and removal of nodes without disruption if backup pathways are available to reach the gateway.

Considering the system requirements and design constraints outlined above, the selection of commercial Zigbee-compatible sensors was deemed optimal at this stage of development due to their proven reliability, ease of installation, and competitive cost. Their performance aligns well with the study's current scope and the spatial configurations of the targeted workplaces. However, we acknowledge that alternative technologies— as sensors based on the Long Range Wide Area Network (LoRaWAN) protocol, which may offer extended communication ranges

[30] https://csa-iot.org/all-solutions/zigbee/ - Accessed 05/05/2025.

and improved energy efficiency—could provide additional benefits in larger or more complex environments. Future research should investigate these options to further enhance the scalability and adaptability of the sensor network.

For the proposed implementation, three types of sensors—each functioning as a simple node—have been selected to monitor key workspace properties. Literature consistently highlights the critical role of the thermal environment in influencing occupant well-being and productivity, which justifies the inclusion of an integrated thermometer and air humidity sensor. In addition, maintaining optimal indoor air quality is essential for comfort and performance; therefore, a contact sensor has been selected to monitor window opening status, which can serve as a proxy for both ventilation and IAQ. Finally, recognizing that social density significantly affects both comfort and productivity, a motion sensor has been incorporated to detect workstation occupancy and enable workspace occupancy counting. To facilitate their deployment, substitution, and maintenance, battery-powered sensors that can be installed without screws have been adopted. For extending the network topology, Zigbee-compatible smart-plugs functioning as repeaters have been deployed. The technical specifications of the adopted sensors is left to the discussion of the system implementation in Chapter 6 and 7.

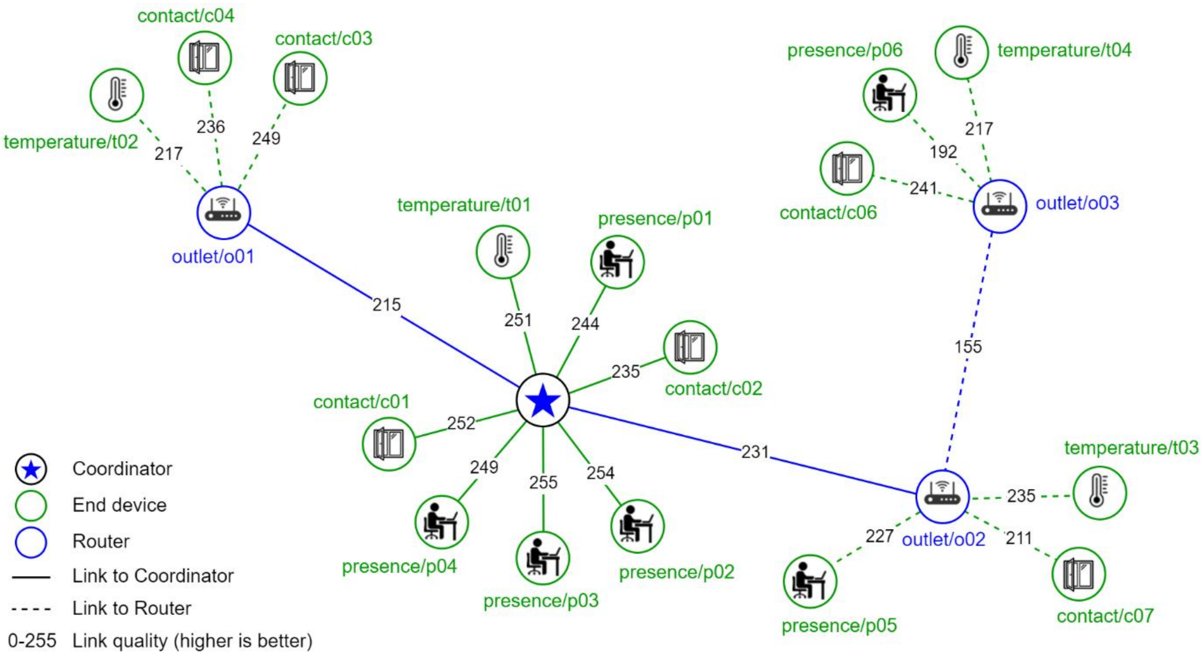

Figure 5.3 Zigbee mesh network sample.

From each node, measurements and metadata (e.g., sensor battery level, signal strength) are transmitted to the coordinator node. In the proposed configuration, the coordinator consists of a universal USB Zigbee gateway running on a Raspberry Pi[31] system-on-chip (SoC), which in turn is linked via Ethernet to the system backend hosted on a server within the workplace organisation. On the Raspberry Pi is installed an open-source Zigbee2MQTT[32] 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 the Message Queuing Telemetry Transport (MQTT) protocol to transfer it outside the network, where can be

[31] https://www.raspberrypi.com/products/raspberry-pi-3-model-b/ - Accessed 05/05/2025.
[32] https://www.zigbee2mqtt.io/ - Accessed 05/05/2025.

used by the system. The MQTT messaging protocol was chosen due to its acknowledged performance in machine-to-machine (M2M) communication and Internet-of-Things (IoT) environments. It is based on the open standard ISO/IEC 20922:2016, runs over TCP/IP or other protocols that ensure ordered, lossless, bi-directional connections and supports one-to-many message distributions. It suits our system requirements because its simple client-server publish/subscribe model can be embedded on mobile devices and microcontrollers with limited resources thanks to its small code footprint and efficient use of bandwidth.

Sensor measurements and metadata are encoded in message packages according to the MQTT protocol and published on dedicated topics (Table 5.4) to an instance of Eclipse Mosquitto[33], selected open source MQTT message broker, running on the backend server. The topic structure is sensor-oriented and completely decoupled from the sensor location. One topic is established for each sensor, identified via a progressive alphanumeric code. This provides greater flexibility in adjusting sensor deployment: when a sensor is moved to a different location or workspace there is no need to adjust the topic hierarchy nor the configuration of the system services subscribing to those topics, such as the agent feeding the time series database with the sensor observation data. Information related to the sensor position, fundamental for interpreting its observations, is stored in the workplace knowledge base according to the classes and properties provided by the SSN ontology. Updating the position property linked to the sensor instance in the workplace knowledge graph is the only necessary action to maintain semantic consistency in the data exchange and interpretation throughout the system when changes occur to the sensor network.

Table 5.4 MQTT topics hierarchy and message payload example for the three sensor types (observations in green).

MQTT Topic	Message payload
sensors/presence/p06	{“battery”:100,”device_temperature”:29,”illuminace”:0,”illuminance_lux”:0,“linkquality”:255, ”occupancy”:true}
sensors/temperature/t13	{“battery”:77,”humidity”:32.18,“linkquality”:255,”power_outage_count”:11,“pressure”:980.5, ”temperature”:25.32}
sensors/contact/c07	{“battery”:100,”contact”:true,”device_temperature”:25,”linkquality”:255, ”power_outage_count”:5}

5.4.2. Time series data storage and processing

The proposed system relies on the semantic integration of static and dynamic workplace data. The latter includes a high volume of sensor observations characterizing the physical environment and subjective worker conditions collected through voluntary feedback. Especially for sensor time series data, converting hundreds if not thousands of data points per day into triples, including measurements and metadata, would not be efficient nor necessary. Depending on the use case requirements, only aggregated data (e.g., hourly mean values) might be of interest and could thus be permanently stored in the workplace graph or retrieved on demand from separate storage. Moreover, integrating dynamic data from heterogeneous sources (e.g., sensors, wearables, feedback) requires a reliable and consistent time reference (timestamp). For these reasons, to avoid the possible loss of any relevant data, a time series database is used to ensure efficient storage of all workplace time series data.

[33] https://mosquitto.org/ - Accessed 05/05/2025.

In the proposed implementation, an InfluxDB[34] time series database is instantiated on the system backend server. InfluxDB is a data platform specialized in the collection, storage, and processing of time series data, which can be hosted on local or cloud servers. It is provided with an intuitive visual interface accessible via browser, featuring tools and functions to facilitate data querying and visualization. In InfluxDB, a named location where time series data is stored is called a "bucket". Organising different data into distinct buckets facilitate their processing. Most importantly, a specific retention period -the duration of time that each data point persists- can be set for each bucket, along with automatic maintenance tasks (e.g., downsampling, decimation). For our system, two buckets have been defined: "sensor" and "feedback".

As discussed in the previous paragraph, messages containing measurements and metadata are transmitted from the deployed sensors to the network gateway according to the Zigbee protocol. Here, they are encoded into MQTT message packages and published to dedicated topics via the Mosquitto MQTT broker. To collect these messages and write them into the sensor bucket, an open-source server agent, Telegraf[35], is implemented on the system backend server and configured to subscribe to all the "sensors" topics published by the broker. In contrast, worker feedback data are recorded in the "feedback" bucket via the InfluxDB API directly from the developed survey web application. Additionally, through the InfluxAPI the bi-directional connection between the time series data and the workplace knowledge base is also enabled as it is used by a system service appointed for their querying, retrieval, and semantic integration (§5.4.4).

5.4.3. Worker feedback web application

For the description of timely worker conditions and experience in the workplace, the system architecture (Figure 5.1) considers two categories of data: health indicators or physiological parameters, objectively observed by wearable sensors, and subjective preferences and self-assessed conditions, reported by voluntarily responding to micro-surveys with Likert-scaled questions. Several studies have demonstrated the feasibility of integrating the collection of both data categories by implementing customized clock-face applications on consumer-level smartwatches (M. M. Abdelrahman et al., 2022; Donkers et al., 2022c; Tartarini et al., 2022). In this dissertation, the system was initially designed to be evaluated under real-world-like conditions involving up to 20 employees. To concentrate on key aspects of the proposed solution, continuous monitoring of workers' physiological parameters via wearables was not pursued and deferred to future work. Instead, a web application with a customizable one-page survey was developed and implemented on the system backend server, enabling the timely collection of worker activities and subjective perceptions (Figure 5.4-Figure 5.5).

Each authorized employee participating in the data collection is granted access to the survey form via browser from their workstation and is requested to voluntarily provide feedback several times during the time they spend at the workplace (i.e., workdays spent in different locations or in home-office are not considered). Four evenly distributed feedback submissions during the workday are recommended to enable the collection of significant data without being too intrusive. However, no minimum or maximum number of feedback is imposed on the

[34] https://www.influxdata.com/ - Accessed 05/05/2025.
[35] https://www.influxdata.com/time-series-platform/telegraf/ - Accessed 05/05/2025.

participants. This approach also gauges the sustainability of the worker data collection system and the extent of survey fatigue, providing useful information for improving the data collection process. In our case, only voluntary feedback provided at the employees' initiative has been considered. Future developments should consider implementing scheduled requests and a notification system for the employee to respond to (grey in Figure 5.5).

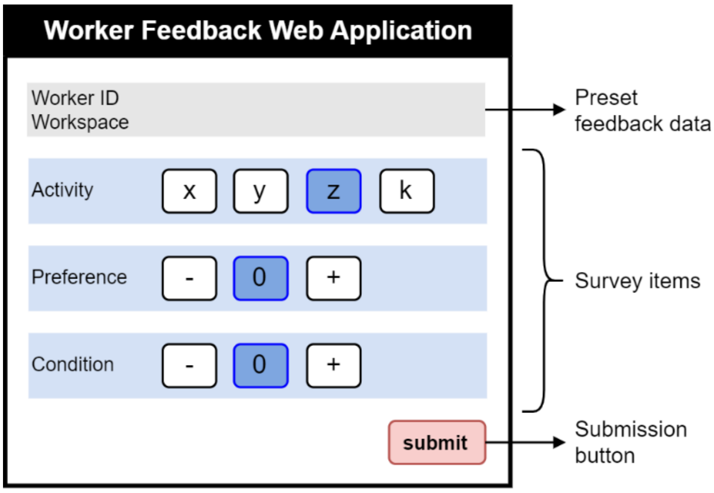

Figure 5.4 Worker Feedback Web Application one-page form layout.

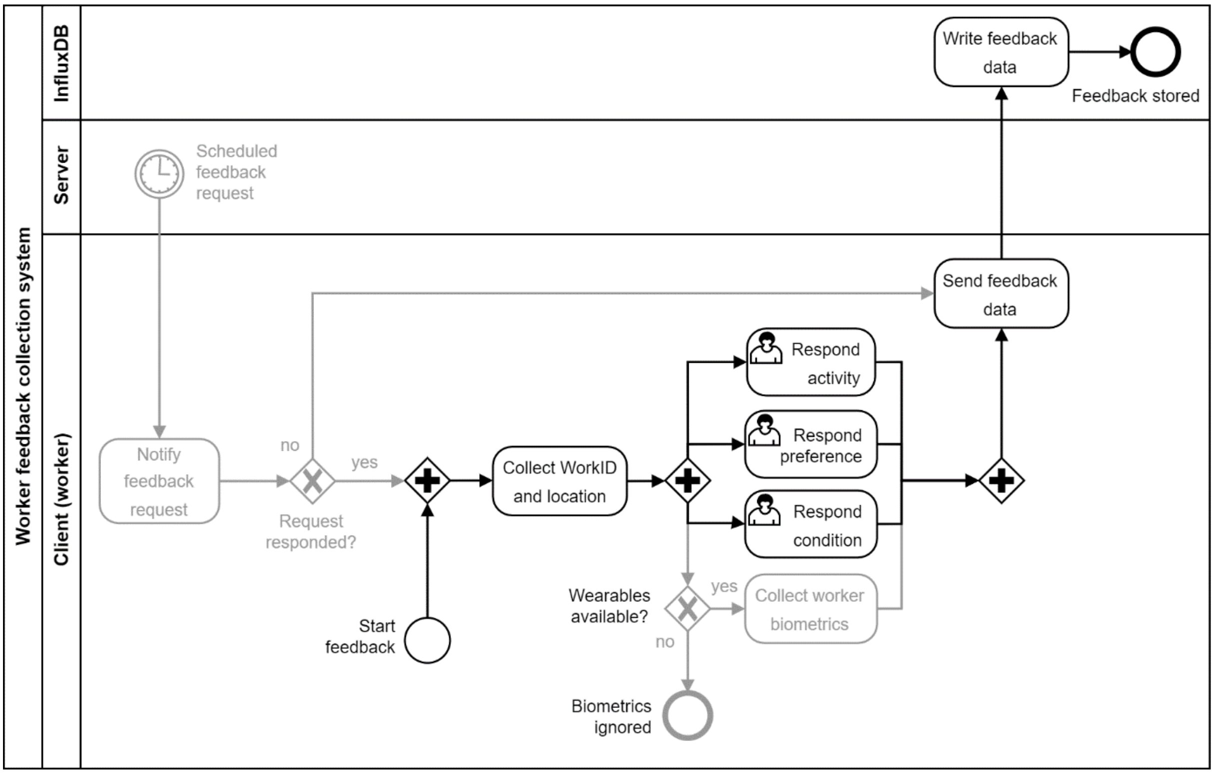

Figure 5.5 Feedback collection process (BPMN diagram).

The survey interface consists of a single page form designed to prevent survey fatigue bias allowing for fast and intuitive responses to multiple-choice questions. Worker ID and current location (workspace) are displayed but not editable, as they are preset based on the allocated workstation. Three survey sections, each with one item, are presented in the following order: current activity, environmental preference, and self-assed condition. Each item includes a written prompt and a set of response buttons with both an icon and a textual caption corresponding to their value. Participants can express their feedback by pressing the buttons, which change to a “selected” state, and they can change their response any time before submitting the form.

This streamlined design was intentionally chosen to capture the three core aspects of the occupant experience assumed in this thesis—what the individual is doing, how they perceive the environment, and how they feel about their own condition—with minimal mental load. For the activity item, the category, type, and social interaction information are included. For the preference and condition items, a minimum three-point scale is recommended, featuring a central neutral value to express satisfaction with the environment or baseline self-assessed condition, accompanied by two additional options indicating opposite directions. For instance, the thermal environment preference can be gauged with “prefer cooler, no change, prefer warmer”, while “not productive, normal, very productive” can relate to self-assessed productivity. Although participants are encouraged to complete all survey items, the form can be submitted even if some items are left unanswered.

To accommodate different use case requirements, the survey form can be customized to always present the same items in terms of environmental preference and self-assessed conditions or to randomize its composition each time with different options. On submission, the worker feedback web application transmits and writes the collected responses to the feedback bucket in the instantiated InfluxDB time-series database using the HTTP POST method and the InfluxDB API. These data points are coherently timestamped and stored alongside the sensor observations and can be retrieved on demand by the system service appointed for their semantic integration with the other static data in the workplace knowledge base.

5.4.4. Workplace knowledge base

In the preceding sections, we discussed the technical solutions identified for collecting and managing dynamic workplace data generated by building sensors and workers’ feedback, as well as its storage within a time-series database. To integrate this dynamic information with static data related to the building and organisation—commonly siloed in various formats and repositories such as BIM, documents, spreadsheets, relational databases—we propose implementing the workplace knowledge base using information containers compliant with the Information Container for linked Document Delivery (ICDD) standard (ISO 21597-1:2020). ICDD containers organise heterogeneous data and documents in a standardized structure (Figure 5.6) that allows for semantic interlinking, querying, and processing according to predefined ontologies.

At the top level of the container, an index file (*index.rdf*) and three folders are provided: *Ontology resources*, for the vocabularies necessary to describe the stored contents; *Payload documents*, for the stored documents; and *Payload triples* for data stored as triples and linksets describing connections among the stored documents and data. The *Linkset.rdf* vocabulary describes the links between the indexed documents, while special link types are defined by *ExtendedLinkset.rdf*. This structure supports deep linking, enabling entities within documents to be interlinked. For instance, using the IFC-GUID, the entity representing a sensor in the workplace IFC model can be linked to its observations stored in triple format.

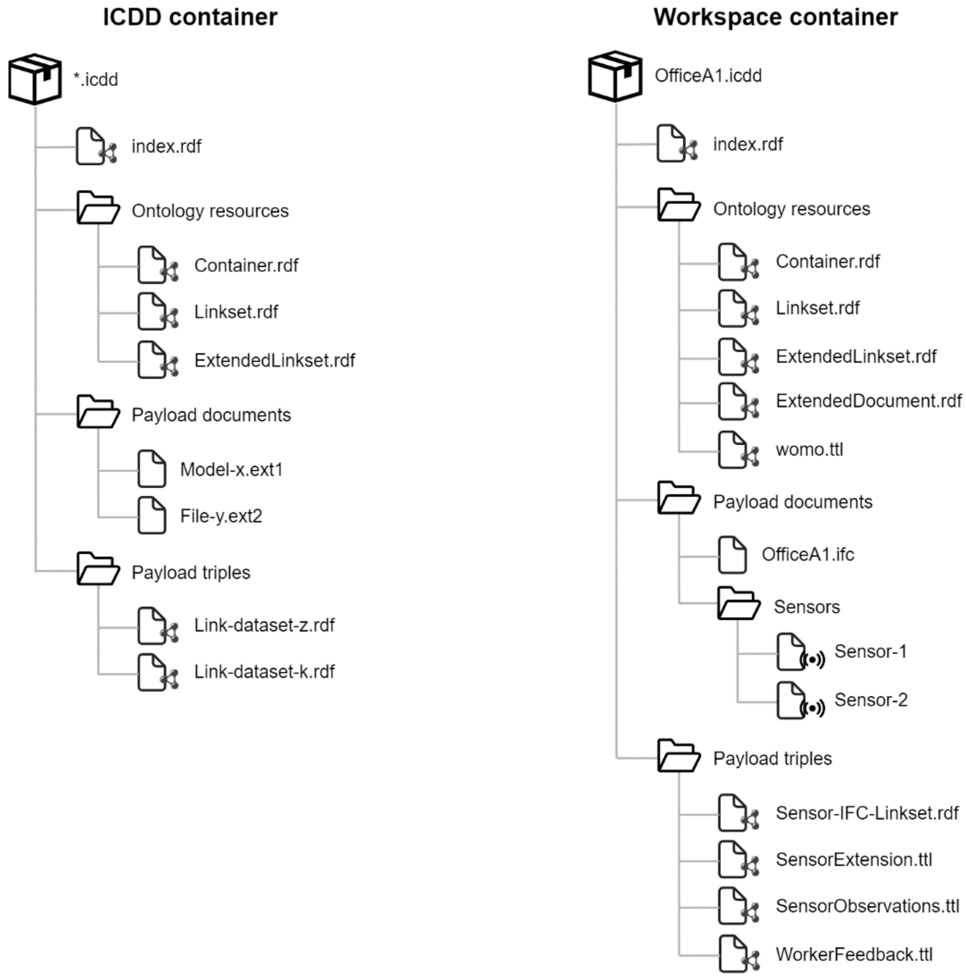

Figure 5.6 ICDD container structure: standard (left), workspace knowledge base (right).

This ICDD structure and its capabilities are used to implement the knowledge base of the proposed workplace semantic digital twin system. On the right side of Figure 5.6, an example ICDD is shown, storing the documents and data for a single workspace (e.g., OfficeA1). This example replicates the knowledge base from the system prototype implementation related to a shared office workspace, which is discussed in Chapter 6.

To store static workplace data and integrate it with sensor observations and worker feedback, in accordance with the classes and properties discussed in Chapter 4, the WOMO vocabulary (*womo.ttl*) is added to the ontology resources. Among the container's payload documents is included an IFC model representing the geometrical and functional characteristics of the workspace, along with documents for the deployed sensors. The building's topological information in the IFC model is mapped to BOT classes (i.e., `bot:Space`, `bot:Element`) and linked on-demand to sensor observations, worker features, preferences, activities, and feedback retrieved from the time-series database. This integration results in a workplace knowledge graph that can be queried to address the system use case requirements.

Sensor documents act as proxies, establishing a connection between the container and the external repository storing the time-series of sensor observations (e.g., InfluxDB). This implementation of non-standard document types overcomes the current ICDD limitations regarding time-series data handling while functionally distinguishing between two identified workplace data stores: ICDD containers for the workplace semantic knowledge base and the time-series database for storing and managing all dynamic workplace data (i.e., sensor observations and worker feedback). Through these sensor proxy documents, sensor observations stored in InfluxDB can be queried, retrieved, and serialized into triples according to the SSN vocabulary, on demand. The workplace data serialized in RDF-compliant format includes separate stores for the linkset between sensor entities and their corresponding IFC elements, the consolidated sensor observations (e.g., hourly mean values), and the worker data and feedback responses. Currently, worker information is not included in any document, and the retrieval of their data and feedback instances is directly handled by the system platform discussed later in section 5.4.5.

The capability to link multiple ICDDs and their respective contents allows for flexible organisation of the workplace knowledge base, depending on use case requirements, as well as the scale and complexity of the monitored workplace in terms of building size, sensor network, and employee population. For the case study conducted to upscale and evaluate the system's prototype, involving data integration from multiple workspaces, multiple ICDDs were interlinked, with a different organisation of contents discussed in Chapter 7.

5.4.5. ICDD platform and Digital Twin services

A crucial aspect of implementing the proposed WSDT framework is the ability to process and integrate the data stored within the ICDD containers that make up the workplace knowledge base. To achieve this, we utilized a customized version of the RUB ICDD platform[36] (Hagedorn, 2022), a web platform originally developed at the Chair of Computing in Engineering of the Ruhr University Bochum. This platform has been extensively tested and has proven effective in storing, querying, processing, and visualizing semantic construction data contained in ICDDs across various use cases, such as rule-based semantic validation of linked building models (Hagedorn & König, 2021), infrastructure asset management (Hagedorn, Liu, et al., 2023), and ontology-driven linking and validation of heterogeneous building data (Hagedorn, Senthilvel, et al., 2023).

To meet the requirements of the proposed WSDT system, the platform was customized to provide the following services:

- *Access control*: The platform distinguishes between different user roles, such as administrators and workplace managers. Administrators have full control over system configurations and user permissions, while workplace managers are granted access to all relevant data and tools for monitoring and managing the workplace. Although a role for employees is not currently implemented, future development should consider providing them with direct access to specific workplace data to support their daily routines (e.g., real-time workspace occupancy and condition monitoring) and to manage the information they choose to share with the system (e.g., customized privacy and feedback settings).
- *ICDD management*: This feature includes a comprehensive set of functions for generating and managing ICDD containers, enabling effective structuring and organisation of their contents. Only administrators can create, edit, and maintain the containers, define the ontology resources to be used to semantically describe the stored

[36] RUB ICDD Platform - https://icdd.vm.rub.de/ui - Accessed 05/05/2025.

knowledge, manage the included documents (e.g., workplace IFC models, sensor proxy documents), and initialize RDF-serialized linksets and datasets (e.g., sensor observations, worker feedback).

- *Time-series data retrieval and storing*: The platform facilitates the seamless connection with the InfluxDB time-series database. Sensor observations and worker feedback data points can be retrieved automatically (e.g., hourly) or manually to meet specific use case requirements. If the retrieved time-series data is relevant for describing the historical evolution of workplace conditions, it is serialized into an RDF-compliant format and stored within the ICDD containers to enrich the workplace knowledge graph. Currently, sensor proxy documents are used to enhance user interaction and visualization of sensor data, while the storage and retrieval of worker information are managed by the administrator.
- *Semantic data querying and processing*: Users can perform advanced queries on the workplace knowledge graph and semantically process the data stored within the ICDD containers using predefined ontologies. The platform's graphical interface allows users to build queries without requiring SPARQL knowledge, facilitating the extraction of meaningful insights to support workplace managers in decision-making.
- *Dashboards*: The platform features user-friendly dashboards designed to provide intuitive access to the aforementioned services, tailored to specific use cases. These dashboards support querying and visualization of workplace data in various formats, such as tables and graphs, thereby enhancing data interpretation and decision-making. The accessibility of these services is crucial for workplace managers.
- *IFC viewer*: An integrated 3D viewer allows for the spatial visualization of BIM-related workplace data. This feature supports a more immediate understanding of the workspaces by combining 3D geometries and building information from the workplace IFC model with sensor and worker time-series data.

The workplace manager user interface of the ICDD platform, customized for the system prototype and its subsequent case study extension (Chapters 6 and 7), is organized into three vertical panels—*Explorer*, *Dashboard*, and *Viewer*—arranged as shown in Figure 5.7. On the left side, the *explorer* panel allows for navigation within the workplace knowledge base. The data and documents stored in the various interconnected ICDDs are presented in their respective folders and can be selected by the user, prompting the *dashboard* and *viewer* panels to display the related information. On the right side, the *viewer* panel offers three data visualization services: an IFC viewer, graphs, and tables, each of which adjusts based on the use case or the type of data being visualized. For instance, when a specific sensor (i.e., sensor proxy document) is selected from the explorer panel, the platform retrieves the linked sensor entity from the workplace IFC model and highlights it in the viewer. Moreover, the most recent sensor observations could be retrieved from the time-series database and displayed in both graph and tabular formats. Additionally, the available sensor properties stored in the workplace knowledge graph are queried and returned to the user for evaluation.

The central part of the interface is occupied by the *dashboard* panel. Although workplace managers can select different dashboards depending on the use case, the layout is fixed and divided into three horizontal sections. The top section—*query builder*—hosts functions and settings that facilitate query definition, with the platform generating the SPARQL code in background. Below this, the *overview* section presents query results in an aggregated form, supporting a more contextualized view of the investigated conditions. For example, when querying worker-reported thermal preferences, this section might display results for each workspace along with the mean values of environmental properties corresponding to both satisfying and unsatisfying conditions (e.g., temperature, humidity, window status).

Finally, in the bottom section, a more granular visualization of the queried data is provided. Continuing with the previous example, selecting a specific workspace in the overview section would list all related reported preferences and corresponding properties (e.g., timestamp, worker, temperature, humidity, window status).

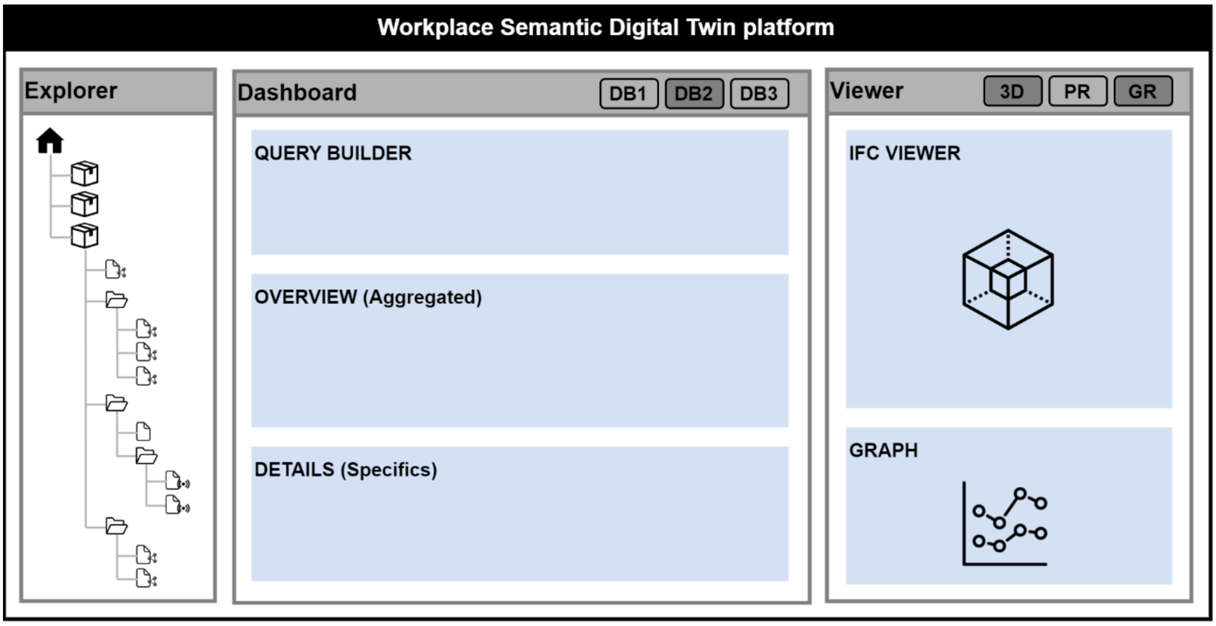

Figure 5.7 Layout of the Workplace Semantic Digital Twin platform interface.

This interface builds on previously implemented services and functions in the ICDD platform, customizing them to provide workplace managers with the necessary tools to leverage insights from the workplace knowledge base and enhance decision-making. Although the current dashboard design is fixed and primarily serves the demonstration of the feasibility of the WSDT system, a more flexible, user-tailored interface is essential for maximizing usability and value. The design already incorporates key principles that enable managers to easily browse and access both structured and unstructured data, evaluate integrated worker–workplace insights, construct queries intuitively without prior SPARQL knowledge, and comprehensively visualize data alongside a 3D workplace model. Future work should further develop these features to tailor the interface to specific use cases and user needs, with its design and functionality undergoing iterative testing and validation with domain experts to ensure usability and effectiveness.

5.4.6. Workplace manager

For the effective implementation of the proposed workplace semantic digital twin system, the workplace manager plays a crucial role in transforming the knowledge derived from the continuous flow of workplace data into actionable strategies and interventions that address identified issues and improve workers' conditions. As discussed earlier, the system services and dashboards enable managers to monitor various aspects of workplace performance, particularly the environment's impact on occupant satisfaction and productivity. By analysing collected feedback, managers can address factors that directly influence employee well-being.

The system monitors IEQ factors and other building metrics to ensure that the physical environment meets employees' needs and expectations. Additionally, it provides insights into space usage and resource allocation, allowing managers to optimise workspace utilization and effectively distribute resources to meet organisational goals.

Through advanced data analysis and semantic integration, the system can detect anomalies and trends indicating potential workplace issues. With future enhancements, such as clustering and learning algorithms, the system aims to offer data-driven recommendations for proactive improvements and corrective actions. Ultimately, by understanding the alignment between workers, their workspace, and their activities, the system supports managers in making informed decisions that enhance the physical environment to better meet employees' needs. This comprehensive approach ensures that the workplace evolves in response to changing conditions and feedback, fostering an environment that promotes well-being, satisfaction, and productivity.

6

Prototype Implementation

In this chapter, the implementation and testing of the prototype system of the proposed Workplace Semantic Digital Twin is presented. The first section outlines the prototype technical implementation, detailing the scope of its room-scale application for the monitoring of a shared office and the adopted hardware and software solutions (§6.1). This is followed by a comprehensive description of the sensor network setup, which provides the necessary infrastructure for workspace data collection (§6.2). The development and deployment of the worker feedback web application are then discussed, emphasizing its role in capturing subjective worker experiences (§6.3). Finally, the workplace knowledge base configuration and the customization of the ICDD platform with the Workplace Performance Dashboard, is addressed showing the system's capability to semantically integrate the collected heterogeneous workplace data and provide insights for the improvement of workplace conditions (§6.4). The chapter concludes with the discussion of the prototype’s strengths, limitations, and opportunities for improvement which will be addressed in the following development for a department-scale case study (§6.5).

If your only tool is a hammer then
every problem looks like a nail.

- Abraham Maslow

6.1. Prototype case study

This chapter discusses the first implementation of the proposed Workplace Semantic Digital Twin conceptual and technical architecture. The design of the system's prototype aimed to demonstrate the feasibility and capabilities of all its technical components and functional areas, initially focusing on a smaller, room-scale scenario. This approach allowed for a more granular evaluation of its performance, the identification of potential drawbacks and issues, and the refinement of the system before scaling up to a full workplace case study, which is discussed in Chapter 7. The case study specifications and room characteristics are reported in Table 6.1 and Figure 6.1.

The monitored workspace chosen for the prototype demonstration is a shared office room within the Chair of Computing in Engineering at the Ruhr University Bochum, located in Bochum, Germany. All components of the system's prototype, from the deployed sensor network to the system's backend server, are hosted within this department. The office is allocated to and accessible by four employees of the department. The space configuration reflects typical modular standards for the internal distribution of tertiary buildings, with a regular rectangular plan of 44 m^2 of gross floor area (11m^2 per employee). It features a partially glazed longitudinal side exposed externally (direction NE). Two manually operable windows provide for the room ventilation, while natural illumination is regulated by a motorized horizontal blind system, which is controlled automatically by an illuminance sensor for the whole façade but can also be manually actioned by the occupants through switches located in the room. The room does not have air conditioning or mechanical ventilation. Heating is provided by two adjustable radiators located beneath the windowsill. The office is equipped with archive cabinets and two double workstation desks, each accommodating two employees, with the necessary power supplies and Ethernet ports for Internet and LAN connections.

Three properties were monitored to describe the workspace conditions over time: thermal quality, occupancy, and window status. Given the office dimensions and configuration, the objective characterization of the thermal environment experienced by the employees was conducted through observations of air temperature and relative humidity at a single position. Additionally, contact sensors on both the operable windows were applied to monitor their opening times and enable the correlation of natural ventilation with workers conditions (e.g., thermal preference, productivity). Lastly, motion sensors were installed at each workstation to monitor occupation patterns and the cumulative workspace occupancy count. The deployed sensors register and transmit the values of the observed properties periodically (e.g., thermometer) or when activated (e.g., motion sensor, contact sensor). This discrete number of observations is stored in the system's time-series database, where it is processed on demand to extract more meaningful values, such as hourly mean temperature, for correlating with worker-generated data.

Worker feedback collection involved all four employees allocated to the monitored office, who provided their informed consent for the collection, processing, and conservation of their feedback data in anonymized form (e.g., worker1, …, worker4) for the system prototype evaluation.

Table 6.1 Case study office and data collection specifications.

Feature	Specifications
Workspace	**Type:** Shared office **Allocation:** 4 employees **Workstations:** 4 workstations (2x double workstation) **Dimensions:** 7,35 m x 6,00 m x 3,75 m **Area and volume:** 44,10 m^2; 165,38 m^3 **Orientation (windows):** North-East **Access:** Restricted only to allocated employees **HVAC:** Adjustable heating (radiators); Natural ventilation only; No air conditioning **Windows:** Two operable windows, adjustable motorized external blinds (horizontal fins)
Observed properties	**Air temperature and relative humidity:** 1x Temperature and humidity sensor (height: 0,70 m) [Aqara WSDCGQ11LM] **Occupancy:** 4x Motion sensors (detecting workstation occupation) [Aqara RTCGQ11LM] **Window status:** 2x Contact sensor (one per operable window) [Aqara MCCGQ11LM]
Worker feedback	**Participants:** 4 employees (allocated to the office) **Worker data:** ID, location (workspace), activity category and type, thermal preference, self-assessed productivity **Data collection system and strategy:** Worker Feedback web application (browser); voluntary (suggested frequency ≥ 4 feedback per worker per day) **Period:** 1x Work week (5 workdays) – 10-14/07/2023

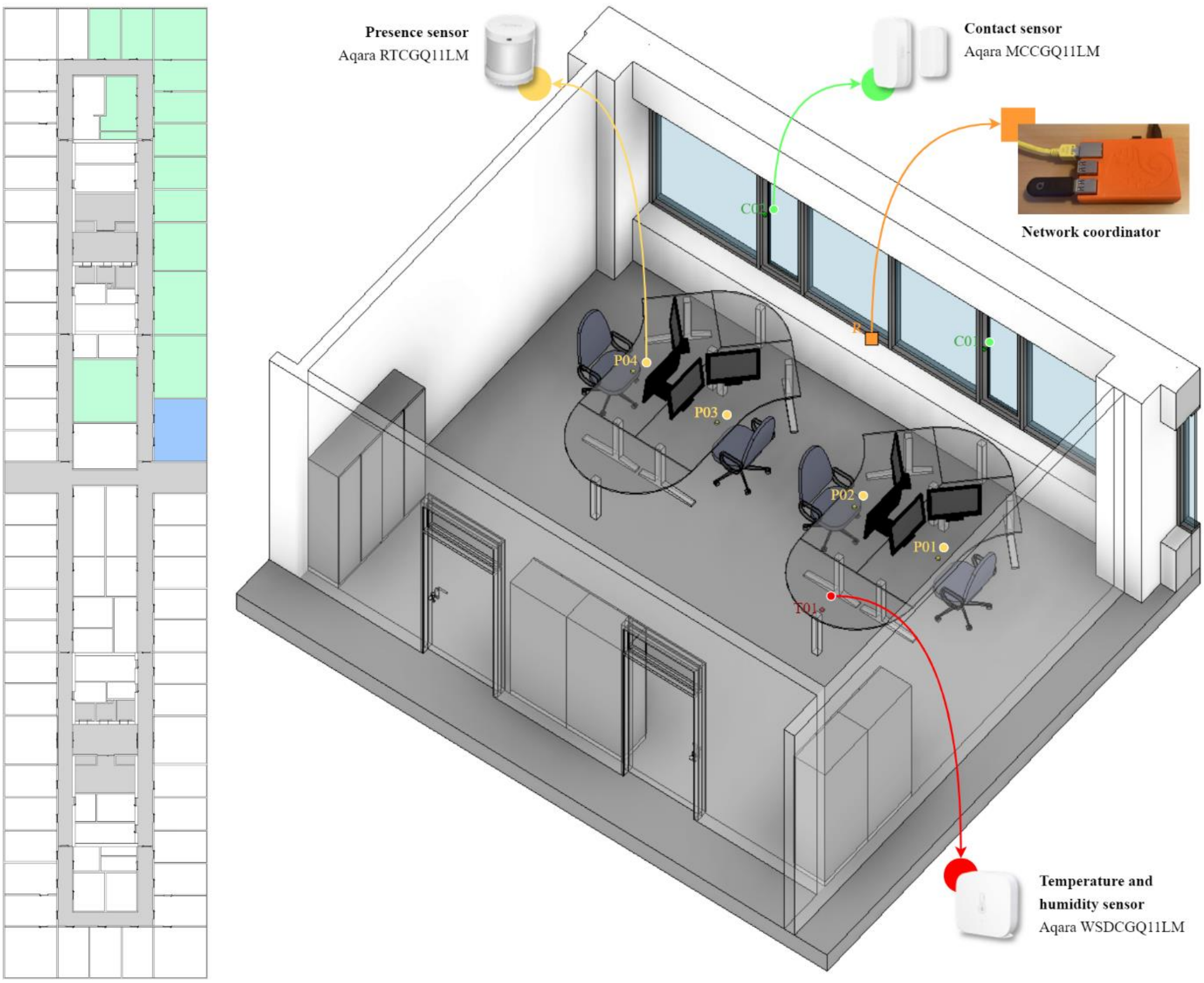

Figure 6.1 [Left] Case study building plan – Level 6 (green department workspaces; blue prototype case study workspace). [Right] Axonometric view of the BIM model of the case study office and sensor setup.

Workers' feedback was collected over a period of one work week (i.e., five workdays), from July 10 to 14, 2023, through a custom-developed single-page survey web application, which is discussed in section 6.3. Each participant was encouraged to provide, at their initiative, at least four feedback responses per day, evenly distributed throughout their workday. Each collected feedback consisted of a time-stamped data point including worker ID, location (workspace), activity category and type, thermal preference, and self-assessed productivity.

The collected office environmental observations and workers' feedback were semantically integrated into a dedicated ICDD container, which was accessible through a customized version of the ICDD web platform (as described in section 5.4.4 and 5.4.5). To evaluate the prototype's effectiveness in supporting workplace managers' decision-making processes, the workplace performance assessment use case was selected. This involved the implementation of dedicated services within a dashboard for querying and visualizing the stored workplace knowledge, as discussed in section 6.4.2.

6.2. Sensor network setup

The sensor network deployed for observing the case study workspace comprised consumer-level sensors and devices compatible with the Zigbee wireless communication standard, commonly used in smart-home applications (see Figure 6.2 for network schema and Table 6.2 for device specifications). All seven sensors are positioned with stickers for easy maintenance and repositioning. They are connected to a gateway installed on the network coordinator node, a Raspberry Pi SoC located within the room (Figure 6.3), and configured as discussed below:

- *Temperature and humidity sensor*: Battery-powered device which integrates the observation of air temperature (°C), relative humidity (%), and atmospheric pressure (kPa, not considered). It is positioned under the desk work plane of one of the two workstations, approximately central to the transversal room axis. This placement does not interfere with other objects and avoids direct exposure to sunlight and heat emissions from radiators and occupants. Positioned at a height of approximately 0,70 m, it represents the local thermal environment experienced by employees while seated.
- *Contact sensor*: Battery-powered device positioned on each operable window at a height of 1,20 m, with the magnet on the movable frame and the sensor on the fixed frame. It registers status changes between open (true) and closed (false).
- *Motion sensor*: Battery-powered device using passive infrared technology (PIR) to detect moving heat-emitting bodies. It is positioned under each workstation's desk work plane, above the employees' laps. The sensor's field-of-view is directed towards the floor, detecting the presence of employees when they are seated. In their absence, the desk frame partially obstructs the sensor's field-of-view, minimizing false positives from worker seated across. In the time-series database, the detected values (true for presence, false for absence) are aggregated over 15-minutes intervals for each workstation and evaluated at the workspace level do determine the room occupancy.
- *Network gateway and coordinator*: A universal USB Zigbee 3.0 gateway device connects all the Zigbee-compatible devices deployed in the prototype network. The gateway device, in the form factor of a USB stick, is connected to a Raspberry Pi SoC, which act as the network coordinator node. The Raspberry Pi is powered, connected via the room Ethernet port to the department LAN, and linked to the system backend server.

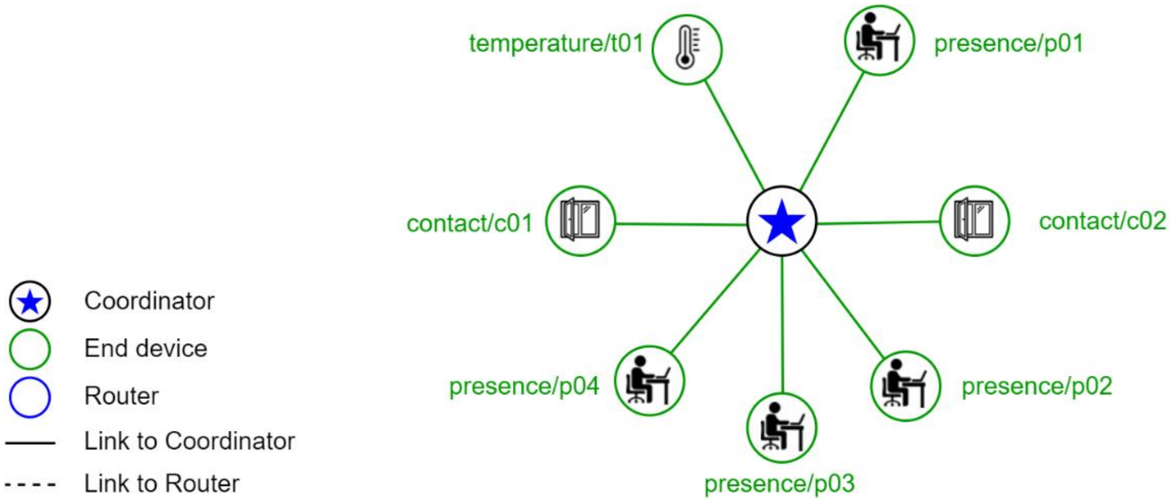

Figure 6.2 Schema of the system prototype's sensor network.

Table 6.2 System prototype sensor network: device specifications.

Qty	Device	Specifications
1	**Temperature and humidity sensor** 	**Model:** Aqara WSDCGQ11LM **Battery:** CR2032 **Dimensions:** 36 × 36 × 9 mm **Temperature range and precision:** -20°C ~ +50°C; ±0.3°C **Humidity range and precision:** 0 – 100% RH; ±3% **Atmospheric range and precision:** 30 kPa – 110 kPa; ±0,12 kPa https://www.aqara.com/en/product/temperature-humidity-sensor/specs/
2	**Contact sensor** 	**Model:** Aqara MCCGQ11LM **Battery:** CR1632 **Dimensions:** 41 × 22 × 11 mm **Maximum detection distance:** 22 mm **Operating temperature and humidity:** -10°C ~ +45°C; 0 - 95% RH https://www.aqara.com/en/product/door-and-window-sensor/specs/
4	**Motion sensor** 	**Model:** Aqara RTCGQ11LM **Battery:** CR2450 **Dimensions:** 30 × 30 × 33 mm **Detection technology:** Passive Infrared (PIR) **Maximum detection distance and angle:** 7 m; 170° **Operating temperature and humidity:** -10°C ~ +45°C; 0 - 95% RH https://www.aqara.com/en/product/human-motion-sensor/specs/
1	**Universal USB Zigbee gateway** 	**Model:** Phoscon ConBee II **Dimensions:** 60 × 18 × 9 mm **Signal range and radio frequency:** 200 m in free line of sight; 2,4 GHz **Radio standard:** IEEE 820.15.4 / Zigbee 3.0 **Operating temperature:** -20°C ~ +55°C **USB interface:** USB 2.0 **Antenna:** Integrated antenna https://phoscon.de/en/conbee2/techspec
1	**Network coordinator (SoC)** 	**Model:** Raspberry Pi 3 Model B **CPU:** 1.2 GHz 64-bit quad-core ARM Cortex-A53 **RAM:** 1 GB LPDDR2 **Wireless:** 802.11n Wireless LAN, Bluetooth 4.1 **Storage:** MicroSD card **Ports:** 4 USB 2.0, HDMI, 1 10/100 Ethernet, CSI, DSI **Dimensions:** 85 × 56 × 17 mm https://www.raspberrypi.com/products/raspberry-pi-3-model-b/

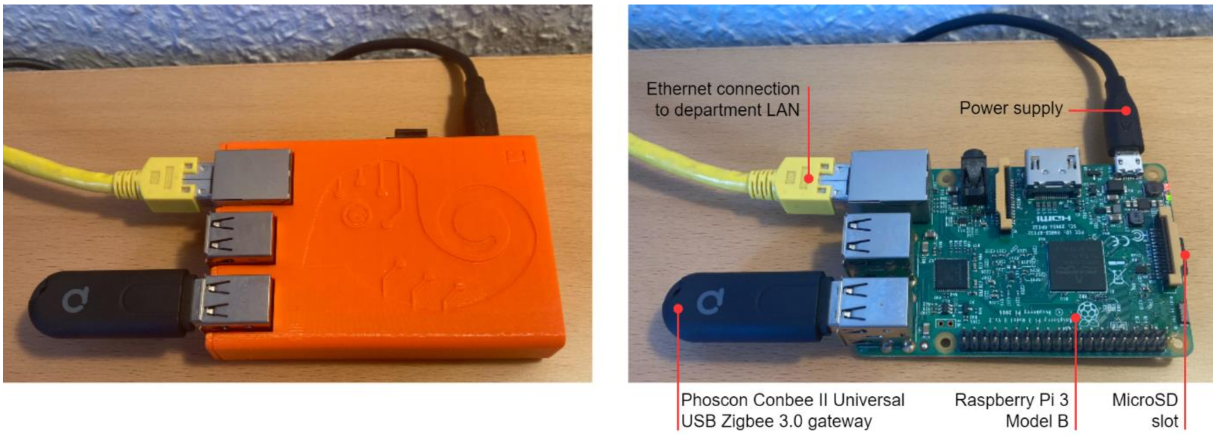

Figure 6.3 Network coordinator with installed network gateway: with case (left), without case (right).

Network configuration and maintenance functions (e.g., device pairing, removal, and settings) are managed by an open-source bridge, Zigbee2MQTT[37], installed on the network coordinator. This bridge is accessible a graphical user interface through a web browser (see Figure 6.4). The incoming sensor data are encoded by the bridge into message packages and published to an MQTT broker, Eclipse Mosquitto, installed on the backend server. The topics' hierarchy follows a three-level structure: *argument*, *sensor type*, and *sensor ID* (see Figure 6.5 and Table 6.3). Sensor localization metadata (e.g., workspace, observed element) are stored exclusively in the workplace knowledge graph and are not included in the MQTT message topics or in the data point record structure in the time-series database.

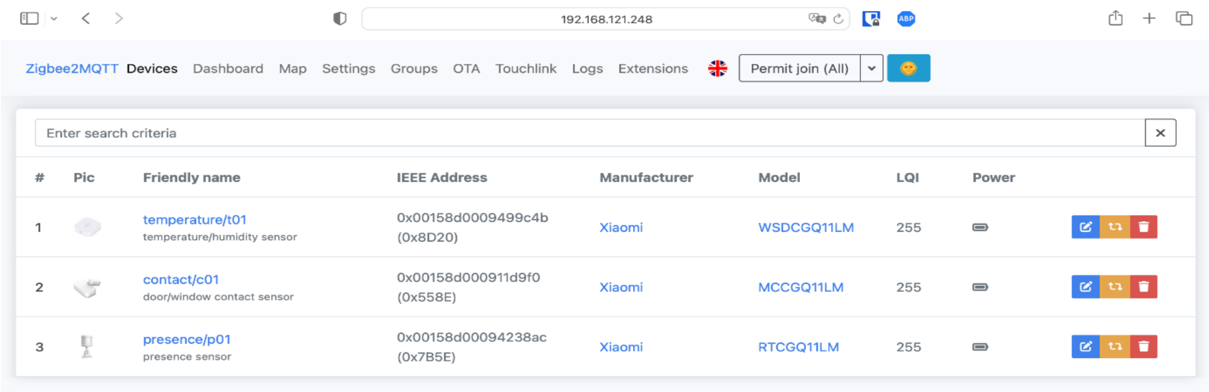

Figure 6.4 Zigbee2MQTT bridge: device pairing and configuration interface.

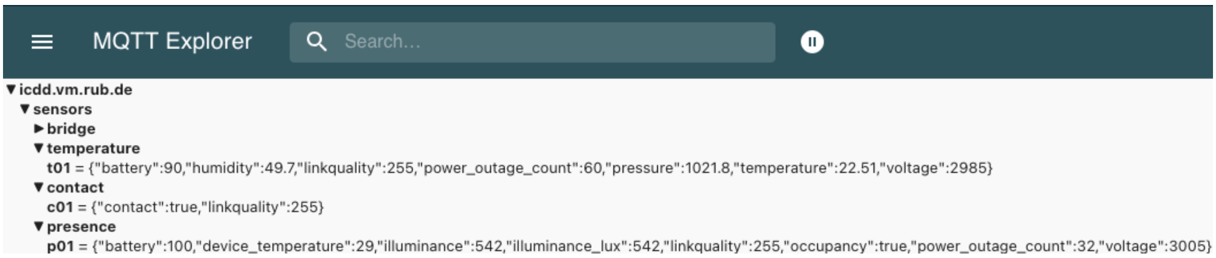

Figure 6.5 Sample of MQTT messages containing sensor observation published on their related topics.

An InfluxDB time-series database, instantiated on the system backend server, is configured with two distinct buckets: one for storing the sensor observations and another for workers' feedback. To feed the database, an agent called Telegraf is configured to subscribe to all the

[37] https://www.zigbee2mqtt.io/ - Accessed 05/05/2025.

MQTT broker's topics where the sensor observation messages are published (i.e., "sensor/#"). Telegraf translates the message payloads into the InfluxDB bucket's data structure, which utilizes two types of fields: *tags* for recurrent data point values, and *fields* for variable values.

Table 6.3 Localization and MQTT topic of the deployed sensors.

Workspace	Sensor	MQTT topic
Case study office	Temperature and humidity sensor	sensors/temperature/t01
	Contact sensor	sensors/contact/c01 sensors/contact/c02
	Motion sensor	sensors/presence/p01 sensors/presence/p02 sensors/presence/p03 sensors/presence/p04

As shown in Figure 6.6 for the deployed motion sensors, our implementation uses two tags - "_measurements" for sensor type and "sensor" for sensor ID – along with several fields depending on the type of observation and message payload (e.g., battery, illuminance, occupancy). The original Boolean data type of the occupancy value detected by the motion sensors and transmitted in the messages' payload is converted by Telegraf into a numerical value (1 for true, 0 for false) to facilitate querying and aggregation of the time-series data.

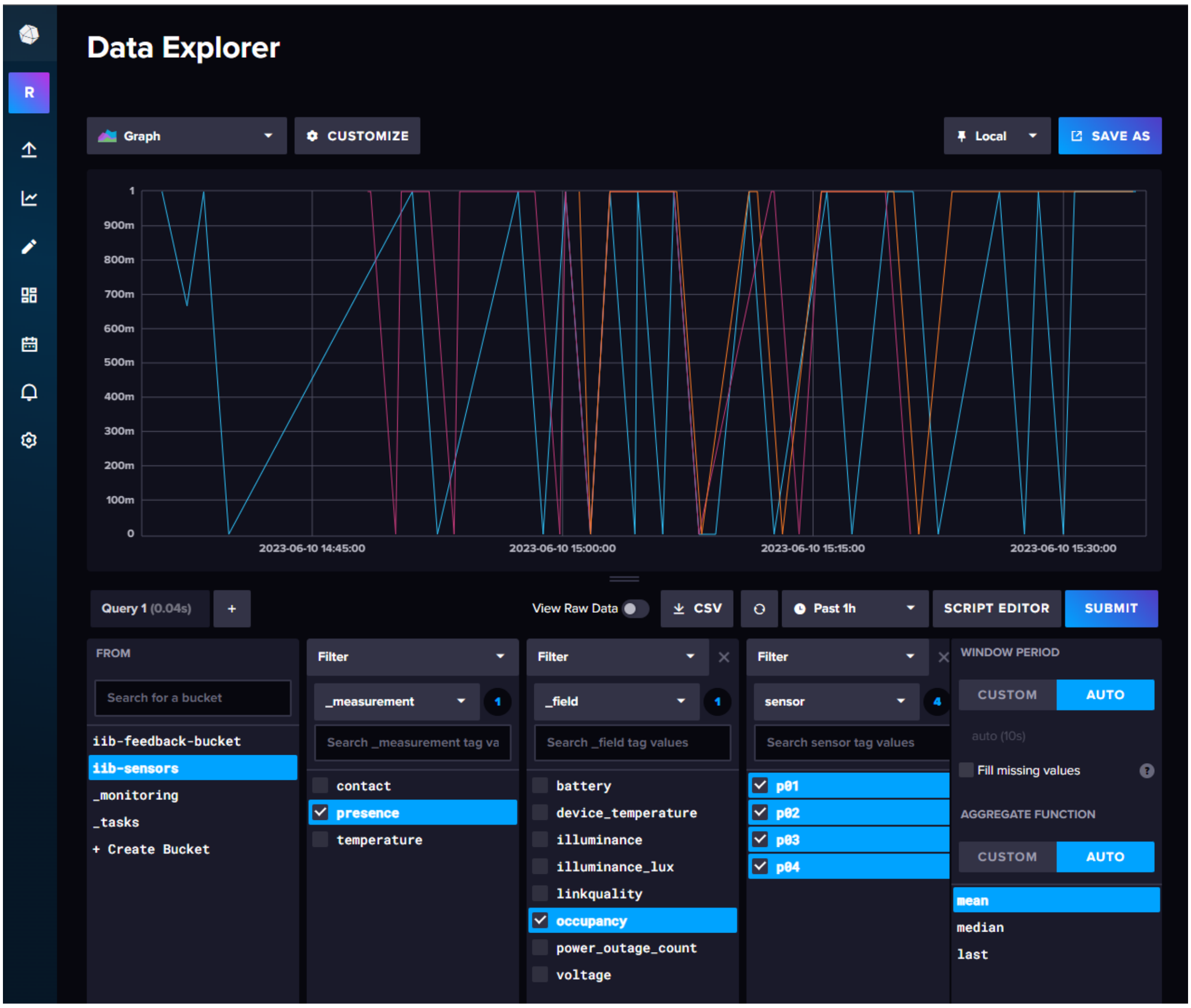

Figure 6.6 InfluxDB time-series data querying and visualization interface (Occupancy data sample).

6.3. Worker data collection

The system prototype implementation integrated the workspace environmental properties discussed above with workers' momentary experiences and subjective perceptions, which were captured through voluntary feedback. The feedback collection covered a period of one work week (July 10-14, 2023) and involved the four employees assigned to the case study office (Table 6.4). For this data collection, a web application featuring a single-page survey form was developed, hosted on the system's backend server, and made accessible via browser from the employees' workstations. The survey was designed to minimize cognitive load and completion time for participants, reducing the risk for survey fatigue and minimizing disruption to their daily routines.

The single-page form comprised four horizontal sections and three survey items (Figure 6.7). These were structured as follow:

- *Worker ID and location*: These fields are essential for contextualizing the feedback and were preset based on the workstation accessing the web application. Given that the workplace monitoring was limited to the case study office and employees had fixed workstations, this data was automatically populated, reducing the participants' input demand. The employee's name and abbreviated last name were displayed, but the final worker ID data was anonymized (e.g., worker1, worker2). The workspace location field identified the current office ID.
- *Activity*: The first survey item required information about the activity category and type that the worker was currently engaged in. The prompt, labelled "*What are you doing?*", was followed by five response buttons including "working solo", "in a call", "group work", "taking a break" and "others". These options encompassed three work activities, a break, and a button for activities not represented by the other choices. Each button mapped the activity to predefined categories, types, and social interaction levels, effectively capturing all three properties with a single input.
- *Preference*: The second survey item captured the worker's subjective satisfaction with the surrounding thermal environment. The prompt, labelled "*Thermal quality feedback*", offered three response buttons: "prefer cooler", "no change", and "prefer warmer". These responses were mapped to a 3-point thermal quality rating scale, assigning values of -1, 0, and +1, respectively.
- *Condition*: The final survey item focused on the worker's self-assessed productivity. Similar to the preference item, this prompt was labelled "*Productivity feedback*" and included three response buttons: "not productive", "normal", and "very productive". These responses were also mapped to a 3-point productivity rating scale, with values of -1, 0, and +1.

Participants were encouraged to access the form and provide feedback at least four times during each workday in the office. The survey form could be exited freely by closing the web page, and none of the fields were mandatory. However, if the submit button was pressed without any input, no data was transmitted to the time-series database, and the feedback was ignored. A feedback submission was considered valid only if at least one item was completed.

The design of the response buttons combined textual captions with graphical icons and colours to facilitate survey completion. For the activity response, the “break” option was highlighted in green, while the “other” option was separated on the right side of the page and distinguished by a grey colour. The preference and condition items featured three buttons aligned with their respective 3-point rating scales. The central button, representing satisfaction with the environment or a baseline condition, featured a happy smiley. The other two options indicated deviations from this condition in opposite directions (e.g., prefer warmer/cooler). Users could visually track their choices, as the selected button’s background turned grey upon clicking. They could also change their selection at any time before submitting the feedback by pressing a different button.

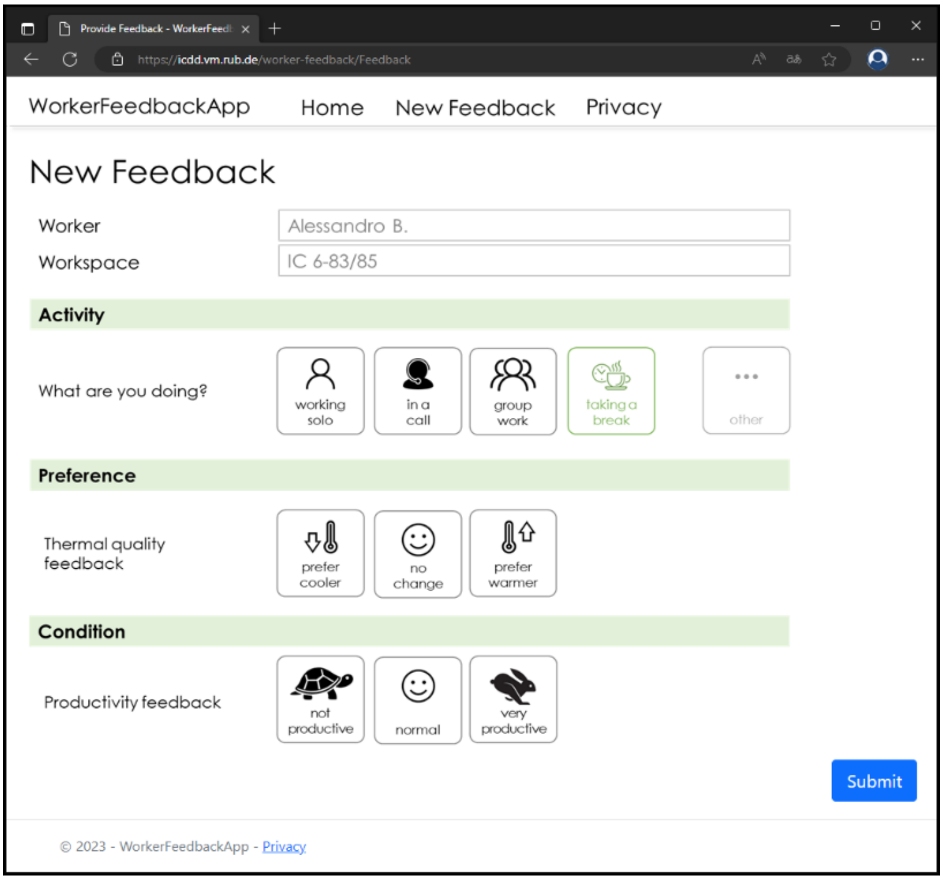

Figure 6.7 Worker feedback web application (Bruttini et al., 2023).

Table 6.4 System prototype case study – Worker data collection participants demographics.

#	Role	Age group	Gender	Workplace/Home-office
1	Research assistant (full time)	20-30	Female	3/2 days (flexible)
2	PhD student (full time)	20-30	Male	3/2 days (flexible)
3	PhD student (full time)	30-40	Male	5/0 days (flexible)
4	Research assistant (full time)	30-40	Female	3/2 days (flexible)

Regarding the workers, this prototype focused exclusively on collecting data related to their subjective experiences through momentary micro-surveys. No wearables devices (e.g., smartwatches) were used for administering the surveys or collecting physiological data (e.g., heart rate).

Upon clicking the submit button, the application transferred the collected survey data to the designated feedback bucket in the InfluxDB time-series database using the HTTP POST method and the Influx API.

6.4. Knowledge base and ICDD platform

This section outlines the final step in the system prototype implementation, which involved deploying an ICDD container to store the workplace knowledge base for the monitored office and customizing the ICDD platform (refer to section 5.4.5) with the necessary services and interfaces. These customizations enabled the integration, querying, and visualization of heterogeneous workplace data to support managers' decision-making effectively. To evaluate these capabilities, a workplace performance assessment use case related to perceived thermal quality was selected, and the following two competency questions (CQs) were formulated:

CQ1: *How has a workspace performed in terms of thermal quality over a certain period?*

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

The organisation of the workplace knowledge base and the evaluation of these CQs were conducted for a single workspace over a data collection period of one week, considering the constraints of the case study.

6.4.1. Prototype knowledge base – Single ICDD container

ICDD containers offer the flexibility to semantically interlink not only different containers but also their documents and data. This capability allows for the adaptable structuring of the workplace knowledge base at the core of the proposed WSDT system, tailored to specific workplace characteristics and use case requirements. To enhance system modularity at the data management level and facilitate information retrieval for the end user (i.e., the workplace manager), the adopted strategy involved separating the data according to the workplace's spatial organisation. As a result, an ICDD container was to be defined for each monitored workspace within the workplace.

In this prototype application, a single ICDD container was implemented for the shared office in the case study, named after its organisational ID tag, IC6-83/85 (Figure 6.8). Among the ontology resources, in addition to the standard vocabularies required for container, linkset, and document descriptions, our WOMO ontology (*womo.ttl*) was included, serialized in Turtle syntax[38]. A BIM model of the case study office is stored in IFC format as a payload document (*IC6-83+85.ifc*). The model contains all relevant information for the geometrical and functional representation of the workspace (Figure 6.1, right), including spatial elements representing the room and workstation volumes (IFC spaces), building elements (e.g., walls, doors, windows), furniture, equipment, system elements, and proxy elements representing the deployed sensors in their correct locations. Additional organisational information, such as room accessibility or employee allocation, is added to the model as room properties, though not leveraged in this implementation. Transforming these IFC entities into the corresponding BOT entities (`bot:Space`, `bot:Element`) builds the workspace domain of workplace knowledge graph,

[38] https://www.w3.org/TR/turtle/ - Accessed 05/05/2025.

enabling connections to the semantics describing workers and their activities, along with the sensor network and observations.

For each deployed sensor, a proxy document is added to the container payload. Administrators use these documents to establish and manage connections with the external database for retrieving the corresponding observation time-series (InfluxDB, sensor bucket). Meanwhile, workplace managers can easily retrieve and visualize the corresponding data by selecting it directly from the ICDD contents explorer on the ICDD platform.

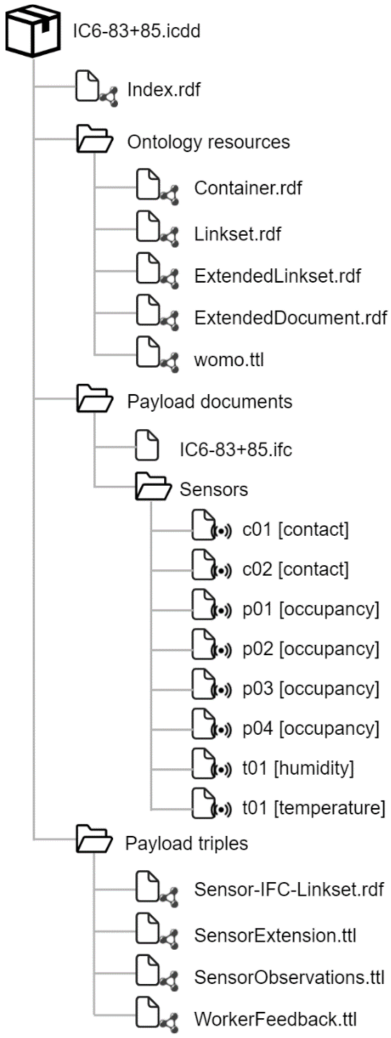

Figure 6.8 Prototype knowledge base – ICDD structure and contents.

Finally, the payload triples folder stores semantic data about sensors and workers according to the WOMO ontology definitions. Regarding the sensors, three files contain: the connection between the instantiated members of the `sosa:Sensor` class and the corresponding entities in the workspace IFC model (*Sensor-IFC-Linkset.rdf*); the properties for configuring the sensor proxy documents (*SensorExtension.ttl*); and the consolidated sensor observations (`sosa:Observation`) retrieved from the time-series database (*SensorObservations.ttl*). All data related to the employees participating in the data collection, including their feedback on environmental preferences, personal conditions, and activities, is stored in the *WorkerFeedback.ttl* file, which is populated with data extracted from time-series stored in the InfluxDB feedback bucket.

The evaluation of the described single-ICDD workplace knowledge base structure for the system prototype allowed assessment of its capabilities and settings for further development of the multiple-ICDD configuration proposed in the case study extension discussed in Chapter 7.

6.4.2. Workplace performance dashboard

The ICDD platform's services and interface were customized to address workplace performance assessment with a dedicated dashboard as shown in Figure 6.9. The interface is organised into three panels. On the left, the explorer panel allows users to browse the workplace knowledge base, displaying the structure and contents of the ICDD container for the shared office featured in this prototype case study.

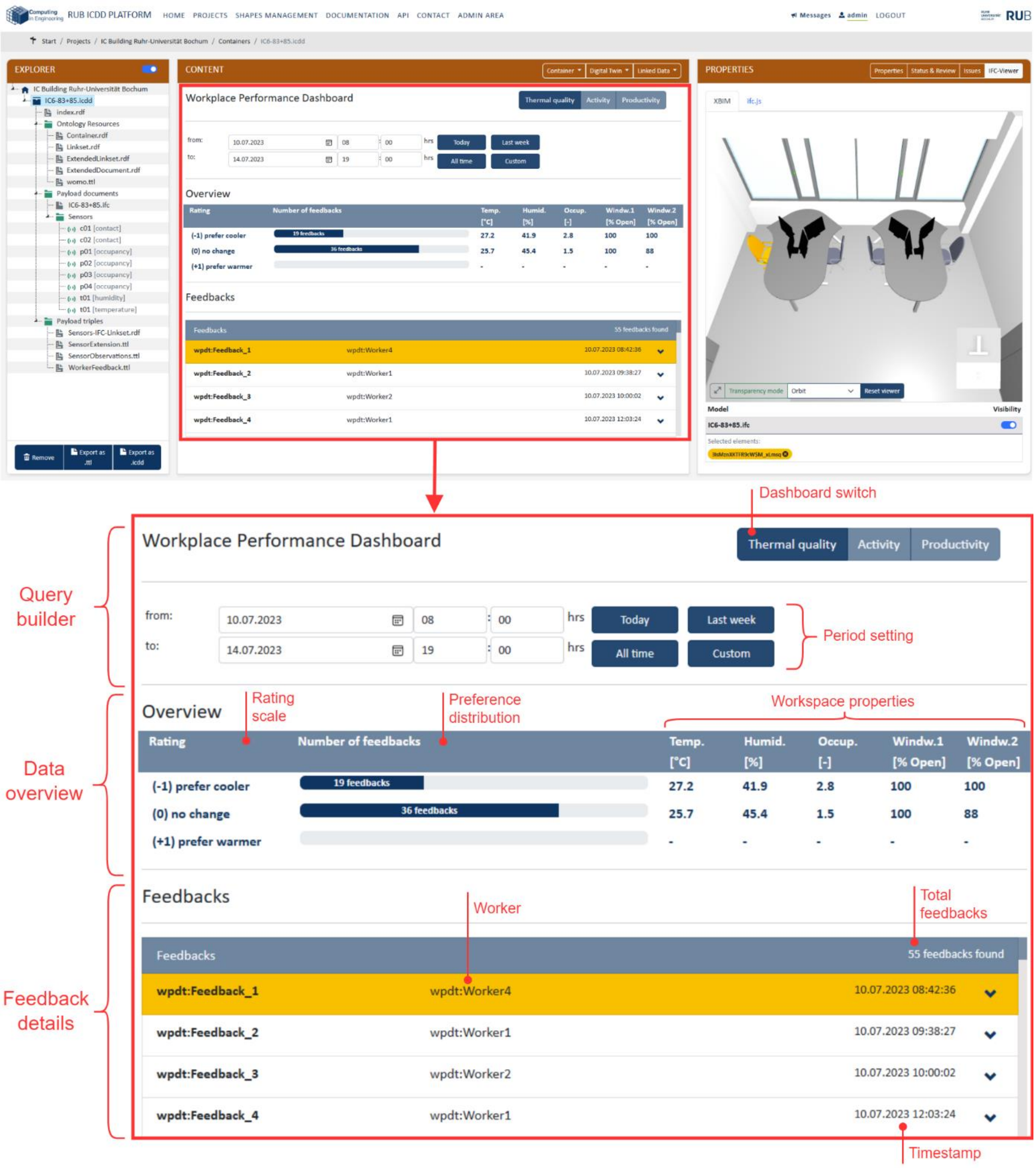

Figure 6.9 ICDD platform interface for the workplace semantic digital twin system prototype (top); Workplace Performance Dashboard (bottom).

The central panel hosts the *Workplace Performance Dashboard* which provides the primary tools for querying and visualizing worker- and building-generated data. The dashboard is organised into three horizontal sections:

- *Query builder*: The top section is designed for constructing queries. In this case study, the interface for evaluating thermal quality was implemented. Three buttons are available to switch between data collected through momentary surveys, each prioritizing an occupant-centric perspective: *Thermal quality*, *Activity*, and *Productivity*. The time interval for data retrieval is displayed below, showing the start and end dates and times. Users can select from four options: *Today* (current day), *Last week* (counting from the current day), *All time* (retrieving all historical records), and *Custom* (requiring specific start-end dates). When the interval is updated, the query is rerun, and the data visualization automatically refreshes.
- *Data overview*: The middle section provides a concise overview on the queried data, integrating them with workplace conditions across time and space. In this case study, the query returns instances of worker feedback on thermal quality within the selected workspace and time frame. The data is organised into three lines, corresponding to the three possible scores on the rating scale used in the survey. By visualizing the distribution of the responses across different scores (via normalized bar graphs and captions), managers can assess workspace performance for thermal quality over a given period (CQ1). Higher numbers of neutral "no change" ratings suggest greater employee satisfaction. Additionally, the environmental conditions recorded closest to the time of each feedback instance are retrieved, averaged for all instances, and presented to provide detailed insights into the conditions associated with reported worker satisfaction or dissatisfaction (CQ2). In the prototype, hourly mean values were considered for temperature, humidity, room occupancy count, and opening time of each operable window. The opening time is calculated using the timestamps of status changes and is normalized over a given hour, with 100% indicating that the window was open for the entire hour.
- *Feedback details*: The bottom section lists all feedback instances that match the query, allowing users to access further details. Feedback data is linked to the workspace's IFC model elements corresponding to their location (i.e., workstation chair), enhancing the visualization of query results. When a specific feedback instance is selected, the related element is highlighted in the IFC viewer. Conversely, users can filter the list of feedback instances by selecting a particular location within the viewer. The right-hand panel can also display full information about the feedback instance, including location, timestamp, worker, preference, activity, and condition, which can be accessed by selecting the "properties" visualization option.

6.5. Discussion

The development and application of the system prototype provided valuable insights, confirming the feasibility of the workplace semantic digital twin conceptual and technical architecture presented in Chapter 5. The prototype successfully addressed the requirements of the workplace performance assessment use case by effectively responding to the formulated

CQs. Below, we discuss the system's strengths and encountered limitations, along with opportunities for enhancement. These insights informed the system's further development for its upscaled application, which will be discussed in Chapter 7.

For monitoring workspace conditions, the adoption of a wireless ecosystem designed for smart-home applications based on the Zigbee communication protocol proved effective in the test workspace. The network configuration and maintenance were straightforward, requiring no specialized knowledge in sensor technology. The installation of seven battery-powered sensors minimized disruption to the office environment. Throughout the test period, no issues were encountered with signal strength or data communication between sensors and the network gateway. The deployed sensors, all commercial devices, provided accuracy suitable for our application. While sensor calibration was not deemed necessary for this research, differences in measurements, especially when comparing data from sensors in different workspaces, should be considered. The measurement frequency for the temperature and humidity sensor could not be configured, but the number of observed values (more than one per hour) was sufficient for our purposes. However, the reliability of the network will require further testing in real-scale applications, particularly in monitoring workplaces with multiple workspaces distributed across different storeys.

The implementation of an InfluxDB database instance on the system's backend server facilitated the efficient handling and storage of incoming building- and worker-generated time series data, organised into two separate buckets. Configuring a Telegraf agent to collect sensor observations transmitted as MQTT messages required manually mapping the payload items to the corresponding fields and tags in InfluxDB's data point structure. While this manual mapping is necessary, it only needs to be set up once per sensor type, which is manageable given the limited number of different sensors currently involved (i.e., temperature and humidity, contact, presence). Similarly, the data associated with each worker feedback instance is written from the survey web application to the database using the InfluxDB API, necessitating mapping of the collected values to the appropriate data points. A notable advantage is the InfluxDB setup flexibility: the bucket structures can be extended with new fields and tags as needed, allowing for seamless additions or modifications as the system evolves. Although the full potential of InfluxDB's proprietary scripting language, Flux[39], was not thoroughly explored in this case study, future developments should focus on leveraging Flux more extensively, particularly for common operations (e.g., calculating hourly mean values) on the time series data retrieved by the ICDD platform. The small volume of data processed in the prototype case study did not necessitate resource optimisation. However, in real-world applications, shifting more of the computational workload to InfluxDB—rather than relying heavily on the platform—could significantly enhance both performance and efficiency.

The worker data collection strategy, based on voluntary feedback via the developed survey web application, proved effective. During the observation period (i.e., one work week), with four participants, the total number of workdays considered was 20. Collectively, the participants were present in the office for 15 out of the 20 workdays and provided 55 feedback instances, averaging 3,67 responses per worker per day (92% of the encouraged number of feedback

[39] https://docs.influxdata.com/flux/v0/ - Accessed 05/05/2025.

submissions). All submitted surveys were fully completed, with participants reporting that the interface and icons were clear and that the survey form was straightforward. While the short duration of the data collection period did not allow for an assessment of survey fatigue, this aspect should be monitored in longer campaigns (e.g., by analysing the distribution of feedback across different times of the day and among participants). Additionally, recording the survey completion time would enable more precise meta-analysis. However, the current implementation also has more relevant limitations to be addressed. Workers could only submit feedback by accessing the preset application via a browser on their workstation, restricting their ability to provide feedback from other workspaces. Furthermore, the system did not allow feedback to be requested at scheduled or random intervals, leaving the initiative entirely up to the participants. This could present a significant limitation in longer campaigns Moreover, wearable devices such as smartwatches or mobile devices were not adopted, excluding the collection of worker physiological data. Future implementations should consider integrating these devices, with clock faces or mobile apps for survey administration and localization technologies (e.g., Bluetooth beacons) to capture the worker's contextual location within the workplace.

As a final aspect of the prototype's evaluation, the organisation of the workplace knowledge base into a single ICDD container and the customization of the ICDD platform's services and interface each demonstrated how the system could be tailored to support workplace performance assessments. The ICDD container structure effectively enabled the semantic integration and storage of data from heterogeneous sources (e.g., BIM, sensor, feedback), while the sensor proxy documents provided a suitable solution for connecting the knowledge base to the time series database and retrieving sensor observations through a dedicated service. The customization of the ICDD platform's interface, along with the design of the workplace performance dashboard, effectively facilitated the querying and visualization of workplace data, fulfilling its intended purpose. However, several limitations were identified. The dashboard was currently limited to evaluating perceived thermal quality and lacked the flexibility to accommodate data with varying rating scales (e.g., 3-point and 5-point scales), a feature that may be needed over time in real applications when worker data collection strategies evolve. Additionally, the interface is fixed and does not offer customization options for users, restricting its adaptability for broader performance assessments. For instance, at the current development stage, users cannot filter which environmental properties to compare with worker thermal preference. Additionally, due to the case study's limitation to a single workspace, no functionality for addressing the spatial variability of data was implemented, which will be necessary in future iterations. Temporally, the "all time" option should be restricted to prevent system lags or overflow when handling large datasets. Further enhancements should include adding dashboards for multiple use cases and enabling easy switching between them (e.g., a sensor dashboard for basic environmental condition monitoring). As a closing remark, it is important to note that the platform's capabilities were tested only internally. A thorough evaluation should be conducted in a real-world case study, where experts can rigorously test the system and provide feedback through focus groups and rounds of structured interviews.

In the following Chapter 7, the lessons learned and limitations encountered during the discussed prototype evaluation will inform the development and scaling of the system for its application in a larger case study.

7

Prototype Extension and Evaluation

Building on the evaluation of the single-room prototype, this chapter describes the development and partial implementation of an extended system prototype for a department-scale case study that more closely approximates a real-world application. The first section discusses the spatial and organisational characteristics of the case study, along with the adopted technical solutions (§7.1). The configuration and deployment of the extended sensor network, as well as the upscaling of the workplace knowledge base to a multi-containerized structure, are detailed in §7.2-7.3. The findings from this implementation are then discussed (§7.4), highlighting both improvements and remaining limitations. Additionally, the chapter explores the conceptualization of potential developments in the worker data collection solution and the introduction of new Digital Twin dashboards to address further use cases, offering directions for future work.

Knowledge isn't free.
You have to pay attention.

- Richard P. Feynman

7.1.Case study extension

The target real-world scenario for the proposed WSDT system involves multistorey buildings with dozens of workspaces, each characterized by unique physical and functional attributes. These workspaces are occupied by a diverse population of employees, varying in demographics, organisational roles, and workspace usage patterns (e.g., fixed, activity-based). To address this diversity and scale, the system prototype has been further developed, building on insights gained from the initial implementation and extending its application to a department-scale case study (Table 7.1). Specifically, this extension involved the configuration and deployment of an expanded sensor network and the upscaling of the knowledge base from a “single-room, single-container” to a multi-containerized structure more suitable to fit multiple workspaces. Additionally, although not implemented, concepts for new worker data collection features and Digital Twin dashboards are introduced, designed to address the specifications of the extended case study outlined in Table 7.2.

Table 7.1 Comparison of the system components and features between the prototype and extended case study.

System feature / component	Prototype	Extended Case Study
Workspaces	1 (single room)	14 (one department)
Workspace properties	(4) Air temperature, relative humidity, occupancy, window status	(4) Air temperature, relative humidity, occupancy, window status
Sensor types	(3) Temperature and humidity sensor, motion sensor, contact sensor	(3) Temperature and humidity sensor, motion sensor, contact sensor
Sensor quantity	7	51
Routers	0	3
Employees	4	18
Data collection period	1 week	4 weeks
Surveyed worker activities	(5) Solo work, Call, Group work, Break, Other	(5) Solo work, Call, Group work, Break, Other
Surveyed worker preferences	(1) Thermal quality	(4) Thermal quality, Indoor Air quality, Visual quality, Acoustic quality
Surveyed worker conditions	(1) Productivity	(3) Productivity, Concentration, Energy
Worker health indicators	No	No
Knowledge base structure	Single ICDD container	Multiple ICDD containers
ICDD Platform – Digital Twin dashboards	(1) Workplace performance dashboard	(4) Performance dashboard, Sensor dashboard, Activity dashboard, Condition dashboard

Figure 7.1 illustrates the configuration of the monitored workspaces and the positions of the sensors. In addition to the previously monitored shared office, all 14 workspaces allocated to the Chair of Computing in Engineering, located on the sixth floor of the IC building at Ruhr University Bochum, Germany, are included. As with the prototype, all system components—from the installed sensors to the backend server—are hosted within the department. The monitored workspaces vary in type, including private and shared offices, a virtual reality laboratory, and the department kitchen, which is used for coffee breaks and occasional meals. Workspace access is restricted, and workstations are assigned to specific employees; however, shared spaces such as the kitchen and the student worker room are accessible to all. Except for the laboratory and kitchen, all workspaces have external exposure (NE or NW-facing) and feature partially glazed façades with operable windows, allowing natural light and ventilation. Occupants control illumination with internal vertical blinds and external motorized horizontal blinds, the latter actioned also automatically by a shared illuminance sensor on the façade.

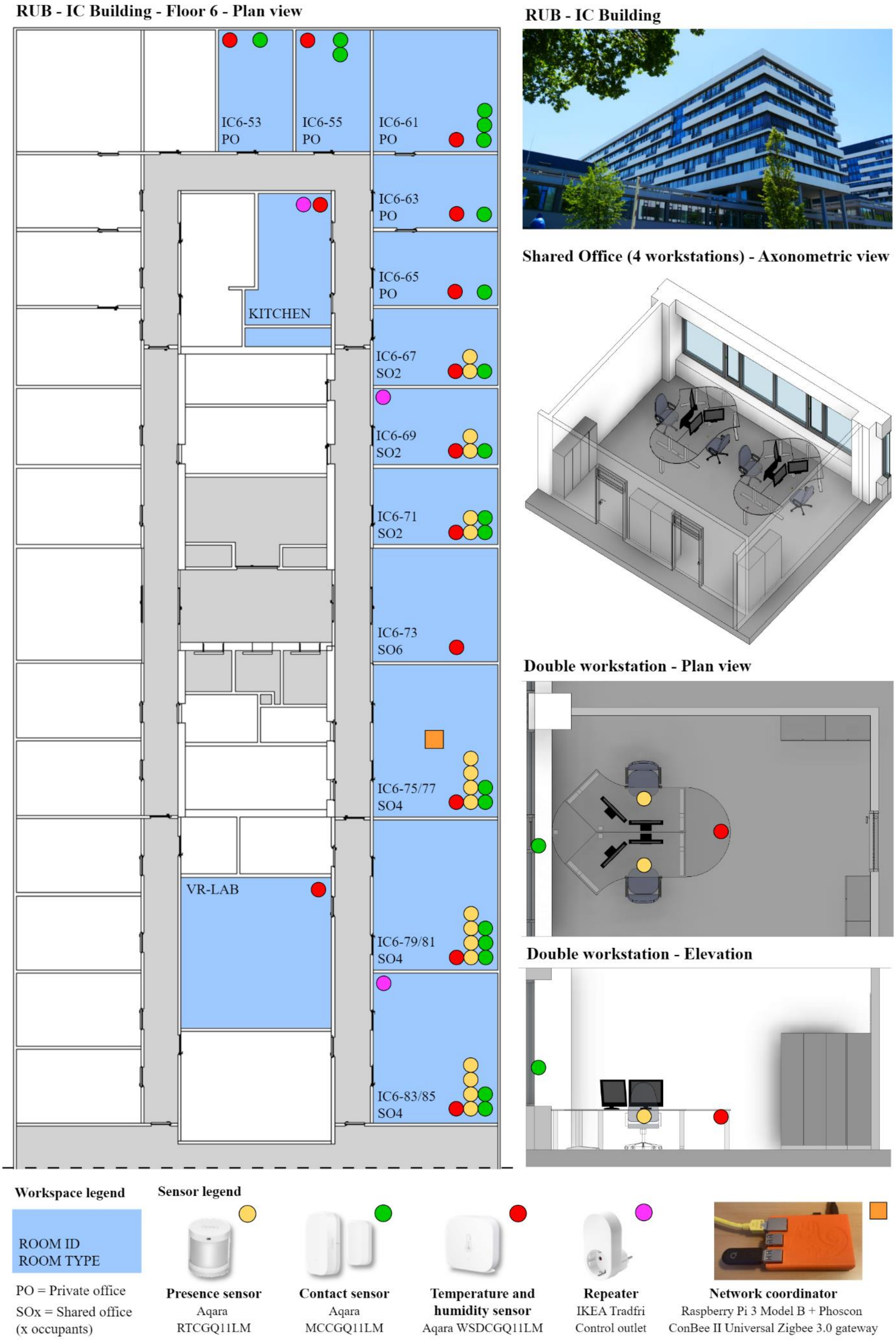

Figure 7.1 Extended case study workplace configuration and sensor position.

Table 7.2 Extended case study workspaces and data collection specifications.

Feature	Specifications
Workspace	**Types and allocation:** Private office (1 employee, fixed) Shared office 2-workstations (2 employees, fixed) Shared office 4-workstations (4 employees, fixed) Student worker room (6 employees, variable) Kitchen (n/a) VR-LAB (n/a) **Workstations:** 29 **Workspace dimensions:** variable Shared office 4-workstations (7,35 m x 6,00 m x 3,75 m) Shared office 2-workstations (3,60 m x 6,00 m x 3,75 m) **Area and volume:** variable Shared office 4-workstations (44,10 m^2; 165,38 m^3) Shared office 2-workstations (21,60 m^2; 81,00 m^3) **Orientation (windows):** North-East, North-West **Access:** Restricted only to allocated employees **HVAC:** Private and shared offices: Adjustable heating (radiators); Natural ventilation only; No air conditioning Student worker room, kitchen, and VR-LAB: Ventilation, heating, and cooling with air conditioning only **Windows:** Curtain wall façade with operable windows, adjustable motorized external horizontal blinds
Observed properties	**Temperature and humidity:** 14x Temperature and humidity sensors [Aqara WSDCGQ11LM] **Occupancy:** 18x Motion sensors (detecting workstation occupation) [Aqara RTCGQ11LM] **Window status:** 19x Contact sensors (one per operable window) [Aqara MCCGQ11LM]
Worker feedback	**Participants:** 18 employees, allocated to 6 workspaces **Worker data:** ID, location (workspace), activity category and type, environmental preference (thermal quality, indoor air quality, visual quality, acoustic quality), self-assessed condition (productivity, concentration, energy) **Data collection system and strategy:** Worker Feedback web application (browser); voluntary (suggested frequency ≥ 4 feedback per worker per day) **Period:** 4x Work weeks (20 work days)

For heating, all the offices are served by adjustable radiators installed beneath the windowsill, while neither air conditioning nor mechanical ventilation are provided. In contrast, the laboratory, kitchen, and student worker room are equipped with air conditioning systems for both ventilation and climatization. The workspaces follow a typical modular distribution, with rectangular plans and at least 10 m^2 per employee, and are equipped with standard office furniture and IT infrastructure (e.g., desks, shelves, power supplies, Ethernet connection).

The monitoring of workspace conditions required expanding the sensor network from the prototype, as detailed in section 7.2. The same workspace properties and Zigbee-compatible sensor types were used: thermal quality (air temperature and relative humidity sensors), occupancy (PIR motion sensors installed at workstations), and window status (contact sensors). Due to insufficient signal range from the network gateway, additional power-supplied devices were deployed to serve as routers and ensure full coverage.

Since the flexibility of InfluxDB's bucket structure allows for seamless addition of new types of data without disrupting the database configuration, for the transmission of the time series sensor observations and worker feedback the already identified solutions (e.g., MQTT broker, Telegraf) are maintained along with the InfluxDB instance already installed on the backend server.

Furthermore, to accommodate and improve the organisation of an increased volume of heterogeneous data to be stored and processed, significant changes were made to the workplace knowledge base, which transitioned from a single ICDD container to a structure incorporating multiple containers, with data for each workspace stored in its own dedicated ICDD, as discussed in section 7.3.

To address the system prototype's limitations in worker data collection and supported use cases, new feedback survey features and additional Digital Twin dashboards were conceptualized. Specifically, an upgraded version of the worker feedback web application is designed for a data collection campaign involving 18 employees across six workspaces with presence sensors over a four-week period. While maintaining the same participant engagement policy (e.g., encouragement to voluntarily provide at least four feedback entries per day), the upgraded version includes additional options for recording preferences and conditions, as discussed in section 7.4.1. Likewise, the ICDD platform services for querying, processing, and visualizing heterogeneous workplace data are retained, with new dashboards proposed to more granularly address aspects of workplace performance assessment (section 7.4.2).

7.2. Sensor network extension

The workspaces to be monitored in the extended case study are located on the same floor within a maximum relative distance of 50 meters (IC6-63 and IC6-83/85). Since the building's lightweight vertical partitions (i.e., drywalls) did not present a significant obstacle to the wireless network signal transmission, the Zigbee-based solution with commercial smart-home devices adopted in the prototype was confirmed. A total of 51 battery-powered sensors was installed to monitor air temperature, relative humidity, window status, and worker presence at workstations (see Table 7.3 and Figure 7.1 for sensor specifications and positioning).

Table 7.3 Extended case study sensor network: device specifications.

Qty	Device	Specifications
14	**Temperature and humidity sensor** 	**Model:** Aqara WSDCGQ11LM **Battery:** CR2032 **Dimensions:** 36 × 36 × 9 mm **Temperature range and precision:** -20°C ~ +50°C; ±0.3°C **Humidity range and precision:** 0 – 100% RH; ±3% **Atmospheric range and precision:** 30 kPa – 110 kPa; ±0,12 kPa www.aqara.com/en/product/temperature-humidity-sensor/specs/
19	**Contact sensor** 	**Model:** Aqara MCCGQ11LM **Battery:** CR1632 **Dimensions:** 41 × 22 × 11 mm **Maximum detection distance:** 22 mm **Operating temperature and humidity:** -10°C ~ +45°C; 0 – 95% RH www.aqara.com/en/product/door-and-window-sensor/specs/
18	**Motion sensor** 	**Model:** Aqara RTCGQ11LM **Battery:** CR2450 **Dimensions:** 30 × 30 × 33 mm **Detection technology:** Passive Infrared (PIR) **Maximum detection distance and angle:** 7 m; 170° **Operating temperature and humidity:** -10°C ~ +45°C; 0 – 95% RH www.aqara.com/en/product/human-motion-sensor/specs/
3	**Smart plug (Router)** 	**Model:** IKEA TRÅDFRI – wireless control outlet, smart **Maximum output power:** 3840 W (16A) **Dimensions:** 100 × 53 × 72 mm **Features:** On/off wireless control, suitable for high-power appliances **Power measurement:** No www.ikea.com/de/de/p/tradfri-steckdose-funkgesteuert-smart-00377314/

All sensors were connected to the universal USB Zigbee 3.0 gateway, installed on the Raspberry Pi SoC acting as the network coordinator node. The sensors were either connected directly or via three power-supplied wireless control outlets functioning as routers (Figure 7.2).

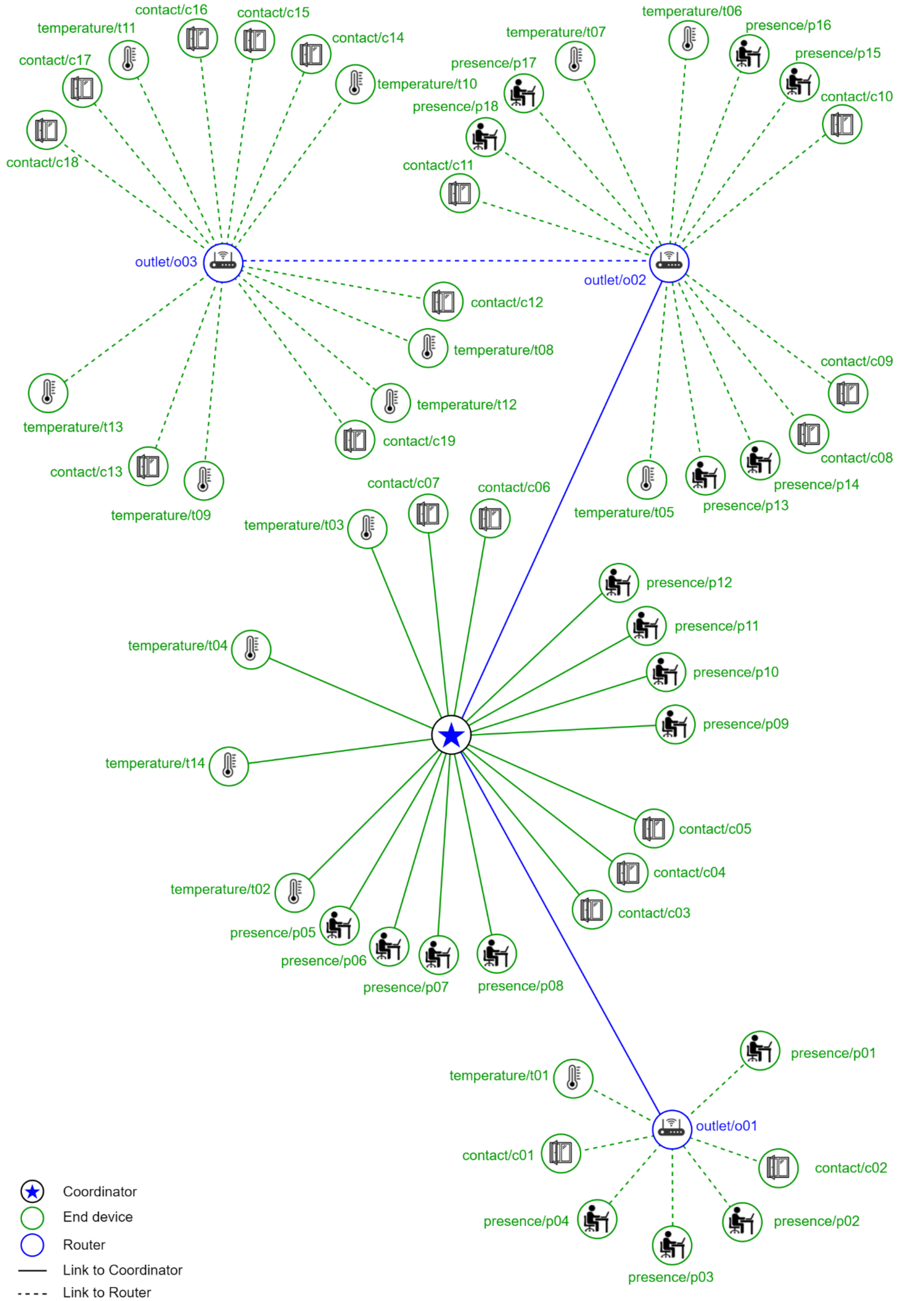

Figure 7.2 Schema of the sensor network deployed for the extended case study.

Table 7.4 Localization and MQTT topic of the sensors deployed for the extended case study.

Workspace	Sensor	MQTT topic
IC6-83/85	Temperature and humidity sensor	sensors/temperature/t01
	Contact sensor	sensors/contact/c01 sensors/contact/c02
	Motion sensor	sensors/presence/p01 sensors/presence/p02 sensors/presence/p03 sensors/presence/p04
	Smart plug (Router)	sensors/outlet/o01
IC6-79/81	Temperature and humidity sensor	sensors/temperature/t02
	Contact sensor	sensors/contact/c03 sensors/contact/c04 sensors/contact/c05
	Motion sensor	sensors/presence/p05 sensors/presence/p06 sensors/presence/p07 sensors/presence/p08
IC6-75/77	Temperature and humidity sensor	sensors/temperature/t03
	Contact sensor	sensors/contact/c06 sensors/contact/c07
	Motion sensor	sensors/presence/p09 sensors/presence/p10 sensors/presence/p11 sensors/presence/p12
IC6-73	Temperature and humidity sensor	sensors/temperature/t04
IC6-71	Temperature and humidity sensor	sensors/temperature/t05
	Contact sensor	sensors/contact/c08 sensors/contact/c09
	Motion sensor	sensors/presence/p13 sensors/presence/p14
IC6-69	Temperature and humidity sensor	sensors/temperature/t06
	Contact sensor	sensors/contact/c10
	Motion sensor	sensors/presence/p15 sensors/presence/p16
	Smart plug (Router)	sensors/outlet/o02
IC6-67	Temperature and humidity sensor	sensors/temperature/t07
	Contact sensor	sensors/contact/c11
	Motion sensor	sensors/presence/p17 sensors/presence/p18
IC6-65	Temperature and humidity sensor	sensors/temperature/t08
	Contact sensor	sensors/contact/c012
IC6-63	Temperature and humidity sensor	sensors/temperature/t09
	Contact sensor	sensors/contact/c13
IC6-61	Temperature and humidity sensor	sensors/temperature/t10
	Contact sensor	sensors/contact/c14 sensors/contact/c15 sensors/contact/c16
IC6-55	Temperature and humidity sensor	sensors/temperature/t11
	Contact sensor	sensors/contact/c17 sensors/contact/c18
IC6-53	Temperature and humidity sensor	sensors/temperature/t12
	Contact sensor	sensors/contact/c19
Kitchen	Temperature and humidity sensor	sensors/temperature/t13
	Smart plug (Router)	sensors/outlet/o03
VR Lab	Temperature and humidity sensor	sensors/temperature/t14

The sensors were positioned following the same approach and criteria adopted in the prototype (see section 6.2) and assigned unique IDs. Using the Zigbee2MQTT bridge, the new network configuration was set up, along with all the MQTT topics dedicated to the transmission of the messages containing the measurement of the additional sensor to the Eclipse Mosquitto MQTT broker installed on the backend server (Table 7.4). The three-level hierarchy of MQTT topics – *argument*, *sensor type*, and *sensor ID* – was maintained, keeping the information about sensor workspace positions or observed elements (e.g., window) decoupled and stored exclusively in the workplace knowledge graph. Similarly, the new sensor observations were collected by the Telegraf agent, which was configured to subscribe to all sensor topics (i.e., /sensors/#) and recorded in the *sensor bucket* of the InfluxDB time series database previously set up on the backend server, without requiring any further intervention. This demonstrated the flexibility of the proposed sensor network and time series data storage solution and its straightforward scalability. However, it bears mentioning that due to the lack of usable existing sensors or controllers in the case study workplace, it was not possible to evaluate the integration of newly deployed sensors with any pre-existing building monitoring or automation infrastructure. In view of broader application of the proposed system in real-world scenarios, this challenge should be addressed and suitable solutions investigated.

7.3. Knowledge base upscaling – Multiple ICDD containers

The transition from a single room to the entire department required reorganisation of the workplace knowledge base structure. Specifically, to store and semantically integrate information common to the whole workplace together with data specific to individual workspaces, multiple interlinked ICDD containers were adopted, as shown in Figure 7.3.

The knowledge base is based on interconnected containers, documents, and data. The first three implemented levels—*organisation*, *building*, and *level*—were not practically applicable to the case study, which was limited to a single department. However, this hierarchy offered a potential representation of real-world scenarios where the workplace concept and the workplace manager's role are expanded at organisational and building scales. This structure suited our study; however, it is worth noting that it can be adjusted independently of the contents of the knowledge base, which are ultimately hosted in one or more ICDD containers, and can be modified to meet various requirements.

At the top level, the workplace data was organised into three folders: *Connected services and containers*, *Data*, and *Interconnections/Linksets*. The first folder presented all the ICDD containers forming the knowledge base. In this implementation, one container stored information relevant to the entire workplace (*IC6.icdd*), and other containers were created for each specific workspace (*IC6-83+85.icdd*, *IC6-79+81.icdd*, etc).

The second folder included the BIM model of the building floor where the workplace is located, stored as an IFC document, along with proxy documents for connecting to InfluxDB and retrieving observations for each sensor. Unlike the prototype, where the BIM model was limited to a single workspace, in this case study, the workplace's geometrical and functional information was modelled and stored as a single IFC model within the common *IC6.icdd* container. This approach ensured spatial consistency, accurate topological relationships across monitored workspaces, and coherent serialization of IFC entities into the BOT and WOMO classes, which are central to the workspace domain representation. Conversely, sensor proxy documents were organised into folders, each named after and separated by workspace (container), to simplify retrieval and management.

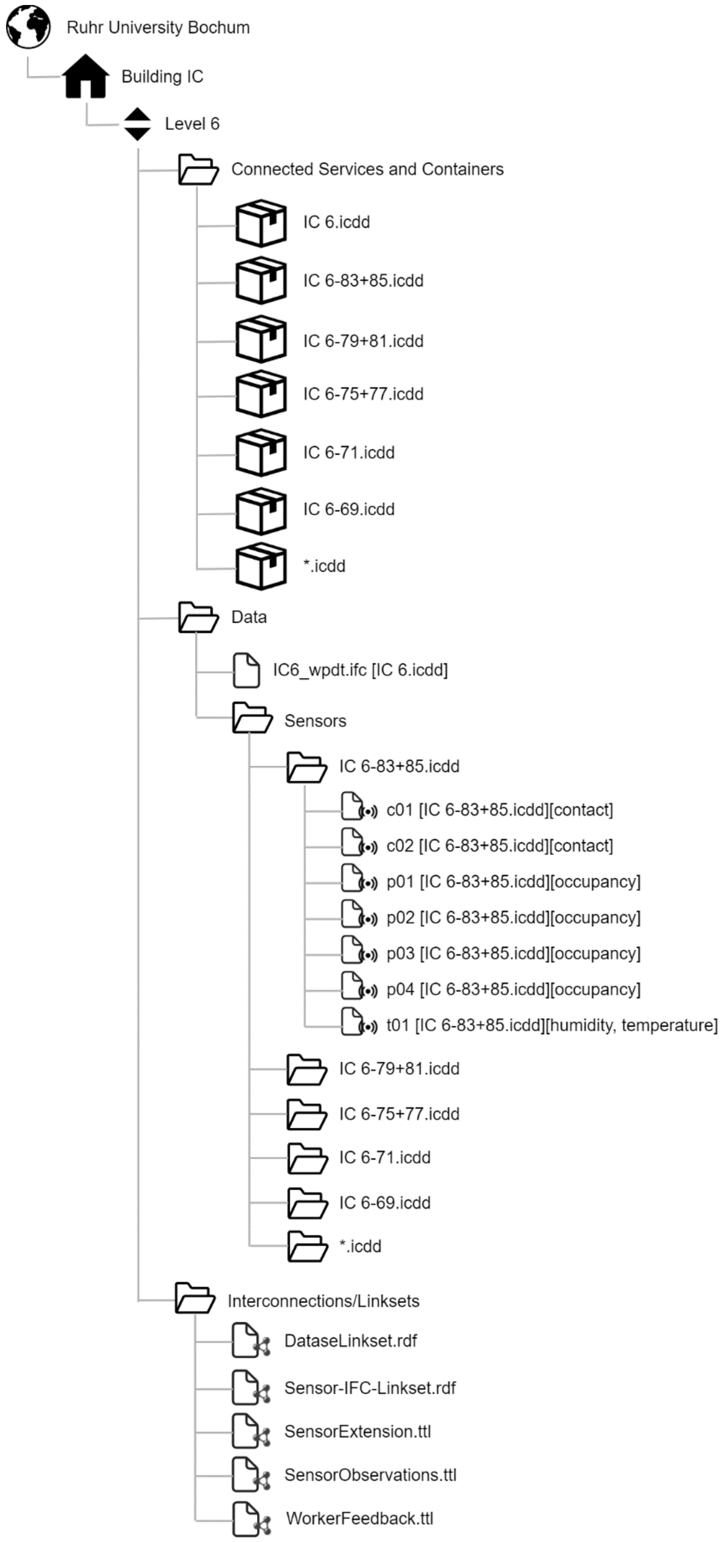

Figure 7.3 Multi-containerized structure of the workplace knowledge base for the extended case study.

In the last folder, workplace semantic data are stored in triple format. The interconnection among the containers, their documents, and data is serialized within the *DatasetLinkset.rdf*. As in the prototype, sensor data are organised into three stores: *Sensor-IFC-Linkset.rdf*, connecting entities from the IFC model with their corresponding knowledge graph entities and properties based on the SSN ontology; *SensorExtension.ttl*, which contains the configuration of sensor proxy documents; and *SensorObservations.ttl*, which holds entities describing workplace conditions, retrieved from the time-series database. Additionally, the *WorkerFeedback.ttl* is set to store worker and feedback data, structured according to the WOMO ontology.

7.4. Discussion

The second development iteration of the WSDT system, presented in this chapter, builds on the evaluation of the single-room prototype and addresses its limitations by scaling it to a department-wide case study.

First, the feasibility of expanding the sensor network solution based on Zigbee-compatible battery-powered commercial devices was evaluated. Zigbee mesh networks require a unique gateway device for each network. To extend the signal range and cover all monitored workspaces, power-supplied repeaters were successfully introduced. This solution resolved the range limitations without causing noticeable performance drops in the gateway, despite the increase from 7 to 51 connected devices. From a software perspective, decoupling the MQTT sensor message topic hierarchy from their locations (e.g., “sensor/contact/c01”) allowed for seamless integration of additional sensor data streams into the network gateway, MQTT broker, and InfluxDB configurations.

However, expanding the sensor network from a single storey (or zone within a storey) to an entire building, with the associated increase in network size, complexity, and reliability requirements, necessitates further evaluation of the suitability of smart-home devices. Different communication standards and radio technologies (e.g., Long Range, LoRa) may be better suited for large or complex scenarios. At the sensor level, improvements could be made to enhance workspace monitoring. For instance, using WiFi radar devices instead of PIR sensors at workstations could provide more accurate, less intrusive occupancy detection by analysing WiFi signal alterations caused by movement and presence in the environment. Additionally, integrating the WSDT system with existing building automation and management systems should be explored to avoid possible redundancy with pre-installed sensor and actuator infrastructures.

The second aspect addressed regarded the structure of the knowledge base. Leveraging the capacity of ICDD containers for allowing data interlinking at multiple levels—between containers, within documents, and down to entities inside documents—a new knowledge base structure has been implemented. This structure separates data common to the entire workplace from data specific to individual workspaces, each housed in distinct ICDD containers. Although the system has already been configured to retrieve and store sensor observations from the extended network according to this new structure, future work should assess the knowledge base’s ability to store, process, and semantically integrate additional worker data once the case study data collection campaign is conducted.

The conceptual development of new features for the remaining two key components of the WSDT system—the worker feedback web application and the Digital Twin dashboards—is discussed in the following sections.

7.4.1. Worker data collection development

For the worker data collection in the extended case study, the approach builds on the design used in the prototype, though further features are proposed conceptually to address larger-scale applications. The single-page survey web application, already tested during the prototype phase, is retained with its participant engagement policy, which invites voluntary feedback with a recommended minimum of four entries per day. In this case, the observation period would extend to four weeks and involve 18 employees across six shared offices: three for two employees (SO2 type) and three for four employees (SO4 type), where the workstations are equipped with motion sensors to monitor occupancy (see Figure 7.1).

The survey form's design continues to prioritize brevity, using a single-page format with three core questions, while minimizing user cognitive load through preset associations between worker ID and workspace location to reduce completion time and prevent survey fatigue (Figure 7.4).

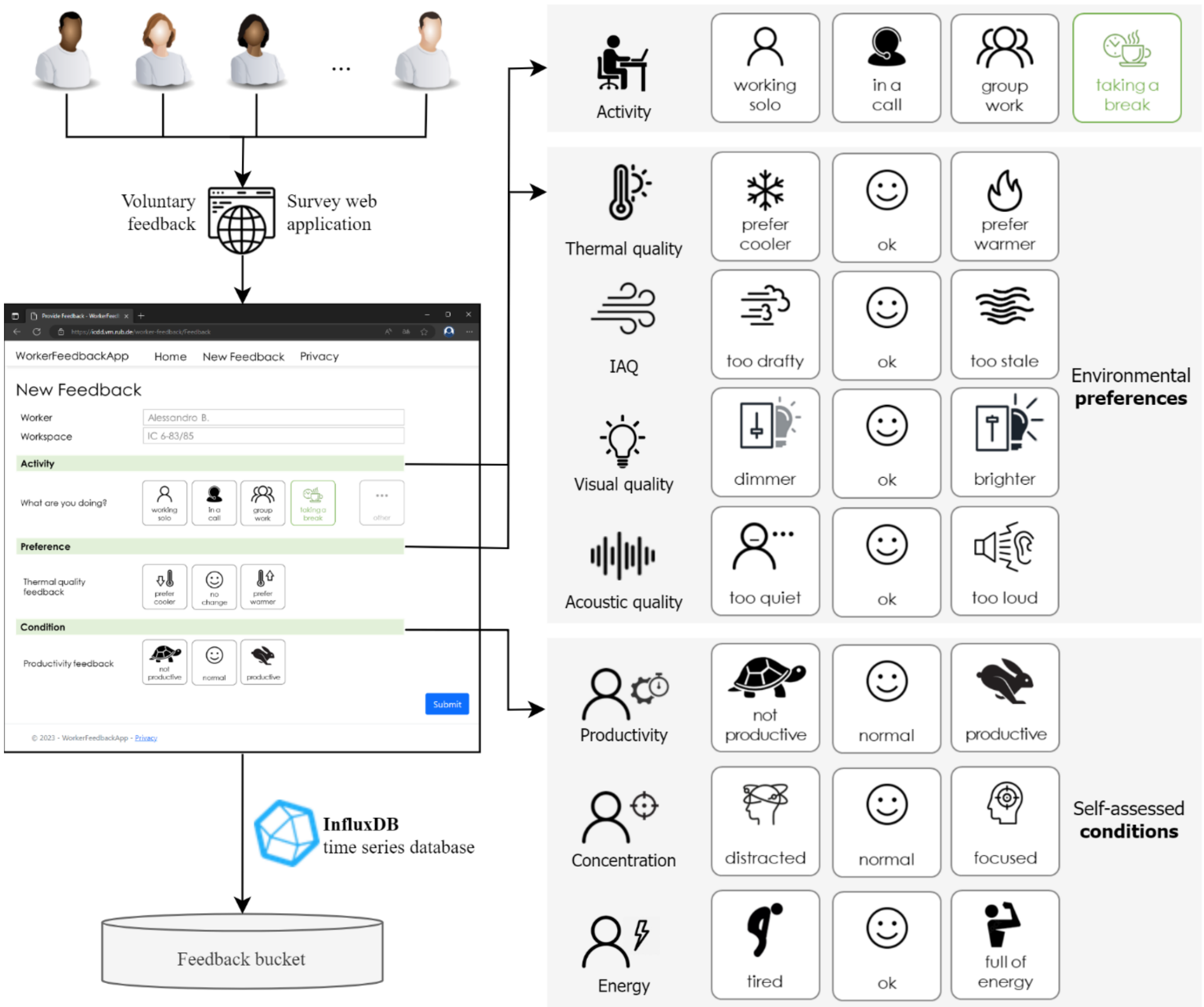

Figure 7.4 Worker data acquisition workflow and additional survey items for environmental preference and self-assessed condition enquiry.

The first question still addresses the type of the worker's activity and social interaction at the time of feedback submission, with the previously introduced options including *solo work*, *calls*, *group work*, *breaks*, or *other* unspecified activities. Meanwhile, improvements are proposed for the second and third survey items, which inquire into environmental preferences and self-assessed personal conditions. In addition to the already implemented assessment of *thermal quality*, the option to gather feedback on three further IEQ properties—*indoor air quality*, *visual quality*, and *acoustic quality*—is proposed. The response format remains a three-point Likert scale, where the neutral option represents satisfaction, and the other two indicate dissatisfaction, reflecting a desire for change in opposite directions. Whether participants are queried about different IEQ properties in a set order or randomized would be flexible and customizable based on use case requirements.

Similarly, the third feedback, which focuses on self-assessment of personal conditions, extends beyond *productivity* (as implemented in the prototype) to include *concentration* and *energy* levels. These enhancements aim to capture more nuanced worker conditions, with potential correlations to well-being, environmental satisfaction, and productivity based on the reported activity. As with the IEQ domains, workplace managers could set a specific strategy for determining which condition to inquire about, or it could be randomized at survey form generation. The three-point Likert scale would again be employed, where the middle point indicates a normal state, and the extremes reflect positive or negative deviations.

During the survey, participants would have the option to exit (i.e., close the web page) or press the *submit* button at any time, regardless of the number of questions answered. However, only feedback from surveys with at least one response would be considered valid and transmitted to the *feedback bucket* in InfluxDB.

With the exception of the activity question, all buttons and icons are monochrome to avoid confusion or overstimulation. To reinforce the three-point Likert scale concept, the same smiley face icon is used for the neutral rating across all preference and condition questions. A visual confirmation is provided by changing the background colour of selected buttons to grey, and responses can be modified at any time before submitting the survey.

At this development stage, the introduction of additional feedback options, a longer observation period, and a larger sample of participants in the extended case study would allow for a more comprehensive evaluation of the worker feedback web application and its ability to track employee engagement trends over time. However, future works should explore other technologies and strategies for both subjective and objective worker data collection. For instance, to overcome the current limitation related to fixed worker locations (tied to assigned workstations) and the absence of physiological measurements, the suitability of wearables (e.g., smartwatches) or mobile devices (e.g., smartphones) should be investigated. Additionally, the introduction of a feedback request and notification system could enhance the current survey administration strategy, which relies entirely on participants' initiative to provide feedback.

Given the significance of worker data collection for the proposed occupant-centric workplace management framework, further research is needed to ensure reliable, sustainable data acquisition, processing, and management, while addressing data security and privacy concerns that, although crucial, fall beyond the scope of this thesis.

7.4.2. Digital Twin dashboards development

Complementary to enhancing worker data collection through new web application features, additional services and dashboards have been conceptually developed to address system limitations and expand beyond the single use case implemented in the prototype. These new dashboards aim to better integrate the ICDD platform capabilities with the multi-containerized knowledge base structure, transforming the WSDT system into a service-oriented solution capable of sharing and utilizing common components (e.g., sensor network, worker feedback web application) and services (e.g., IFC model viewer, user authentication, semantic data querying, processing, and visualization). At this development stage, four Digital Twin dashboards have been conceptually designed to focus on different aspects of workplace performance assessment:

- *Performance dashboard*: Provides an overview of workplace performance based on employee satisfaction with surveyed environmental properties (thermal quality, indoor air quality, acoustic quality, and visual quality) as reported through voluntary feedback.
- *Sensor dashboard*: Monitors workplace conditions and elements (e.g., windows) as recorded by deployed sensors.
- *Activity dashboard*: Analyses workspace usage patterns based on time, category, and type of activity.
- *Condition dashboard*: Monitors self-assessed worker conditions in relation to contextual worker activity and environmental properties, such as workspace occupancy.

All dashboards retain the three-panel layout previously implemented for the prototype (see Figure 5.7 and Figure 6.9), combining data querying and visualization in the *explorer*, *dashboard*, and *viewer* panels. With reference to a sample mock-up of the new sensor dashboard (Figure 7.5), the proposed features are detailed as follows.

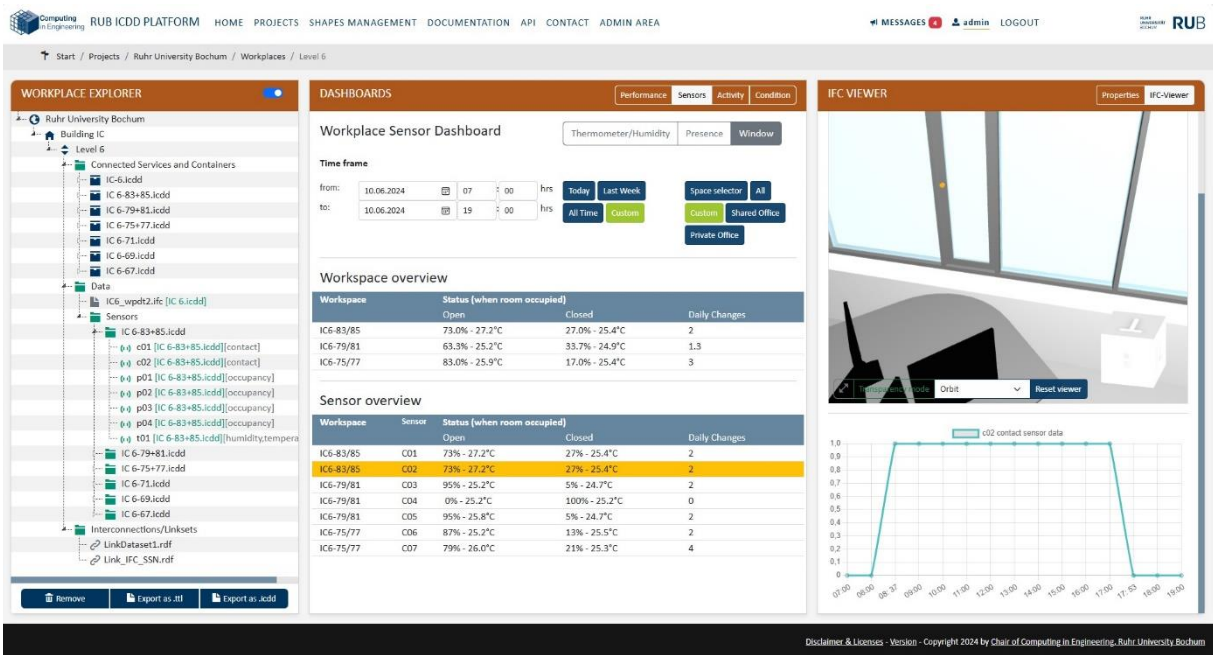

Figure 7.5 Mock-up of the new sensor dashboard interface (RUB ICDD platform).

The left-hand panel, the *workplace explorer*, allows access to WSDT resources stored within multiple interconnected ICDD containers that form the workplace knowledge base (see section 7.3). This panel remains consistent across all dashboards. At this stage, the explorer is designed for content structure visualization only, with editing restricted to admin users.

The central *dashboard* panel includes four buttons in the header, allowing users to switch between dashboards. At the top of each dashboard, the *query builder* offers customization beyond the prototype's time window options (i.e., today, last week, all time, custom interval). User would be able to select specific set of workspaces for which the information needs to be retrieved either by clicking directly in the IFC viewer (space selector), choosing from a pop-up list (custom), or selecting by workspace type (shared or private office). Additional buttons would allow the query to be limited to specific features of interest based on the use case (see Table 7.5). For all dashboards except the activity dashboard—where workspace usage is analysed across all activities surveyed—worker preferences and self-assessed conditions are considered individually by type, as well as sensor observations. Any changes to time, workspace, or feature selection would automatically update the query and results, which are displayed in the middle panel (aggregated data) and bottom panel (detailed data), as specified in Table 7.6.

Table 7.5 Dashboard panel – top section: Query builder options.

Dashboard	Feature of interest	Time	Workspace
Performance dashboard	Thermal Quality, Indoor Air Quality, Visual Quality, Acoustic Quality	Today, Last Week, All time, Custom	Space Selector, All, Custom, Shared Office, Private Office
Sensor dashboard	Thermometer/Humidity, Presence, Window		
Activity dashboard	-		
Condition dashboard	Productivity, Concentration, Energy		

In the *performance dashboard*, for each investigated IEQ property, the aggregated distribution of the three related preferences is visualized with normalized bars in the middle section for the entire workspace selection. Additional related properties, such as the mean occupancy ratio, are also provided to support contextualization. For example, alongside acoustic quality preferences, the mean occupancy ratio of the workspaces would be shown to allow correlation with the social context. In the bottom section, a more detailed view focuses on neutral preferences score (participant satisfaction) and the corresponding workspace conditions for each individual workspace. Selecting a workspace from this list recentres the IFC viewer on the relevant part of the model, while specific feedback details for that workspace are displayed below the 3D viewer, including the distribution of dissatisfying ratings and the associated workspace conditions.

In the *sensor dashboard*, for each sensor type (i.e., thermometer/humidity, presence, window), the middle section provides mean values of the measured properties in aggregated form, both for the entire selection and for individual workspaces. The bottom section visualizes the query results at the sensor level. By clicking on a listed sensor, the IFC viewer recentres on the linked model entity, which is then highlighted. Below the viewer, the corresponding sensor observations are plotted on a graph. This panel also includes a "Properties" tab at the top, where users can access stored sensor metadata (e.g., model) and updated operational conditions (e.g., battery status, network link quality).

The *activity dashboard* offers a general understanding of activities conducted across various workspaces. Activity data, collected as discrete instances linked to voluntary feedback entries provided through the discussed web application, would be visualized in the middle section with normalized bars representing their distribution for the entire workspace selection. A more granular view would be offered below, displaying the same data for each workspace individually. Selecting a workspace from the list recentres the IFC viewer, providing a spatial understanding of the workspace and its associated activities.

Table 7.6 Dashboard panel – middle and bottom section: aggregated and detailed data visualization.

Dashboard	Feature of interest	Aggregated view	Detailed view
Performance dashboard	Thermal Quality	Selection: Prefer cooler [normalized bar] Ok [normalized bar] Prefer warmer [normalized bar] + mean (temp. [°C], humidity [%], occupancy [%])	Individual workspaces: Ok [normalized bar] + mean (temp. [°C], humidity [%], occupancy [%])
	Indoor Air Quality	Selection: Too drafty [normalized bar] Ok [normalized bar] Too stale [normalized bar] + mean (temp. [°C], humidity [%], occupancy [%], windows open [%])	Individual workspaces: Ok [normalized bar] + mean (temp. [°C], humidity [%], occupancy [%], windows open [%])
	Visual Quality	Selection: Prefer dimmer [normalized bar] Ok [normalized bar] Prefer brighter [normalized bar]	Individual workspaces: 8:00-10:00: Ok [normalized bar] 10:00-12:00: Ok [normalized bar] 12:00-14:00: Ok [normalized bar] 14:00-16:00: Ok [normalized bar] 16:00-18:00: Ok [normalized bar] 18:00-20:00: Ok [normalized bar]
	Acoustic Quality	Selection: Too quiet [normalized bar] Ok [normalized bar] Too loud [normalized bar] + mean occupancy [%]	Individual workspaces: Ok [normalized bar] + mean occupancy [%]
Sensor dashboard	Thermometer/ Humidity	Selection and individual workspaces: Mean temp. [°C] and humidity [%]	Individual sensors: Mean temp. [°C] and humidity [%]
	Presence	Selection and individual workspaces: 8:00-10:00: count [float], ratio [%] 10:00-12:00: count [float], ratio [%] 12:00-14:00: count [float], ratio [%] 14:00-16:00: count [float], ratio [%] 16:00-18:00: count [float], ratio [%] 18:00-20:00: count [float], ratio [%]	Individual sensors (workstations): 8:00-10:00: count [float], ratio [%] 10:00-12:00: count [float], ratio [%] 12:00-14:00: count [float], ratio [%] 14:00-16:00: count [float], ratio [%] 16:00-18:00: count [float], ratio [%] 18:00-20:00: count [float], ratio [%]
	Window	Selection and individual workspaces: Open: Time [%], mean temp. [°C] Closed: Time [%], mean temp. [°C] Daily status changes: [float]	Individual sensors (windows): Open: Time [%], mean temp. [°C] Closed: Time [%], mean temp. [°C] Daily status changes: [float]
Activity dashboard	-	Selection: Working solo [normalized bar] In a call [normalized bar] Group work [normalized bar] Taking a break [normalized bar] Other [normalized bar]	Individual workspaces: Working solo [normalized bar] In a call [normalized bar] Group work [normalized bar] Taking a break [normalized bar] Other [normalized bar]
Condition dashboard	Productivity	Selection: Not productive [normalized bar] Normal [normalized bar] Productive [normalized bar] + activity types [%], occupancy [%]	Individual workspaces: Productive [normalized bar] + activity types [%], occupancy [%]
	Concentration	Selection: Distracted [normalized bar] Normal [normalized bar] Focused [normalized bar] + activity types [%], occupancy [%]	Individual workspaces: Focused [normalized bar] + activity types [%], occupancy [%]
	Energy	Selection: Tired [normalized bar] Ok [normalized bar] Full of energy [normalized bar] + activity types [%], occupancy [%]	Individual workspaces: Full of energy [normalized bar] + activity types [%], occupancy [%]

Finally, the *condition dashboard* complements the performance dashboard by providing insights into employees' self-assessed conditions (i.e., productivity, concentration, energy). For the selected condition, the middle section visualizes the distribution of the three possible ratings using normalized bars for the entire workspace selection, along with the most frequently reported activity type and the mean occupancy ratio for context. The bottom section details the more positive ratings (e.g., "focused" for concentration) for each workspace. Selecting a workspace recentres the IFC viewer on that space, and additional details on the other two ratings are shown in the right-hand panel, offering a more detailed understanding of the workspace and the reported self-assessed conditions.

Together with the addition of the new environmental properties and personal conditions to be collected via the worker feedback web application, the implementation of the proposed dashboards is expected to enhance the WSDT system's ability to address diverse workplace management use cases and would allow for a more comprehensive evaluation in the department-scale case study. The dashboards would retain the functionality for workplace managers to query and visualize data within the workplace knowledge base (e.g., BIM data, sensor observations, worker feedback) without requiring programming or SPARQL knowledge, supporting specialized occupant-centric workplace management use cases such as environmental condition monitoring, space usage tracking, and the assessment of worker environmental satisfaction and subjective conditions.

However, despite these developments, several limitations remain. Further evaluation should include focus groups with facility managers and workplace supervisors, along with additional testing in real-world applications. The system's capability to integrate and link heterogeneous data within the workplace knowledge base should be expanded. For environmental performance evaluation, the current sensor network does not include sensors for measuring critical IEQ factors such as illuminance, sound pressure, and CO_2 or other air pollutant concentrations. Integration with sensors already available from HVAC systems or other automated building systems should be considered to enhance the sensor network.

In terms of sensor monitoring, features like notifications or alerts should be enabled for anomaly detection (e.g., unwanted window openings outside working hours) or operational conditions requiring attention (e.g., low battery levels). While the proposed method for workspace usage monitoring provides qualitative insights into activity trends, drawing quantitative conclusions would require more privacy-intrusive methods like activity recognition via computer vision. Nonetheless, valuable insights can still be extracted from the current approach.

Regarding the ICDD platform, more advanced data visualization capabilities should be implemented to fully exploit the availability of 3D BIM data. The IFC model of the workplace could be used to superimpose data and apply customized visualizations (e.g., colour schemes, labels, visibility filters). From a data integration perspective, connecting the WSDT system to databases and systems both within and outside the organisation (e.g., human resources management, building automation, public datasets like weather and traffic data) would enhance its utility. This extension could be achieved by linking external resources or services and by enriching the WOMO ontology with new concepts, either original or from existing specialized ontologies, as discussed in section 4.8.

Finally, a crucial future step will involve implementing reasoning capabilities to support advanced use cases, such as issue discovery, preferences clustering, and recommendations—areas for which the development of the necessary DT services and dashboards was beyond the scope of this thesis.

8

Conclusions

This thesis explores the collection, integration, and processing of heterogenous workplace data to enable occupant-centric approaches in workplace management, aiming to enhance workers' well-being and productivity by providing a more granular understanding of their experience and interaction with the workplace environment. A framework for realizing a workplace semantic digital twin is proposed, alongside the conceptual and technical development of a viable system, its prototypical implementation, evaluation, and extension through a real-scale case study. This chapter is organised into three sections: first, an overview of the study is provided, explicitly linking the findings to the research questions (§8.1); second, the research contributions are highlighted, along with their implications for both practice and research, and at a broader societal level (§8.2); finally, the study's limitations are discussed, and direction for future work are outlined (§8.3).

Problems cannot be solved by
thinking within the framework in
which the problems were created.

- Albert Einstein

8.1. Summary and deliverables

In contemporary workplace management, providing indoor environments that meet the needs and preferences of occupants while supporting their activities has become a key priority for organisations. Traditional building-centric management approaches, which focus at best on monitoring environmental parameters and reactively adjusting building systems, have proven limited in addressing occupant expectations. Viewing building occupants as passive recipients for whom ideal indoor conditions can be achieved solely by monitoring physical environmental parameters leads to suboptimal results. Additionally, conventional POE methods, which rely on the quantitative analysis of qualitative survey responses, are usually missing reliable contextual information about the experienced environment and are prone to be affected by recall bias. In contrast, occupant-centric approaches seek to enhance workers' well-being and productivity by dynamically monitoring the complex interactions between occupants and their environment. This would ideally allow workplace managers with the insights necessary to make informed decisions for the optimisation of both the physical and organisational aspects of the workplace. However, the implementation of methods and tools that facilitate the effective adoption of the related multidisciplinary perspective—integrating building science with social, psychological, and physiological dynamics—is still in its infancy and faces significant challenges.

The overarching goal of this thesis is to contribute to addressing this issue by exploring the collection, integration, and processing of both objective and subjective data generated by buildings and workers. For this purpose, the thesis developed, implemented, and tested an original framework for a Workplace Semantic Digital Twin system that enables occupant-centric workplace management.

The framework was informed by the insights derived from the literature review, which was conducted on the basis of the defined research questions (§1.2). As a first step, studies characterizing the complex indoor workplace ecosystem—where physical environmental properties interact with social and psycho-physiological dynamics to influence worker experience, well-being, and job performance (RQ1-2)—were examined. This exploration underscored the significance of often-overlooked factors, such as individual preferences, current activities, and social interactions, in shaping the perception of workspace and its impact on well-being and productivity. These findings informed the semantic characterization of the workplace knowledge domain and laid the foundation for defining the core concepts in the Occupant-centric Workplace Management Ontology (WOMO).

Following this, we reviewed state-of-the-art methodologies and technologies for building and occupant monitoring to identify the most suitable solutions for workplace and worker data collection (RQ3). This investigation emphasized the role of BIM and IoT paradigms for modeling and representing building-related aspects of the workplace, as well as the use of sensors for dynamically monitoring environmental conditions. For worker data collection, we identified the need to move beyond traditional POE methods by adopting an EMA approach. This strategy enables the frequent collection of momentary feedback, including workers' activities, environmental preferences, and self-assessed conditions, and allows their integration with the contextual environmental data collected by sensors.

Finally, we explored methodological frameworks and technological solutions for realizing a virtual representation of the workplace ecosystem tailored to our aims, with particular attention to methods for collecting, integrating, and extracting insights from the heterogeneous data generated by both buildings and occupants (RQ4-RQ5). To this end, Semantic Web technologies and formal ontologies—specifically within the LBD approach—were identified as promising solutions for enabling structured knowledge representation and interoperability across diverse data sources. These semantic models can be implemented through an ICDD-based knowledge base and integrated within a Digital Twin platform. Such an infrastructure can support the deployment of dedicated data processing services designed to extract meaningful insights from real-time sensor data and subjective worker feedback, ultimately facilitating informed and occupant-centric workplace management.

From this review, two primary research gaps emerged: first, the lack of formal conceptualizations for capturing and describing the worker-activity-workplace fit to support performance assessment and inform improvement actions; and second, the lack of a Digital Twin framework tailored specifically to occupant-centric management of indoor workplaces.

In addressing these gaps, this thesis presents three main and interlinked deliverables:

- a high-level framework of Digital Twin to support decision-making for occupant-centric workplace management based on the collection, semantic integration and extraction of insights from building and worker generated data;
- an original semantic characterization of indoor workplaces and formal representation of the related knowledge with the Occupant-centric Workplace Management Ontology (WOMO), central in the realization of the framework;
- the development, implementation, and testing of a Workplace Semantic Digital Twin system, comprising the definition of its conceptual and technical architecture which integrates BIM, IoT, and Semantic Web technologies with a Linked Data approach.

The conceptual design of the system was implemented and evaluated in two stages. Initially, a prototype was developed to test the chosen hardware and software solutions in a minimum viable case study, monitoring a single workspace with the participation of four employees at Ruhr University Bochum. This prototype confirmed the feasibility and reliability of deploying a lightweight sensor network infrastructure using battery-powered commercial smart home devices based on Zigbee communication protocol, with minimal disruption to the workplace environment. The collection of worker location data and feedback via micro-surveys, voluntarily provided through a dedicated web application, also proved effective, despite limitations. In addition, separating the management and storage of time-series data—for both sensor observations and worker feedback—from the semantic knowledge base proved to be a flexible and effective approach. This design choice allowed for interfacing with decentralized services and data stores through a containerized solution based on the ICDD standard. Customizing the existing RUB ICDD platform[40] (Hagedorn, 2022) enabled the creation and management of the system knowledge base, as well as the semantic data integration, querying, and visualization within user-friendly dashboards tailored for workplace managers with no programming expertise.

[40] RUB ICDD Platform - https://icdd.vm.rub.de/ui - Accessed 05/05/2025.

Lessons learned from the initial room-scale implementation informed further development for an extended case study, covering 14 workspaces within the same department. This larger study was designed to evaluate the system's feasibility in a setting more closely aligned with real-world dimensions and requirements. To support the expanded scale, both the sensor network and workplace knowledge base configurations were upscaled. The sensor network extension was straightforward, involving the pairing of additional sensors to the existing gateway and the addition of router devices to extend signal range. For the knowledge base, the structure evolved from a single-container to a multi-containerized solution, leveraging the ICDD's capabilities for interlinking at container, document, and data levels. This setup facilitated the separation of data common to the entire workplace from data specific to individual workspaces. Prototype limitations, particularly in worker feedback collection and the ICDD platform's querying and visualization functionalities, were also addressed. Additional features were conceptualized for the web feedback application, enabling the collection of feedback on additional environmental properties and worker self-assessed conditions. Moreover, although not implemented, four new dashboards were designed to expand the system's use cases, supporting performance, sensor, activity, and worker condition monitoring.

8.2. Impacts, benefits and contributions to knowledge

This thesis introduces the Workplace Semantic Digital Twin (WSDT) conceptual framework and technical implementation as a novel approach to occupant-centric management of indoor workplaces. Its impacts span both academic and practical domains by demonstrating how the Semantic Digital Twin paradigm can be effectively applied through the integration of BIM, IoT, and Semantic Web technologies, structured according to a Linked Data approach. The results demonstrate how meaningful, actionable insights can be extracted from diverse workplace-related data streams generated by buildings and their occupants. These insights can inform strategies that enhance the quality and performance of workplaces, ultimately benefiting worker well-being and productivity, and, by extension, contributing to organisational effectiveness and resilience.

Importantly, the potential impacts of this work extend beyond its disciplinary boundaries, contributing to broader societal and environmental goals in line with the United Nations Sustainable Development Goals (SDGs)[41]. The WSDT framework enables data-driven, human-centric workplace management with implications across three key dimensions:

- *Well-being and inclusion* (SDGs 3, 5, 10): By incorporating subjective feedback and individual preferences, the system supports healthier, more comfortable indoor environments while promoting inclusive management practices that account for diverse worker needs, helping reduce stress and foster equity across gender and minority groups.
- *Workforce productivity and innovation* (SDGs 8, 9): The framework facilitates responsive, adaptive workplaces that can enhance job satisfaction and organizational performance, while also advancing the digital transformation of workplace infrastructure through the integration of BIM, IoT, and Semantic Web technologies.

[41] The 17 Goals | Sustainable Development - https://sdgs.un.org/goals - Accessed 05/05/2025.

- *Environmental efficiency and sustainability* (SDGs 11, 12): By supporting smarter resource management and optimization of environmental conditions, the system contributes to more sustainable building operation, helping reduce energy consumption and promote responsible use of indoor space.

In addition to these broader benefits, this thesis makes three core contributions to knowledge in the fields of facility management and digital twin research and practice.

First, it introduces the *activity* dimension into the representation and analysis of the indoor workplace ecosystem—an aspect traditionally overlooked in favour of monitoring the variation of IEQ properties and occupants' conditions or preferences over time. By incorporating activity, the aim is to provide a richer, more contextualised understanding of how space is experienced in relation to how it is used. Unlike previous studies that enhanced the integration of occupant data with spatial features (M. M. Abdelrahman et al., 2022), or efforts that focused on advanced approaches to knowledge discovery from integrated occupant-building data (Donkers et al., 2022a; Donkers et al., 2022c), or explored intensive longitudinal data collection through wearable devices and mobile applications (Jayathissa et al., 2019; Jayathissa et al., 2020; Tartarini et al., 2022), this thesis addresses a more holistic challenge: the integration of real-time subjective feedback with activity-aware environmental monitoring within a unified semantic framework.

Second, this thesis delivers the *WOMO ontology* which formalizes the core concepts and relationships underlying the workplace ecosystem. While previous efforts focused on the semantic integration of occupant feedback with building data for environmental comfort understanding (Donkers et al., 2022b) or on modeling occupant behaviour primarily for energy optimisation purposes (Hong, D'Oca, Taylor-Lange, et al., 2015; Hong, D'Oca, Turner, et al., 2015; Chávez-Feria, Poveda-Villalón, et al., 2020), WOMO contributes to the growing body of work within the LBD community, addressing a critical gap in current ontological resources by targeting occupant-centric applications specifically in the context of workplace management and the improvement of worker–workplace fit.

Third, the *technical implementation of the WSDT system* in a case study setting demonstrates both the feasibility and scalability of the proposed framework. This includes the design of a low-cost, minimally invasive sensor infrastructure; the development of a web-based worker feedback application; the instantiation of a semantic knowledge base using standardized ICDD containers; and the customization of a previously developed web platform for managing, querying, and visualizing the related workplace semantic data. Together, these components constitute a working prototype which offers a replicable model for future research and practical application.

8.3. Limitations and future work

While the framework and system implementation proposed in this work move meaningful steps towards adopting SDTs for occupant-centric workplace management, several limitations remain that present valuable opportunities for further research and development. The following points outline the primary limitations encountered and suggest potential directions for future exploration:

- *Extension of the WSDT framework* – Currently, the framework is conceived to support workplace managers in decision-making, requiring human intervention to translate insights from the digital twin into actions within the physical workplace. While this approach is suitable for strategic decisions and major interventions (e.g., workspace reorganisation, resource allocation), future work could explore opportunities to increase integration with building management systems (BMSs), allowing the environment to adjust dynamically based on monitored or anticipated occupant needs. Additionally, more active employee involvement—obtainable by providing workers access to dedicated insights on workspace conditions—could foster greater participation and trust in the system, potentially enhancing data quality and improving workplace operations overall.
- *Extension of the WOMO ontology capabilities* – The WOMO ontology is designed to support occupant-centric management of indoor workplaces by enabling insight extraction from contextual interpretations of building conditions monitored by sensors and worker data collected via the EMA method. However, to fully address practical managerial scenarios and support advanced reasoning and learning applications—such as issue discovery, employee profiling, and spatial recommendations—further development and testing are needed to extend the core ontology modules. This could involve proposing additional concepts and properties or integrating specialized ontologies to enhance its scope.
- *Extension of WSDT sensing capabilities and integration with existing building systems* – The hardware and software infrastructure in the prototype was chosen to maximize flexibility and minimize workplace disruption and relied on commercial battery-powered sensors based on the Zigbee communication protocol. However, scaling from a department-level to a building- or facility-wide deployment, with hundreds of devices monitoring workspaces and building elements across extended areas and multiple stories, requires increased reliability for networks that are larger in size and complexity. This shift necessitates evaluating alternative sensor technologies for large-scale applications, such as LoRa devices. Additionally, future WSDT development could incorporate more sensor types to capture additional environmental properties (e.g., illuminance, sound pressure, and CO_2 concentration). Occupancy measurement at workspace level could be improved by replacing PIR sensors at workstations with WiFi radar devices, which detect presence and movement in larger areas through the analysis of reflected WiFi signals. Furthermore, with the increasing deployment of sensors in existing buildings, especially for environmental monitoring and HVAC integration, future WSDT iterations should explore ways to interface and acquire data from existing sensor networks to minimize redundancy.
- *Improvement of worker data collection and management of personal data privacy and security concerns* – The repeated collection of objective (e.g., location, physiological parameters, activity) and subjective (e.g., environmental preferences, self-assessed conditions) worker data through voluntary feedback provided via a dedicated survey web application is central to the proposed framework. Future iterations should investigate more sophisticated strategies for data collection to better address current and potential use cases, such as Bluetooth beacon technologies for indoor localization and

wearable or mobile devices for health indicator collection and survey administration. Additionally, aiming at deploying the system in real-world applications, the management of personal data privacy and security is crucial. Therefore, the implementation of data encryption methods, secure data storage protocols, and transparent data governance policies must be thoroughly investigated to ensure that workers' data is treated legitimately. While these critical aspects of data handling and security were not fully addressed within the scope of this thesis, they represent crucial aspects for future development. Providing transparency about data usage and obtaining informed consent from workers are essential steps to build trust and encourage participation, which is vital for successful occupant-centric system implementation in real-world applications.

- *Implementation of advanced WSDT use cases and expert evaluation* – The implementation of the WSDT system prototype presented in this thesis has demonstrated its potential for integrating semantic sensor observations and worker feedback data to extract insights that primarily support workplace performance assessment use cases. However, future development iterations should aim to advance the system's exploitation of the semantic knowledge base by incorporating reasoning and learning capabilities. This will enable the system to address more complex use cases, such as issue discovery, worker preference and needs profiling, and spatial recommendations. Within the ICDD platform, additional Digital Twin services for querying and visualizing workplace data should be developed to support these advanced use cases, including the recognition and evaluation of recurring patterns in worker-workspace data. This enhancement would allow the system to offer tailored recommendations based on learned worker preferences and needs. Furthermore, future development stages should involve evaluations of the provided features through focus groups comprising experts in workplace and human resources management. This approach will facilitate the collection of critical feedback on the feature development directions, ensuring that the system effectively supports decision-makers in enhancing worker well-being and productivity.

As automation capabilities advance and commercial solutions make Artificial Intelligence-driven technologies increasingly accessible and effective, the future of knowledge work is set to shift away from menial tasks, focusing instead on value-added contributions and quality over time. Consequently, the quality, responsiveness, and adaptability of indoor workplace environments to the preferences and needs of their occupants will emerge as critical performance indicators for organisations. As the research discussed in this thesis will be object of further developments, it is anticipated that both academia and industry will increasingly direct their efforts toward developing SDT solutions to support the implementation of occupant-centric management approaches. These advancements promise to meet the evolving requirements of modern workplaces, ultimately enhancing worker well-being and quality of life.

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Appendices

Appendix A – Occupant-centric Workplace Management Ontology documentation

The Occupant-centric Workplace Management ontology (WOMO)

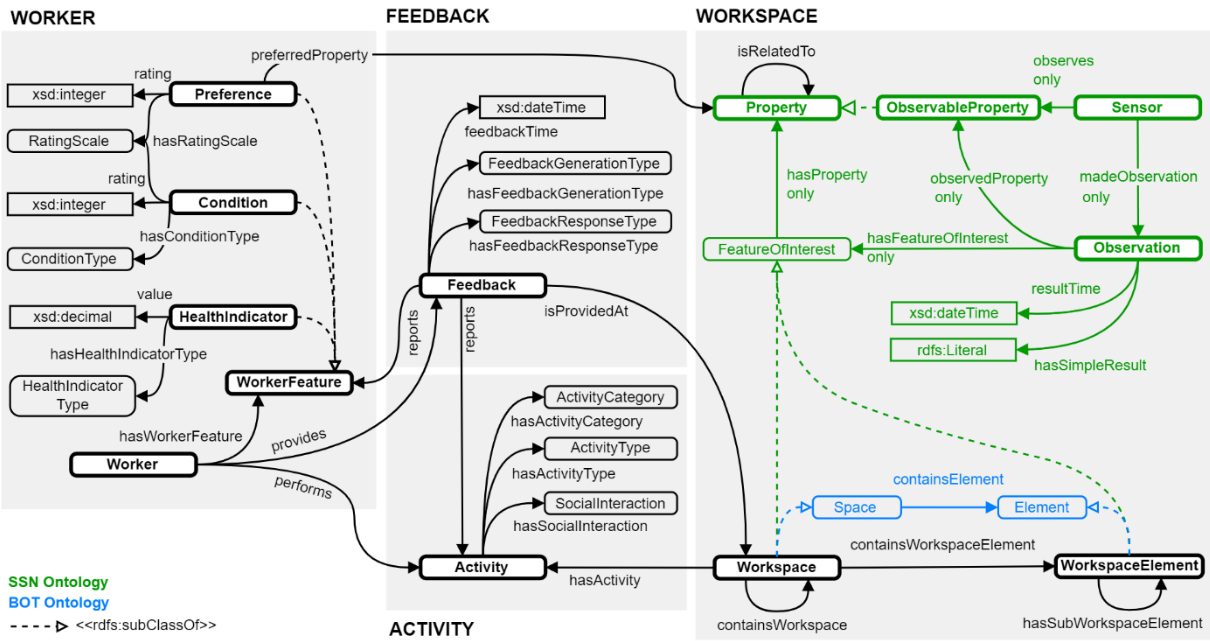
Metadata	
IRI	https://w3id.org/womo#
Creator(s)	Alessandro Bruttini (alessandro.bruttini@unifi.it) of University of Florence, IT
Created	2023-07-19
Version Information	1.0
License	CC-BY-40
Ontology RDF	https://github.com/AlessandroBruttini/womo/blob/main/ontology.ttl

Description

The Occupant-centric Workplace Management (WOMO) ontology describes knowledge related to office environments and enables the development of a workplace Digital Twin system centred on the occupant experience.

Table of Contents

Overview



Classes

Activity, ActivityCategory, ActivityType, CommonSpace, Condition, ConditionType, Department, EnclosedOffice, Feedback, FeedbackGenerationType, FeedbackResponseType, HealthIndicator, HealthIndicatorType, MechanicalVentilationControlType, Member, NaturalVentilationControlType, NotRespondedFeedback, Office, Organisation, Preference, RatingScale, RespondedFeedback, Room, SocialInteraction, VentilationType, Worker, WorkerFeature, Workspace, WorkspaceElement, WorkspaceType, Workstation.

Activity

Property	Value
IRI	https://w3id.org/womo#Activity
Description	Thing that the worker is doing.
Super-classes	owl:Thing (c)
In domain of	womo:hasActivityCategory (op) womo:hasSocialInteraction (op) womo:isPerformedBy (op) womo:hasActivityType (op) womo:isPerformedAt (op)
In range of	womo:isActivityCategoryOf (op) womo:performs (op) womo:isActivityTypeOf (op) womo:hasActivity (op) womo:isSocialInteractionOf (op)

Activity Category

Property	Value
IRI	https://w3id.org/womo#ActivityCategory
Description	Specifies the category of the activity that the worker is performing.
Super-classes	owl:Thing (c)
In domain of	womo:isActivityCategoryOf (op)
In range of	womo:hasActivityCategory (op)

Activity Type

Property	Value
IRI	https://w3id.org/womo#ActivityType
Description	Specifies the type of activity that the worker is performing.
Super-classes	owl:Thing (c)
In domain of	womo:isActivityTypeSupportedBy (op) womo:isActivityTypeOf (op)
In range of	womo:hasActivityType (op) womo:supportsActivityType (op)

Common Space

Property	Value
IRI	https://w3id.org/womo#CommonSpace
Super-classes	womo:WorkspaceType (c)

Condition

Property	Value
IRI	https://w3id.org/womo#Condition
Super-classes	womo:WorkerFeature (c)
In domain of	womo:hasConditionType (op)
In range of	womo:isConditionTypeOf (op)

Condition Type

Property	Value
IRI	**https://w3id.org/womo#ConditionType**
Super-classes	**owl:Thing (c)**
In domain of	**womo:isConditionTypeOf (op)**
In range of	**womo:hasConditionType (op)**

Department

Property	Value
IRI	https://w3id.org/womo#Department
Super-classes	womo:Organisation (c)

Enclosed Office

Property	Value
IRI	https://w3id.org/womo#EnclosedOffice
Super-classes	womo:Office (c)

Feedback

Property	Value
IRI	https://w3id.org/womo#Feedback
Super-classes	owl:Thing (c)
In domain of	womo:hasFeedbackGenerationType (op) womo:feedbackTime (dp) womo:hasFeedbackResponseType (op) womo:feedbackRequestTime (dp) womo:isProvidedAt (op) womo:feedbackStartTime (dp) womo:responseDuration (dp) womo:isProvidedBy (op) womo:reports (op) womo:responseRatio (dp)
In range of	womo:isReportedBy (op) womo:isFeedbackResponseTypeOf (op) womo:provides (op) womo:hasFeedback (op) womo:isFeedbackGenerationTypeOf (op)

Feedback Generation Type

Property	Value
IRI	https://w3id.org/womo#FeedbackGenerationType
Description	Instances of this class enumerates possible feedback request generation types.
Super-classes	owl:Thing (c)
In domain of	womo:isFeedbackGenerationTypeOf (op)
In range of	womo:hasFeedbackGenerationType (op)

Feedback Response Type

Property	Value
IRI	https://w3id.org/womo#FeedbackResponseType
Description	Instances of this class enumerates possible feedback response types.
Super-classes	owl:Thing (c)
In domain of	womo:NotRespondedFeedback (c) womo:RespondedFeedback (c)

Health Indicator

Property	Value
IRI	https://w3id.org/womo#HealthIndicator
Super-classes	womo:WorkerFeature (c)
In domain of	womo:value (dp) womo:hasHealthIndicatorType (op)
In range of	womo:isHealthIndicatorTypeOf (op)

Health Indicator Type

Property	Value
IRI	https://w3id.org/womo#HealthIndicatorType
Super-classes	owl:Thing (c)
In domain of	womo:isHealthIndicatorTypeOf (op)
In range of	womo:hasHealthIndicatorType (op)

Mechanical Ventilation Control Type

Property	Value
IRI	https://w3id.org/womo#MechanicalVentilationControlType
Super-classes	owl:Thing (c)
In domain of	womo:isMechanicalVentilationControlTypeOf (op)
In range of	womo:hasMechanicalVentilationControlType (op)

Member

Property	Value
IRI	https://w3id.org/womo#Member
Super-classes	owl:Thing (c)
Sub-classes	womo:Worker (c)
In domain of	womo:isMemberOf (op)
In range of	womo:hasMember (op)

Natural Ventilation Control Type

Property	Value
IRI	https://w3id.org/womo#NaturalVentilationControlType
Super-classes	owl:Thing (c)
In domain of	womo:isNaturalVentilationControlTypeOf (op)
In range of	womo:hasNaturalVentilationControlType (op)

Not Responded Feedback

Property	Value
IRI	https://w3id.org/womo#NotRespondedFeedback
Description	Instances of this class enumerates possible types of not responded feedback.
Super-classes	womo:FeedbackResponseType (c)

Office

Property	Value
IRI	https://w3id.org/womo#Office
Super-classes	womo:Room (c)
Sub-classes	womo:EnclosedOffice (c)

Organisation

Property	Value
IRI	https://w3id.org/womo#Organisation
Super-classes	owl:Thing (c)
Sub-classes	womo:Department (c)
In domain of	womo:organisationLogo (dp) womo:hasMember (op) womo:isPartOf (op) womo:hasPart (op) womo:organisationName (dp) womo:ownsWorkspace (op)
In range of	womo:hasPart (op) womo:isWorkspaceOf (op) womo:isMemberOf (op) womo:isPartOf (op)

Preference

Property	Value
IRI	https://w3id.org/womo#Preference
Super-classes	womo:WorkerFeature (c)
In domain of	womo:isPreferenceFor (op)
In range of	womo:isPreferredAs (op)

Rating Scale

Property	Value
IRI	https://w3id.org/womo#RatingScale
Super-classes	owl:Thing (c)
In domain of	womo:ratingScalePrompt (dp) womo:ratingScaleName (dp) womo:ratingScaleOptions (dp) womo:isRatingScaleOf (op)
In range of	womo:hasRatingScale (op)

Responded Feedback

Property	Value
IRI	https://w3id.org/womo#RespondedFeedback
Description	Instances of this class enumerates possible types of responded feedback.
Super-classes	womo:FeedbackResponseType (c)

Room

Property	Value
IRI	https://w3id.org/womo#Room
Super-classes	womo:WorkspaceType (c)
Sub-classes	womo:Office (c)

Social Interaction

Property	Value
IRI	https://w3id.org/womo#SocialInteraction
Super-classes	owl:Thing (c)
In domain of	womo:isSocialInteractionOf (op)
In range of	womo:hasSocialInteraction (op)

Ventilation Type

Property	Value
IRI	https://w3id.org/womo#VentilationType
Super-classes	owl:Thing (c)
In domain of	womo:isVentilationTypeOf (op)
In range of	womo:hasVentilationType (op)

Worker

Property	Value
IRI	https://w3id.org/womo#Worker
Super-classes	womo:Member (c) owl:Thing (c)
In domain of	womo:hasWorkerFeature (op) womo:performs (op) womo:hasAllocatedWorkspace (op) womo:provides (op)
In range of	womo:isWorkerFeatureOf (op) womo:isAllocatedTo (op) womo:isProvidedBy (op) womo:isPerformedBy (op)

Worker Feature

Property	Value
IRI	https://w3id.org/womo#WorkerFeature
Super-classes	owl:Thing (c)
Sub-classes	womo:Condition (c) womo:HealthIndicator (c) womo:Preference (c)
In domain of	womo:isWorkerFeatureOf (op)
In range of	womo:hasWorkerFeature (op)

Workspace

Property	Value
IRI	https://w3id.org/womo#Workspace
Super-classes	https://w3id.org/bot#Space (c) owl:Thing (c) sosa:FeatureOfInterest (c)
In domain of	womo:workspaceVolumePerOccupant (dp) womo:supportsActivityType (op) womo:workspaceNetFloorArea (dp) womo:hasVentilationType (op) womo:isWorkspaceOf (op) womo:workspaceOccupancyNumber (dp) womo:hasNaturalVentilationControlType (op) womo:workspacePubliclyAccessible (dp) womo:workspaceHeight (dp) womo:isAllocatedTo (op) womo:workspaceLocalID (dp) womo:workspaceNetVolume (dp) womo:hasMechanicalVentilationControlType (op) womo:workspaceAreaPerOccupant (dp) womo:hasFeedback (op) womo:hasWorkspaceType (op) womo:workspaceIsShared (dp) womo:hasWorkspace (op) womo:hasActivity (op) womo:containsWorkspaceElement (op)
In range of	womo:isProvidedAt (op) womo:hasAllocatedWorkspace (op) womo:hasWorkspace (op) womo:isNaturalVentilationControlTypeOf (op) womo:isVentilationTypeOf (op) womo:isMechanicalVentilationControlTypeOf (op) womo:isPerformedAt (op) womo:isWorkspaceTypeOf (op) womo:isActivityTypeSupportedBy (op) womo:ownsWorkspace (op)

Workspace Element

Property	Value
IRI	https://w3id.org/womo#WorkspaceElement
Super-classes	owl:Thing (c) https://w3id.org/bot#Element (c) sosa:FeatureOfInterest (c)
In domain of	womo:hasSubWorkspaceElement (op)
In range of	womo:containsWorkspaceElement (op) womo:hasSubWorkspaceElement (op)

Workspace Type

Property	Value
IRI	https://w3id.org/womo#WorkspaceType
Super-classes	owl:Thing (c)
Sub-classes	womo:Room (c) womo:Workstation (c) womo:CommonSpace (c)
In domain of	womo:isWorkspaceTypeOf (op)
In range of	womo:hasWorkspaceType (op)

Workstation

Property	Value
IRI	https://w3id.org/womo#Workstation
Super-classes	womo:WorkspaceType (c)

Object Properties

containsWorkspaceElement, hasActivity, hasActivityCategory, hasActivityType, hasAllocatedWorkspace, hasConditionType, hasFeedback, hasFeedbackGenerationType, hasFeedbackResponseType, hasHealthIndicatorType, hasMechanicalVentilationControlType, hasMember, hasNaturalVentilationControlType, hasPart, hasRatingScale, hasSocialInteraction, hasSubWorkspaceElement, hasVentilationType, hasWorkerFeature, hasWorkspace, hasWorkspaceType, isActivityCategoryOf, isActivityTypeOf, isActivityTypeSupportedBy, isAllocatedTo, isConditionTypeOf, isFeedbackGenerationTypeOf, isFeedbackResponseTypeOf, isHealthIndicatorTypeOf, isMechanicalVentilationControlTypeOf, isMemberOf, isNaturalVentilationControlTypeOf, isPartOf, isPerformedAt, isPerformedBy, isPreferenceFor, isPreferredAs, isProvidedAt, isProvidedBy, isRatingScaleOf, isRelatedTo, isReportedBy, isSocialInteractionOf, isVentilationTypeOf, isWorkerFeatureOf, isWorkspaceOf, isWorkspaceTypeOf, ownsWorkspace, performs, provides, reports, supportsActivityType.

contains Workspace Element

Property	Value
IRI	https://w3id.org/womo#containsWorkspaceElement
Super-properties	https://w3id.org/bot#containsElement
Domain(s)	womo:Workspace (c)
Range(s)	womo:WorkspaceElement (c)

has Activity

Property	Value
IRI	https://w3id.org/womo#hasActivity
Domain(s)	womo:Workspace (c)
Range(s)	womo:Activity (c)

has Activity Category

Property	Value
IRI	https://w3id.org/womo#hasActivityCategory
Domain(s)	womo:Activity (c)
Range(s)	womo:ActivityCategory (c)

has Activity Type

Property	Value
IRI	https://w3id.org/womo#hasActivityType
Domain(s)	womo:Activity (c)
Range(s)	womo:ActivityType (c)

has Allocated Workspace

Property	Value
IRI	https://w3id.org/womo#hasAllocatedWorkspace
Domain(s)	womo:Worker (c)
Range(s)	womo:Workspace (c)

has Condition Type

Property	Value
IRI	https://w3id.org/womo#hasConditionType
Domain(s)	womo:Condition (c)
Range(s)	womo:ConditionType (c)

has Feedback

Property	Value
IRI	https://w3id.org/womo#hasFeedback
Domain(s)	womo:Workspace (c)
Range(s)	womo:Feedback (c)

has Feedback Generation Type

Property	Value
IRI	https://w3id.org/womo#hasFeedbackGenerationType
Domain(s)	womo:Feedback (c)
Range(s)	womo:FeedbackGenerationType (c)

has Feedback Response Type

Property	Value
IRI	https://w3id.org/womo#hasFeedbackResponseType
Domain(s)	womo:Feedback (c)
Range(s)	womo:FeedbackResponseType (c)

has Health Indicator Type

Property	Value
IRI	https://w3id.org/womo#hasHealthIndicatorType
Domain(s)	womo:HealthIndicator (c)
Range(s)	womo:HealthIndicatorType (c)

has Mechanical Ventilation Control Type

Property	Value
IRI	https://w3id.org/womo#hasMechanicalVentilationControlType
Domain(s)	womo:Workspace (c)
Range(s)	womo:MechanicalVentilationControlType (c)

has Member

Property	Value
IRI	https://w3id.org/womo#hasMember
Domain(s)	womo:Organisation (c)
Range(s)	womo:Member (c)

has Natural Ventilation Control Type

Property	Value
IRI	https://w3id.org/womo#hasNaturalVentilationControlType
Domain(s)	womo:Workspace (c)
Range(s)	womo:NaturalVentilationControlType (c)

has Part

Property	Value
IRI	https://w3id.org/womo#hasPart
Domain(s)	womo:Organisation (c)
Range(s)	womo:Organisation (c)

has Rating Scale

Property	Value
IRI	https://w3id.org/womo#hasRatingScale
Domain(s)	(womo:Condition (c) or womo:Preference (c))
Range(s)	womo:RatingScale (c)

has Social Interaction

Property	Value
IRI	https://w3id.org/womo#hasSocialInteraction
Domain(s)	womo:Activity (c)
Range(s)	womo:SocialInteraction (c)

has Sub Workspace Element

Property	Value
IRI	https://w3id.org/womo#hasSubWorkspaceElement
Super-properties	https://w3id.org/bot#hasSubElement
Domain(s)	womo:WorkspaceElement (c)
Range(s)	womo:WorkspaceElement (c)

has Ventilation Type

Property	Value
IRI	https://w3id.org/womo#hasVentilationType
Domain(s)	womo:Workspace (c)
Range(s)	womo:VentilationType (c)

has Worker Feature

Property	Value
IRI	https://w3id.org/womo#hasWorkerFeature
Domain(s)	womo:Worker (c)
Range(s)	womo:WorkerFeature (c)

has Workspace

Property	Value
IRI	https://w3id.org/womo#hasWorkspace
Super-properties	https://w3id.org/bot#hasSpace
Domain(s)	womo:Workspace (c)
Range(s)	womo:Workspace (c)

has Workspace Type

Property	Value
IRI	https://w3id.org/womo#hasWorkspaceType
Domain(s)	womo:Workspace (c)
Range(s)	womo:WorkspaceType (c)

is Activity Category Of

Property	Value
IRI	https://w3id.org/womo#isActivityCategoryOf
Domain(s)	womo:ActivityCategory (c)
Range(s)	womo:Activity (c)

is Activity Type Of

Property	Value
IRI	https://w3id.org/womo#isActivityTypeOf
Domain(s)	womo:ActivityType (c)
Range(s)	womo:Activity (c)

is Activity Type Supported By

Property	Value
IRI	https://w3id.org/womo#isActivityTypeSupportedBy
Domain(s)	womo:ActivityType (c)
Range(s)	womo:Workspace (c)

is Allocated To

Property	Value
IRI	https://w3id.org/womo#isAllocatedTo
Domain(s)	womo:Workspace (c)
Range(s)	womo:Worker (c)

is Condition Type Of

Property	Value
IRI	https://w3id.org/womo#isConditionTypeOf
Domain(s)	womo:ConditionType (c)
Range(s)	womo:Condition (c)

is Feedback Generation Type Of

Property	Value
IRI	https://w3id.org/womo#isFeedbackGenerationTypeOf
Domain(s)	womo:FeedbackGenerationType (c)
Range(s)	womo:Feedback (c)

is Feedback Response Type Of

Property	Value
IRI	https://w3id.org/womo#isFeedbackResponseTypeOf
Domain(s)	womo:FeedbackResponseType (c)
Range(s)	womo:Feedback (c)

is Health Indicator Type Of

Property	Value
IRI	https://w3id.org/womo#isHealthIndicatorTypeOf
Domain(s)	womo:HealthIndicatorType (c)
Range(s)	womo:HealthIndicator (c)

is Mechanical Ventilation Control Type Of

Property	Value
IRI	https://w3id.org/womo#isMechanicalVentilationControlTypeOf
Domain(s)	womo:MechanicalVentilationControlType (c)
Range(s)	womo:Workspace (c)

is Member Of

Property	Value
IRI	https://w3id.org/womo#isMemberOf
Domain(s)	womo:Member (c)
Range(s)	womo:Organisation (c)

is Natural Ventilation Control Type Of

Property	Value
IRI	https://w3id.org/womo#isNaturalVentilationControlTypeOf
Domain(s)	womo:NaturalVentilationControlType (c)
Range(s)	womo:Workspace (c)

is Part Of

Property	Value
IRI	https://w3id.org/womo#isPartOf
Domain(s)	womo:Organisation (c)
Range(s)	womo:Organisation (c)

is Performed At

Property	Value
IRI	https://w3id.org/womo#isPerformedAt
Domain(s)	womo:Activity (c)
Range(s)	womo:Workspace (c)

is Performed By

Property	Value
IRI	https://w3id.org/womo#isPerformedBy
Domain(s)	womo:Activity (c)
Range(s)	womo:Worker (c)

is Preference For

Property	Value
IRI	https://w3id.org/womo#isPreferenceFor
Domain(s)	womo:Preference (c)
Range(s)	ssn:Property (c)

is Preferred As

Property	Value
IRI	https://w3id.org/womo#isPreferredAs
Domain(s)	ssn:Property (c)
Range(s)	womo:Preference (c)

is Provided At

Property	Value
IRI	https://w3id.org/womo#isProvidedAt
Domain(s)	womo:Feedback (c)
Range(s)	womo:Workspace (c)

is Provided By

Property	Value
IRI	https://w3id.org/womo#isProvidedBy
Domain(s)	womo:Feedback (c)
Range(s)	womo:Worker (c)

is Rating Scale Of

Property	Value
IRI	https://w3id.org/womo#isRatingScaleOf
Domain(s)	womo:RatingScale (c)
Range(s)	womo:Condition (c) womo:Preference (c)

is Related To

Property	Value
IRI	https://w3id.org/womo#isRelatedTo
Domain(s)	ssn:Property (c)
Range(s)	ssn:Property (c)

is Reported By

Property	Value
IRI	https://w3id.org/womo#isReportedBy
Domain(s)	(womo:Activity (c) or womo:WorkerFeature (c))
Range(s)	womo:Feedback (c)

is Social Interaction Of

Property	Value
IRI	https://w3id.org/womo#isSocialInteractionOf
Domain(s)	womo:SocialInteraction (c)
Range(s)	womo:Activity (c)

is Ventilation Type Of

Property	Value
IRI	https://w3id.org/womo#isVentilationTypeOf
Domain(s)	womo:VentilationType (c)
Range(s)	womo:Workspace (c)

is Worker Feature Of

Property	Value
IRI	https://w3id.org/womo#isWorkerFeatureOf
Domain(s)	womo:WorkerFeature (c)
Range(s)	womo:Worker (c)

is Workspace Of

Property	Value
IRI	https://w3id.org/womo#isWorkspaceOf
Domain(s)	womo:Workspace (c)
Range(s)	womo:Organisation (c)

is Workspace Type Of

Property	Value
IRI	https://w3id.org/womo#isWorkspaceTypeOf
Domain(s)	womo:WorkspaceType (c)
Range(s)	womo:Workspace (c)

owns Workspace

Property	Value
IRI	https://w3id.org/womo#ownsWorkspace
Domain(s)	womo:Organisation (c)
Range(s)	womo:Workspace (c)

performs

Property	Value
IRI	https://w3id.org/womo#performs
Domain(s)	womo:Worker (c)
Range(s)	womo:Activity (c)

provides

Property	Value
IRI	https://w3id.org/womo#provides
Domain(s)	womo:Worker (c)
Range(s)	womo:Feedback (c)

reports

Property	Value
IRI	https://w3id.org/womo#reports
Domain(s)	womo:Feedback (c)
Range(s)	womo:Activity (c) womo:WorkerFeature (c)

supports Activity Type

Property	Value
IRI	https://w3id.org/womo#supportsActivityType
Domain(s)	womo:Workspace (c)
Range(s)	womo:ActivityType (c)

Datatype Properties

feedbackRequestTime, feedbackStartTime, feedbackTime, fromIFCDatatypeProperties, organisationLogo, organisationName, rating, ratingScaleName, ratingScaleOptions, ratingScalePrompt, responseDuration, responseRatio, value, workspaceAreaPerOccupant, workspaceHeight, workspaceIsShared, workspaceLocalID, workspaceNetFloorArea, workspaceNetVolume, workspaceOccupancyNumber, workspacePubliclyAccessible, workspaceVolumePerOccupant.

feedback Request Time

Property	Value
IRI	https://w3id.org/womo#feedbackRequestTime
Description	Time of feedback request.
Domain(s)	womo:Feedback (c)
Range(s)	xsd:dateTime (c)

feedback Start Time

Property	Value
IRI	https://w3id.org/womo#feedbackStartTime
Description	Time of feedback response start.
Domain(s)	womo:Feedback (c)
Range(s)	xsd:dateTime (c)

feedback Time

Property	Value
IRI	https://w3id.org/womo#feedbackTime
Description	Time of feedback response conclusion.
Domain(s)	womo:Feedback (c)
Range(s)	xsd:dateTime (c)

from IFC Datatype Properties

Property	Value
IRI	https://w3id.org/womo#fromIFCDatatypeProperties

organisation Logo

Property	Value
IRI	https://w3id.org/womo#organisationLogo
Domain(s)	womo:Organisation (c)
Range(s)	xsd:string (c)

organisation Name

Property	Value
IRI	https://w3id.org/womo#organisationName
Domain(s)	womo:Organisation (c)
Range(s)	xsd:string (c)

rating

Property	Value
IRI	https://w3id.org/womo#rating
Domain(s)	(womo:Condition (c) or womo:Preference (c))
Range(s)	xsd:integer (c)

rating Scale Name

Property	Value
IRI	https://w3id.org/womo#ratingScaleName
Domain(s)	womo:RatingScale (c)
Range(s)	xsd:string (c)

rating Scale Options

Property	Value
IRI	https://w3id.org/womo#ratingScaleOptions
Domain(s)	womo:RatingScale (c)
Range(s)	xsd:string (c)

rating Scale Prompt

Property	Value
IRI	https://w3id.org/womo#ratingScalePrompt
Domain(s)	womo:RatingScale (c)
Range(s)	xsd:string (c)

response Duration

Property	Value
IRI	https://w3id.org/womo#responseDuration
Description	Elapsed time between feedback response start and conclusion (sec).
Domain(s)	womo:Feedback (c)
Range(s)	xsd:integer (c)

response Ratio

Property	Value
IRI	https://w3id.org/womo#responseRatio
Description	Ratio of answered questions (%).
Domain(s)	womo:Feedback (c)
Range(s)	xsd:integer (c)

value

Property	Value
IRI	https://w3id.org/womo#value
Domain(s)	womo:HealthIndicator (c)
Range(s)	xsd:float (c)

workspace Area Per Occupant

Property	Value
IRI	https://w3id.org/womo#workspaceAreaPerOccupant
Super-properties	womo:fromIFCDatatypeProperties (dp)
Domain(s)	womo:Workspace (c)
Range(s)	xsd:decimal (c)

workspace Height

Property	Value
IRI	https://w3id.org/womo#workspaceHeight
Super-properties	womo:fromIFCDatatypeProperties (dp)
Domain(s)	womo:Workspace (c)
Range(s)	xsd:decimal (c)

workspace Is Shared

Property	Value
IRI	https://w3id.org/womo#workspaceIsShared
Domain(s)	womo:Workspace (c)
Range(s)	xsd:boolean (c)

workspace Local ID

Property	Value
IRI	https://w3id.org/womo#workspaceLocalID
Super-properties	womo:fromIFCDatatypeProperties (dp)
Domain(s)	womo:Workspace (c)
Range(s)	xsd:string (c)

workspace Net Floor Area

Property	Value
IRI	https://w3id.org/womo#workspaceNetFloorArea
Super-properties	womo:fromIFCDatatypeProperties (dp)
Domain(s)	womo:Workspace (c)
Range(s)	xsd:decimal (c)

workspace Net Volume

Property	Value
IRI	https://w3id.org/womo#workspaceNetVolume
Super-properties	womo:fromIFCDatatypeProperties (dp)
Domain(s)	womo:Workspace (c)
Range(s)	xsd:decimal (c)

workspace Occupancy Number

Property	Value
IRI	https://w3id.org/womo#workspaceOccupancyNumber
Super-properties	womo:fromIFCDatatypeProperties (dp)
Domain(s)	womo:Workspace (c)
Range(s)	xsd:integer (c)

workspace Publicly Accessible

Property	Value
IRI	https://w3id.org/womo#workspacePubliclyAccessible
Super-properties	womo:fromIFCDatatypeProperties (dp)
Domain(s)	womo:Workspace (c)
Range(s)	xsd:boolean (c)

workspace Volume Per Occupant

Property	Value
IRI	https://w3id.org/womo#workspaceVolumePerOccupant
Super-properties	womo:fromIFCDatatypeProperties (dp)
Domain(s)	womo:Workspace (c)
Range(s)	xsd:decimal (c)

Named Individuals

AcousticQuality, AirQuality, AirTemperature, AutomaticMVControlOnly, AutomaticNVControlOnly, Away, Break, BreakCoffee, BreakMeal, BreakUnspecified, Busy, CO2Concentration, Concentration, Concentration3PointsScale, ConferenceRoom, Cubicle, DailyStepCount, Direct, EventFeedback, Group, HeartRate, HomeOffice, Illuminance, IndirectVentilationOnly, Inferred_MeanVal_Hour, Inferred_SingleVal, ManualMVControlOnly, ManualNVControlOnly, MechanicalVentilationOnly, MixedMVControl, MixedNVControl, MixedVentilation, NaturalVentilationOnly, NoiseLevel, Observed_SingleVal, OccupancyCount, OccupancyRatio, OpenOffice, Pair, Postponed, PrivateOffice, Productivity, Productivity3PointsScale, RandomFeedback, RelativeHumidity, ScheduledFeedback, SharedOffice, SmallGroup, Solo, TeamRoom, ThermalQuality, ThermalQuality3PointsScale, Timeout, Unspecified, VisualQuality, VoluntaryFeedback, Work, WorkCall, WorkGroup, WorkSolo, WorkUnspecified.

Acoustic Quality ni

Property	Value
IRI	https://w3id.org/womo#AcousticQuality
belongs to	ssn:Property

Air Quality ni

Property	Value
IRI	https://w3id.org/womo#AirQuality
belongs to	ssn:Property

Air Temperature ni

Property	Value
IRI	https://w3id.org/womo#AirTemperature
belongs to	sosa:ObservableProperty

Automatic MV Control Only ni

Property	Value
IRI	https://w3id.org/womo#AutomaticMVControlOnly
belongs to	womo:MechanicalVentilationControlType

Automatic NV Control Only ni

Property	Value
IRI	https://w3id.org/womo#AutomaticNVControlOnly
belongs to	womo:NaturalVentilationControlType

Away ni

Property	Value
IRI	https://w3id.org/womo#Away
Description	Feedback request declined because the worker is not at the workplace.
belongs to	womo:NotRespondedFeedback

Break ni

Property	Value
IRI	https://w3id.org/womo#Break
Description	Activity that is a break from the worker's job.
belongs to	womo:ActivityCategory

Break Coffee ni

Property	Value
IRI	https://w3id.org/womo#BreakCoffee
Description	Coffee break, usually short.
belongs to	womo:ActivityType

Break Meal ni

Property	Value
IRI	https://w3id.org/womo#BreakMeal
Description	Break involving a meal. (e.g. lunch)
belongs to	womo:ActivityType

Break Unspecified ni

Property	Value
IRI	https://w3id.org/womo#BreakUnspecified
Description	Unspecified break.
belongs to	womo:ActivityType

Busy ni

Property	Value
IRI	https://w3id.org/womo#Busy
Description	Feedback request declined because the worker is too busy.
belongs to	womo:NotRespondedFeedback

CO2 Concentration ni

Property	Value
IRI	https://w3id.org/womo#CO2Concentration
belongs to	sosa:ObservableProperty

Concentration ni

Property	Value
IRI	https://w3id.org/womo#Concentration
belongs to	womo:ConditionType

Concentration 3 Points Scale ni

Property	Value
IRI	https://w3id.org/womo#Concentration3PointsScale
belongs to	womo:RatingScale

Conference Room ni

Property	Value
IRI	https://w3id.org/womo#ConferenceRoom
belongs to	womo:Room

Cubicle ni

Property	Value
IRI	https://w3id.org/womo#Cubicle
belongs to	womo:Office

Daily Step Count ni

Property	Value
IRI	https://w3id.org/womo#DailyStepCount
Description	Daily step count measured in (step).
belongs to	womo:HealthIndicatorType

Direct ni

Property	Value
IRI	https://w3id.org/womo#Direct
Description	Feedback request responded directly.
belongs to	womo:RespondedFeedback

Event Feedback ni

Property	Value
IRI	https://w3id.org/womo#Direct
Description	Indicates a feedback request triggered by an event.
belongs to	womo:FeedbackGenerationType

Group ni

Property	Value
IRI	https://w3id.org/womo#Group
Description	The worker is performing the activity in a larger group. Total of 5 or more workers.
belongs to	womo:SocialInteraction

Heart Rate ni

Property	Value
IRI	https://w3id.org/womo#HeartRate
Description	Heart rate measured in (bpm).
belongs to	womo:HealthIndicatorType

Home Office ni

Property	Value
IRI	https://w3id.org/womo#HomeOffice
Description	Feedback request declined because the worker is working from home.
belongs to	womo:NotRespondedFeedback

Illuminance ni

Property	Value
IRI	https://w3id.org/womo#Illuminance
belongs to	sosa:ObservableProperty

Indirect Ventilation Only ni

Property	Value
IRI	https://w3id.org/womo#IndirectVentilatioOnly
belongs to	womo:VentilationType

Inferred Mean Val Hour ni

Property	Value
IRI	https://w3id.org/womo#Inferred_MeanVal_Hour
belongs to	sosa:Procedure

Inferred Single Val ni

Property	Value
IRI	https://w3id.org/womo#Inferred_SingleVal
belongs to	sosa:Procedure

Manual MV Control Only ni

Property	Value
IRI	https://w3id.org/womo#ManualMVControlOnly
belongs to	womo:MechanicalVentilationControlType

Manual NV Control Only ni

Property	Value
IRI	https://w3id.org/womo#ManualNVControlOnly
belongs to	womo:NaturalVentilationControlType

Mechanical Ventilation Only ni

Property	Value
IRI	https://w3id.org/womo#MechanicalVentilationOnly
belongs to	womo:VentilationType

Mixed MV Control ni

Property	Value
IRI	https://w3id.org/womo#MixedMVControl
belongs to	womo:MechanicalVentilationControlType

Mixed NV Control [ni]

Property	Value
IRI	https://w3id.org/womo#MixedNVControl
belongs to	womo:NaturalVentilationControlType

Mixed Ventilation [ni]

Property	Value
IRI	https://w3id.org/womo#MixedVentilation
belongs to	womo:VentilationType

Natural Ventilation Only [ni]

Property	Value
IRI	https://w3id.org/womo#NaturalVentilationOnly
belongs to	womo:VentilationType

Noise Level [ni]

Property	Value
IRI	https://w3id.org/womo#NoiseLevel
belongs to	sosa:ObservableProperty

Observed Single Val [ni]

Property	Value
IRI	https://w3id.org/womo#Observed_SingleVal
belongs to	sosa:Procedure

Occupancy Count [ni]

Property	Value
IRI	https://w3id.org/womo#OccupancyCount
belongs to	sosa:ObservableProperty

Occupancy Ratio [ni]

Property	Value
IRI	https://w3id.org/womo#OccupancyRatio
belongs to	sosa:ObservableProperty

Open Office [ni]

Property	Value
IRI	https://w3id.org/womo#OpenOffice
belongs to	womo:Office

Pair [ni]

Property	Value
IRI	https://w3id.org/womo#Pair
Description	The worker is doing the activity together with another colleague.
belongs to	womo:SocialInteraction

Postponed [ni]

Property	Value
IRI	https://w3id.org/womo#Postponed
Description	Feedback request responded after being postponed.
belongs to	womo:RespondedFeedback

Private Office [ni]

Property	Value
IRI	https://w3id.org/womo#PrivateOffice
belongs to	womo:EnclosedOffice

Productivity [ni]

Property	Value
IRI	https://w3id.org/womo#Productivity
belongs to	womo:ConditionType

Productivity 3 Points Scale ni

Property	Value
IRI	https://w3id.org/womo#Productivity3PointsScale
belongs to	womo:RatingScale

Random Feedback ni

Property	Value
IRI	https://w3id.org/womo#RandomFeedback
Description	Indicates a feedback request generated at a random time within a daily time frame (e.g. 9:00-11:00 AM).
belongs to	womo:FeedbackGenerationType

Relative Humidity ni

Property	Value
IRI	https://w3id.org/womo#RelativeHumidity
belongs to	sosa:ObservableProperty

Scheduled Feedback ni

Property	Value
IRI	https://w3id.org/womo#ScheduledFeedback
Description	Indicates a feedback request generated at a scheduled time (e.g. 13:00).
belongs to	womo:FeedbackGenerationType

Shared Office ni

Property	Value
IRI	https://w3id.org/womo#SharedOffice
belongs to	womo:EnclosedOffice

Small Group ni

Property	Value
IRI	https://w3id.org/womo#SmallGroup
Description	The worker is performing the activity in a small group. Total of 3 or 4 workers.
belongs to	womo:SocialInteraction

Solo ni

Property	Value
IRI	https://w3id.org/womo#Solo
Description	The worker is doing the activity on his own.
belongs to	womo:SocialInteraction

Team Room ni

Property	Value
IRI	https://w3id.org/womo#TeamRoom
belongs to	womo:EnclosedOffice

Thermal Quality ni

Property	Value
IRI	https://w3id.org/womo#ThermalQuality
belongs to	ssn:Property

Thermal Quality 3 Points Scale ni

Property	Value
IRI	https://w3id.org/womo#ThermalQuality3PointsScale
belongs to	womo:RatingScale

Timeout ni

Property	Value
IRI	https://w3id.org/womo#Timeout
Description	Feedback request canceled after timeout.
belongs to	womo:NotRespondedFeedback

Unspecified [ni]

Property	Value
IRI	https://w3id.org/womo#Unspecified
Description	Feedback request declined for unspecified reasons.
belongs to	womo:NotRespondedFeedback

Visual Quality [ni]

Property	Value
IRI	https://w3id.org/womo#VisualQuality
belongs to	ssn:Property

Voluntary Feedback [ni]

Property	Value
IRI	https://w3id.org/womo#VoluntaryFeedback
Description	Indicates feedback provided voluntarily by the worker/occupant at a given time.
belongs to	womo:FeedbackGenerationType

Work [ni]

Property	Value
IRI	https://w3id.org/womo#Work
Description	Activity that is part of the worker's job.
belongs to	womo:ActivityCategory

Work Group [ni]

Property	Value
IRI	https://w3id.org/womo#WorkGroup
Description	Work activity performed by the worker together with one or more colleagues.
belongs to	womo:ActivityType

Work Solo [ni]

Property	Value
IRI	https://w3id.org/womo#WorkSolo
Description	Work activity performed by the worker on his own.
belongs to	womo:ActivityType

Work Unspecified [ni]

Property	Value
IRI	https://w3id.org/womo#WorkUnspecified
Description	Unspecified work activity.
belongs to	womo:ActivityType

Namespaces

bot	https://w3id.org/bot#
dc	http://purl.org/dc/terms/
ifcOWL	https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2_TC1/OWL#
owl	http://www.w3.org/2002/07/owl#
rdf	http://www.w3.org/1999/02/22-rdf-syntax-ns#
rdfs	http://www.w3.org/2000/01/rdf-schema#
schema	https://schema.org/
sosa	http://www.w3.org/ns/sosa/
ssn	http://www.w3.org/ns/ssn/
vann	http://purl.org/vocab/vann/
womo	https://w3id.org/womo#
xml	http://www.w3.org/XML/1998/namespace
xsd	http://www.w3.org/2001/XMLSchema#

Legend

Classes (c); Object Properties (op); Data Properties (dp); Named Individuals (ni).