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The Future of Construction in the Context of Digitalization and Decarbonization

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Edited by: Chansik Park, Nashwan Dawood, Farzad Pour Rahimian, Akeem Pedro and Dongmin Lee

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Chansik Park, Chung-Ang University, South Korea

Nashwan Dawood, Teesside University, UK

Farzad Pour Rahimian, Teesside University, UK

Akeem Pedro, Chung-Ang University, South Korea

Dongmin Lee, Chung-Ang University, South Korea

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LINKED DATA APPROACH FOR OCCUPANT-CENTRIC WORKPLACE MANAGEMENT

Alessandro Bruttini
Department of Civil and Environmental Engineering (DICEA), University of Florence, Florence, Italy
Chair of Computing in Engineering, Department of Civil and Environmental Engineering, Ruhr University Bochum, Bochum, Germany

Vito Getuli
Department of Architecture (DIDA), University of Florence, Florence, Italy

Pietro Capone
Department of Architecture (DIDA), University of Florence, Florence, Italy

Markus König
Chair of Computing in Engineering, Department of Civil and Environmental Engineering, Ruhr University Bochum, Bochum, Germany

ABSTRACT:

The assessment of the quality and performance of existing indoor workplaces plays a crucial role in employees' health, well-being and productivity. In recent years, in order to overcome the limitations of existing Post-Occupancy Evaluation (POE) methods and to improve Facility Management (FM) processes, research has focused on occupant-centric approaches that capture occupants' behaviours and feedback and leverage their interpretation with contextual building conditions. In turn, their implementations have increasingly relied on the integration of Building Information Modeling (BIM), sensor networks and Semantic Web technologies. Nonetheless, their adoption for workplace management purposes still struggles to gain momentum mostly for the lack of an effective semantic representation of the complex mutual interactions between workers and workplace.
This contribution proposes a concept for an ontology dedicated to the integration of worker-generated data, collected through the Ecological Momentary Assessment (EMA) method, with workplace's observable conditions, to enable the extraction of insights that can drive managers' decisions for the improvement of employees' well-being and productivity. The scope is restricted to office environments whose occupants are involved in knowledge-based activities. Existing ontologies are reused for the representation of the building domain, while original concepts describing the worker, its activity and conditions are related to them with a linked data approach. Eventually, the proposed ontology capabilities are evaluated for a demonstrative use case.
This work is the first contribution of an ongoing research which foresees further developments, including its implementation and validation in a real-world scenario.

KEYWORDS: *Workplace management, Occupants' well-being and productivity, Office workers, Ecological momentary assessment (EMA), Linked data, Ontology.*

1. INTRODUCTION

Nowadays, with an expected two-thirds of the world population likely to live in urban areas by 2050 (UN Habitat, 2019), the quality and sustainability of indoor environments is receiving unprecedented attention from policymakers because of their impact on human life, health and well-being. In this context, the improvement of the operation and management of workplaces and, in particular, of indoor office environments is catalyzing the efforts of professionals and researchers in the Facility Management (FM) field. In fact, with people spending up to 90 % of their lives inside buildings (ASHRAE, 2016) and with the global economy shifting from manufacturing towards knowledge-based services (World Green Building Council, 2014), in developed countries, adults spend most of their active lives in office environments. In addition, considering that employees' costs typically have a prominent impact on the organizations' bottom line, largely exceeding building operational and rental costs, the improvement of their satisfaction with the workplace is also in the employers' best economic interest because of its beneficial returns on productivity (Al Horr, Arif, Kaushik, et al., 2016).

For these reasons, the recent development of occupant-centric approaches for the design, control and operation of buildings has been witnessed as the long-awaited paradigm shift that could eventually provide spaces that meet their occupants' expectations and needs (O'Brien et al., 2020). In this regard, recent applications of Linked Building Data (LBD)[1] principles for the integration of Building Information Modeling (BIM), sensor networks and Semantic Web technologies have demonstrated the feasibility of systems that enable a better understanding and management of the physical, functional and psychological factors influencing individual occupant satisfaction. However, the application of similar systems in use cases that could serve workplace management purposes appears to be still at an early development stage and to rely on data models that do not represent effectively the knowledge related to the worker-workplace mutual interactions.

This paper presents the concept of an ontology dedicated to supporting occupant-centric management of indoor workplaces with the ultimate goal of improving workers' well-being and productivity. After the discussion of the findings of relevant related works (Section 2), the broader research framework is described in Section 3 along with the methodological aspects. In Section 4, the semantic characterization of the workplace is presented, and the ontology concept is discussed. The ontology capabilities are evaluated employing a demonstrative use case in Section 5. Finally, the discussion of the results, limitations and outlooks of this work is provided in Section 6. Further developments of the proposed ontology, including its implementation and validation in a real-world scenario, are currently ongoing and will be object of future contributions.

2. BACKGROUND

In recent times, the interest in occupant-centric approaches for the improvement of workers' well-being and productivity has shown exponential growth thanks to the possibilities offered by the integration of BIM, sensor networks and Semantic Web technologies in the FM sector.

Leaving aside the broader debate on the definition of *well-being* and *productivity*, in this work Vischer's comprehensive concept of environmental comfort in the workplace is taken as reference as the combination of three conditions: *physical comfort*, as a state of satisfaction in relation to the physical characteristics of the surrounding environment (e.g. definition of thermal comfort, ANSI/ASHRAE 55-2020); *functional comfort* or "how well users perceive their tasks and activities to be supported (or unsupported) by the physical environment in which they work"; and *psychological comfort* which, concerning the occupied space, relies on the three main determinants of territoriality, privacy, and control (Vischer & Wifi, 2017).

In the following paragraphs, an overview of the fundamental aspects and opportunities related to the assessment of the conditions experienced by occupants in indoor workplaces is provided through a selection of recent studies and applications. Eventually, the emerging open issues that motivated this research are reported.

2.1. Workplace as a complex system

The assessment of the extent to which a building matches occupants' needs and expectations is a fundamental indicator of its performance. Organizations seek employees' satisfaction with the workplace to reap its benefits on their health, well-being and productivity (Veitch, 2018). Nonetheless, assessing workers' conditions is challenging due to the existing difficulties in the collection and correlation of user- and building-generated data.

In the investigation of workers' satisfaction with the workplace, most efforts have been spent on understanding how observable physical factors (e.g. air temperature) affect the assessment of Indoor Environmental Quality (IEQ). However, few studies involved multiple domains or explored the cross-correlations and mutual influences with other physical or non-physical aspects. In fact, despite the attention is mostly catalyzed by thermal quality, indoor air quality (IAQ), visual quality and acoustic quality (Al Horr, Arif, Katafygiotou, et al., 2016), evidence suggests that other physical factors cannot be ignored. Among the most important for office buildings, the spatial configuration shall be mentioned for its long-debated and misunderstood trade-off between communication and concentration in open plans and more enclosed layouts. Nowadays, it is acknowledged that the match (or mismatch) between workspace configuration and employees' work patterns alters their perception of other environmental factors and affects their productivity (Haynes, 2008; Kim & de Dear, 2013).

Moreover, numerous other correlations between psychological and physical factors in workers' perception and behaviour in indoor workplaces are confirmed in the literature. Among these, it bears mentioning the benefits to employees provided by often overlooked factors, such as: personal control of the environment to raise

[1] W3C Linked Building Data (LBD) Community Group - https://www.w3.org/community/lbd/ - (accessed 22/08/2022)

discomfort tolerability thresholds (Luo et al., 2016) and nature exposure to improve restoration and stress coping mechanisms (Sadick & Kamardeen, 2020).

Monitoring and understanding how these and other factors affect occupants' conditions and perceptions of indoor environmental quality is a challenging task for which different methods can be comprised under three categories: subjective assessment (e.g. feedback), indirect assessment (e.g. observation of behaviours and coping mechanisms); and physical parameters' measurement (e.g. CO_2 concentration) (Al Horr, Arif, Kaushik, et al., 2016). Concepts from each method have been considered in this work since the proposed ontology aims to enable the collection and integration of both subjective and objective data related to the workplace and its occupants.

2.2. Occupant-centric approaches for the workplace

"Occupant behaviour-centric" (also "occupant-centric") is a term used to effectively combine decades-worth of research to implement occupancy and occupant behaviour in building design and operation to improve energy performance and occupant comfort (International Energy Agency, 2018). Evidence suggests that despite the best efforts of practitioners and stakeholders, buildings mostly fail to meet the needs and expectations of their occupants. In this regard, the idea that providing "ideal" indoor environmental conditions described only by physical parameters to occupants seen as "average" passive recipients stands out among the root causes (O'Brien et al., 2020). Nowadays, a paradigm shift from the building- to the occupant-related aspects of the system is claimed to overcome these limitations.

From a methodological perspective, the adoption of multidisciplinary approaches and the integration of social science insights with building physics theories have been proved to bring innovative knowledge into the understanding of human-building interactions in office workspaces, especially with respect to workers' perceived control, comfort, satisfaction and productivity (D'Oca et al., 2018). Concerning prototypical applications of these concepts, the use of BIM and sensor technologies to establish data environments where human behaviours and experiences of indoor surroundings can be quantified and understood to inform the operation of better physical spaces shows promising opportunities (Zaki, Lucas, & Francu, 2018). Furthermore, recent works' findings fostered the development of recommendation systems based on occupants' environmental preferences learning and on the prediction of the optimal fit for thermal comfort (Abdelrahman, Chong, & Miller, 2021) and activity-based workspaces in office buildings (Sood, Janssen, & Miller, 2020), paving the way towards scaled-up real-world scenarios.

2.3. Ecological Momentary Assessment (EMA)

Although with different purposes and technological implementations, the research efforts discussed above show a common thread in their dependence on the frequent and reliable assessment of occupant conditions. While sensor and wearable technologies can deal with objective observations (e.g. indoor location, bio-parameters), the evaluation of occupants' subjective experiences still relies mostly on the collection of feedback. In this regard, the following limitations in the administration of long and well-established Post-Occupancy Evaluation (POE) surveys need to be addressed: low frequency (e.g. one or few times per year), lack of contextual information (e.g. general responses); asynchronous data collection and recall biases.

From early web-based surveys (Zagreus, Huizenga, Arens, & Lehrer, 2004) to recent deployments of wearable technologies for temporary data collection (Jayathissa, Quintana, Sood, Nazarian, & Miller, 2019), the growing adoption of Ecological Momentary Assessment (EMA) approaches (Shiffman, Stone, & Hufford, 2008) have been considered the most viable solution for the collection of frequent, real-time feedback (momentary) directly in subjects' natural workplace environments (ecological) (Engelen & Held, 2019; Jayathissa, Quintana, Abdelrahman, & Miller, 2020). In fact, in overcoming traditional POE surveys' limitations, EMA opens new opportunities to achieve a deeper understanding of the timely correlation between subjective data and objective measurements, hence enabling the operation of better spaces (Park, Loftness, & Aziz, 2016).

2.4. Linked Building Data

In order to reap the benefits of the application of occupant-centric approaches to workplace management, the collection, correlation and understanding of worker- and building-generated data shall be enabled. In this respect, the acknowledged limitations of the standard Industry Foundation Classes (IFC) data schema[2] turned

[2] ISO 16739-1:2018 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries — Part 1: Data schema

researchers' attention to possible alternatives. From this impulse, experts gathered in the LBD Community Group[1] sought a solution in the adoption of an ecosystem of light, modular and extensible ontologies covering sub-domains of building data and maintaining interoperability with IFC (Petrova & Pauwels, 2021). In particular, LBD approaches for linking static and dynamic domain-specific data to building information are crucial for the real-time digital representation of physical built assets broadly referred to as Digital Twins (Mavrokapnidis et al., 2021).

Concerning the efforts directed at enabling the reasoning about occupant experiences in indoor spaces, Qiu *et al.* proposed the Human Comfort in Building (HBC) ontology; despite its evaluation in two use cases for office buildings, workspace representation appears limited and workers' activities are not considered (Qiu, Schneider, Kauppinen, Rudolph, & Steiger, 2018). Moreover, aiming to improve indoor environments while reducing energy use, Hong *et al.* formalized energy-related human behaviour in buildings using the four key concepts of Drivers-Needs-Actions-Systems (i.e. DNAS framework), stressing the importance from a human perspective of the distinction of an "inside world", made of cognitive processes, and the "outside world" of the building environment (Hong, D'Oca, Taylor-Lange, et al., 2015; Hong, D'Oca, Turner, & Taylor-Lange, 2015). However, besides the comprehensive schemas cited above, most of the recent case-study applications focused on the collection of building- and occupant-data in form of sensor data streams and feedback. In this regard, Donkers *et al.* showed the opportunities for improvements in the occupants' experiences understanding provided by the combination of methods for knowledge discovery in databases and Sematic Web technology applied to feedback collected through a smartwatch app (Donkers, de Vries, & Yang, 2022).

2.5. Open issues

Serving also as motivations for this paper, the main open issues that emerged from related works are listed below:

- The improvement of workers' health, well-being and productivity in an indoor workplace requires the adoption of an occupant-centric approach that relies on the contextual assessment of occupants' objective conditions and subjective experiences in relation to multiple physical, functional and psychological factors. Recent findings pointed out the integration of BIM, sensors and Semantic Web technologies with the LBD methodology as an effective solution, although further research efforts are still required.
- The collection of frequent and reliable data from the occupant is key in the understanding of its interaction with the building space. Limitations of POE surveys can be overcome with the adoption of the EMA approach and wearable devices for the effective collection of occupant subjective feedback and objective measurements.
- Despite numerous proposals, the existing semantic descriptions of occupants in buildings are not suitable for a comprehensive description of a worker within an indoor workplace. A formal representation dedicated to capture worker conditions and that enables reasoning for workplace management purposes is missing.

3. RESEARCH FRAMEWORK AND METHODOLOGY

Following the emerged open issues, and with the broader goal of leveraging occupant-generated data linked with building data to realize the upcoming digital twin paradigm for workplaces, the general research framework shown in Fig. 1 is proposed. Aiming to address the core data integration process, the concept of an ontology for occupant-centric workplace management has been developed. In fact, the semantic reasoning capabilities enabled by such formal knowledge representations have been sought to deal with the highly heterogeneous data involved and to foster the extraction of insights that could drive managers' decisions for the sake of the workers. This research focuses on the three objectives discussed below along with the methodology:

1) *Workplace semantic characterization*: In order to overcome the limitations of previous proposals and to provide a firmer foundation to the proposed ontology, a coherent semantic characterization of the targeted human-building system, is sought. Following the review of the literature, the standard definition of "workplace" adopted in the Facility Management field (ISO 41011:2017) was chosen for its comprehensiveness and effectiveness, broken down and further specified into three main knowledge domains (see § 4.1).
2) *Ontology conceptualization*: The development process that drove the conceptualization of the proposed ontology involved tasks that are common to several knowledge modeling methods, from the long-established METHONTOLOGY (Fernandez, Gómez-Pérez, & Juristo, 1997) to more recent approaches (e.g. Linked Open Terms, LOT, methodology (Poveda-Villalón, Fernández-Izquierdo, Fernández-López, & García-Castro, 2022), namely: the specification of scope and main purposes (see §4.2); the identification of the requirements

(see §4.3); and finally, the specification of the ontology concept comprising its classes and properties against the physical system it represents (see §4.4). Further, the relation with established data schemas (e.g. IFC) has been considered along with the integration with existing ontologies adopted in LBD applications. In this regard, two ontologies were reused, namely: Building Topology Ontology (BOT)[3], and Semantic Sensor Network ontology (SSN)[4]. The ontology concept is described in the standardized Web Ontology Language (OWL).

3) *Demonstration*: Eventually, the evaluation of the ontology capabilities was carried out through a preliminary demonstration against a specific use case defined for workspace performance assessment and applied to a test dataset (see § 5). A thorough evaluation, comprehensive of an exhaustive range of use cases, is deferred to future developments of this research.

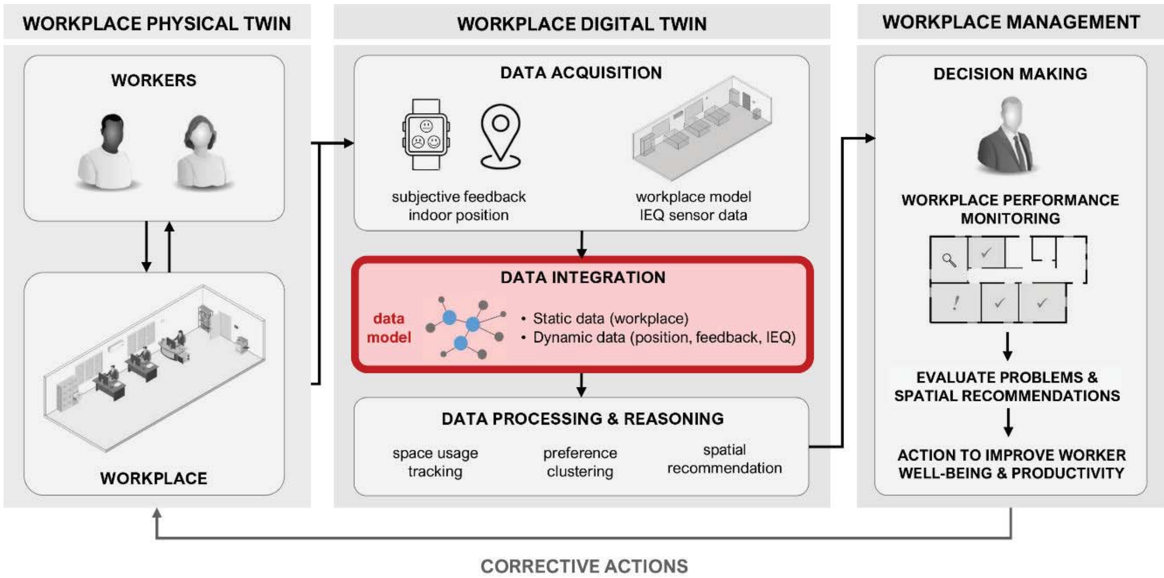


Fig. 1 Framework for Occupant-centric workplace management using Digital Twins

4. PROPOSED ONTOLOGY

In this Section, the concept of the proposed *Occupant-centric Workplace Management Ontology (WOMO)* is discussed. The ordered development steps taken to address the first two objectives of this work correspond to the following paragraphs; the demonstration is presented in Section 5.

4.1. Semantic characterization of the workplace

A workplace is a complex physical system whose detailed description represents a challenging task that practitioners and researchers have performed with different outcomes under specific perspectives and needs. Therefore, the preliminary step for the development of the proposed ontology aimed to establish a coherent semantic foundation to build upon.

A comprehensive, acknowledged and flexible definition of a workplace has been sought in order to support a broad range of current and potential use cases for occupant-centric workplace management. For this reason, the standard definition of a workplace - "*physical location where work is performed*" - was adopted from the FM field (ISO 41011:2017) and further specified to identify the core semantic areas of interest.

With the explicit assumption of a human-worker performing the job and with the limitation of the location to an indoor environment, the workplace is determined as the semantic intersection of three principal knowledge domains: *building*, *occupant* and *activity* (Fig. 2). The specifications for these domains are assumed as follow:

- *Building domain* – Including building elements and spaces with their physical and abstract characteristics (e.g. window geometry and materials; observed noise level in space; space type and function).
- *Occupant domain* – Including human individuals temporarily occupying a certain building space while performing some activity.

[3] https://w3c-lbd-cg.github.io/bot/ - (accessed 22/08/2022)
[4] https://www.w3.org/TR/vocab-ssn/ - (accessed 22/08/2022)

- *Activity domain* – Including actions or tasks performed by an occupant as part of its working routine (e.g. for office activities: solo work, group work, call, presentation, remote meeting, etc.).

Fig. 2 Workplace knowledge domains (Venn diagram)

This logical operation leads to the definition of a workplace explicitly suited for our purpose: "*building location where work is performed by the occupants*". In fact, any combination of just two of the cited domains falls beyond our field of interest: building occupants not involved in work-related activities (e.g. public, customers, etc.); outdoor workplaces (e.g. construction sites); building spaces where work is carried out mainly by machines and the human intervention can be considered episodic and not continuative (e.g. machine or technical rooms).

4.2. Scope and purpose

The provided definition of workplace applies to a wide variety of indoor working environments, ranging from manufacturing activities carried out in factories to tertiary businesses operating in commercial buildings. On this ground and for the motivations previously discussed (see Section 1), the ontology scope has been limited to *office environments*, including support spaces (e.g. kitchen, common space, etc.), and hence to *knowledge workers* whose tasks are intellectual rather than physical. In addition, since such individual and collaborative activities are rightly paced with periodic breaks and leisure social interactions with other co-workers, these are also included in the scope due to their importance for workers' performance and well-being.

According to the scope and recalling the broader goal underpinning the research framework, the main ontology purposes have been specified. At a comprehensive level, the ontology shall enable the timely correlation between objective and subjective data related to workers' and workplaces' conditions for the extraction of insights that can support managers' decisions for the improvement of the employees' well-being and productivity. In turn, this is intended to be achieved by supporting workplace managers in the three areas synthesized below:

1) *Workplace performance assessment* - Understanding how each workspace (e.g. office), or set of workspaces, is perceived by the occupants, and hence how it is performing in respect of different features, through the correlation between the collected worker feedback and the observed workspace conditions. To a certain extent, feedback data alone could suffice where sensor data are missing, or their deployment is hindered or denied. However, while the prevalence of "Prefer warmer" feedback collected in a workspace can inform managers of overlooked unsatisfactory conditions, more valuable insights result from their comparison with observed environmental parameters (e.g. air temperature, window opening time, etc.).
2) *Workplace issue discovery* - Understanding which factors contributed to the occurrence of unsatisfactory conditions. This is not to be confused with drawing causal links from simple correlations that, besides being almost always misleading, is not the purpose of the ontology. Nonetheless, returning to the previous example, noticing an even distribution of "Prefer warmer" feedback among workers who shared the same space could point out that the issue is related to its general environmental conditions and could be confirmed via sensor observations (e.g. HVAC failure). On the contrary, an uneven feedback distribution, with just one or few dissatisfied individuals, could spot localized issues (e.g. leaking window beside workstation) or a mismatch between the environment and the worker preferences and needs. In this regard, it should be noticed that when the environment doesn't provide functional comfort, supporting activity-related needs (e.g. privacy, focus, light conditions, etc.), it can heavily compromise the worker's well-being and productivity.
3) *Worker preference clustering & Recommendation*: Understanding recurrent patterns (e.g. environmental preferences, activities, etc.) to predict ideal environmental conditions for each worker or group of workers and hence automatically recommend solutions to occurring issues, support decisions for workplace foreseen

changes (manager side) and suggest ideal spaces to workers (worker side). Either way, the ontology shall enable artificial intelligence methods to support a proactive, rather than reactive, use of the collected data.

In an iterative ontology development process, these purposes can be considered as progressive milestones corresponding to the expansion of the ontology capabilities and of the system that implements it. Although the authors' ultimate goal is to fulfill them all, at this stage the work focused principally on the first two. From these, the requirements discussed in the next paragraph are drawn.

4.3. Requirements

In this paragraph, the identified general requirements of the ontology are reported. Specific use-case requirements will be then drawn from these in form of competency questions to be addressed in the ontology evaluation as shown in Section 5.

1) *Worker temporary assessment* - The description of each worker in terms of its temporary conditions, both observed (objective) and perceived (subjective), shall be enabled. Among the former can be included: indoor location at different resolutions (e.g. workspace, workstation, coordinates); bio-parameters (e.g. heart rate); current activity (e.g. meeting). For the latter, perceptions shall be distinguished between outward-directed (e.g. preference for the thermal environment) from inward-directed (e.g. feeling focused, relaxed, tired, etc). Further static, or slowly changing, properties attributable to a worker that could serve management purposes shall be addressed (e.g. demographics, organizational role, etc).
2) *Spatiotemporal variability of data* – The collection and spatiotemporal correlation of heterogeneous data generated both from sensors, in form of data streams for properties related to a workspace (e.g. office people count), an element (e.g. equipment functioning), a worker (e.g. heart rate variability), and from workers in form of provided temporary feedback (e.g. environmental preferences, self-perceived conditions) shall be enabled.
3) *Objective and subjective data* – Regarding both objective and subjective data, different system deployments and management needs shall be addressed. Data collection shall be flexible yet provide unambiguous information. For sensor measurements, beside the specification of the value, unit of measure, position and time of each data point, further metadata are crucial (e.g. frequency, precision, etc). In turn, subjective data shall be based on the collection of rated feedback responses to brief temporary surveys administered to the workers. Therefore, the adopted rating scale shall be customizable and retrievable (e.g. three-point scale for thermal preference: -1 Cooler, 0 Ok, +1 Warmer), along with additional metadata on the feedback itself, like for instance: generation type (e.g. scheduled, voluntary, etc) and response type (e.g. responded, postponed, etc).
4) *Activity temporary assessment* - Capturing the characteristics of the activity performed at the time when worker data are collected is essential for their comprehensive understanding and workspace usage monitoring. In this regard, the minimum set of information shall specify the activity category (e.g. work, break), type (e.g. solo work, meeting, etc) and type of occurring social interaction (e.g. solo, one-to-one, group, etc).
5) *Workspace spatial, functional and environmental representation* - The physical system to which worker-generated data are related consists of building spaces and all the comprised elements (e.g. walls, windows, desks, lamps, etc) on one hand, and their dynamic environmental and functional properties on the other. Topological relationships among spaces and elements (e.g. containment) shall be represented as well as the timely measurements with which sensors observe their properties. Further static properties attributable to a workspace or element shall be addressed to serve management purposes (e.g. room occupancy profile).

4.4. Concept

In order to streamline the development process and to facilitate future extensions and integrations, the proposed ontology is organized, conceptually but not physically, into four modules: *Worker*, *Activity*, *Feedback* and *Workspace*. In the overview reported in Fig. 3 colours apply to the classes and properties reused from two existing ontologies for the description of the building domain: BOT (blue) and SSN (green). For their renowned effectiveness in LBD applications, these ontologies resulted in a lighter, better suited but still compliant alternative to the IFC. In the discussion below, the tentative prefix `womo` is used for the original classes and properties, while the suggested prefixes of the reused ontologies are adopted: `bot`, `ssn`, `sosa`.

During the time spent at the workplace, it can be assumed that a worker is located in a certain workspace where it performs some activity while having a subjective experience of the surrounding environment and of its personal condition. Considering spatiotemporal variability, this pattern applies to every worker, space and moment within the workplace. Furthermore, the objective conditions of this system can be observed in a quasi-continuous fashion and with adequate accuracy through the deployment of dedicated sensors (e.g. worker indoor position, indoor environmental quality properties, etc). However, the same does not fully apply to worker's subjective perceptions. In fact, despite some research has explored the implementation of computer vision and wearable technologies for the detection and recognition of human activities, and occupant physical and even psychological conditions, their current limitations oriented the authors to rely on the collection of EMA feedback for the effective assessment of the worker perceptions.

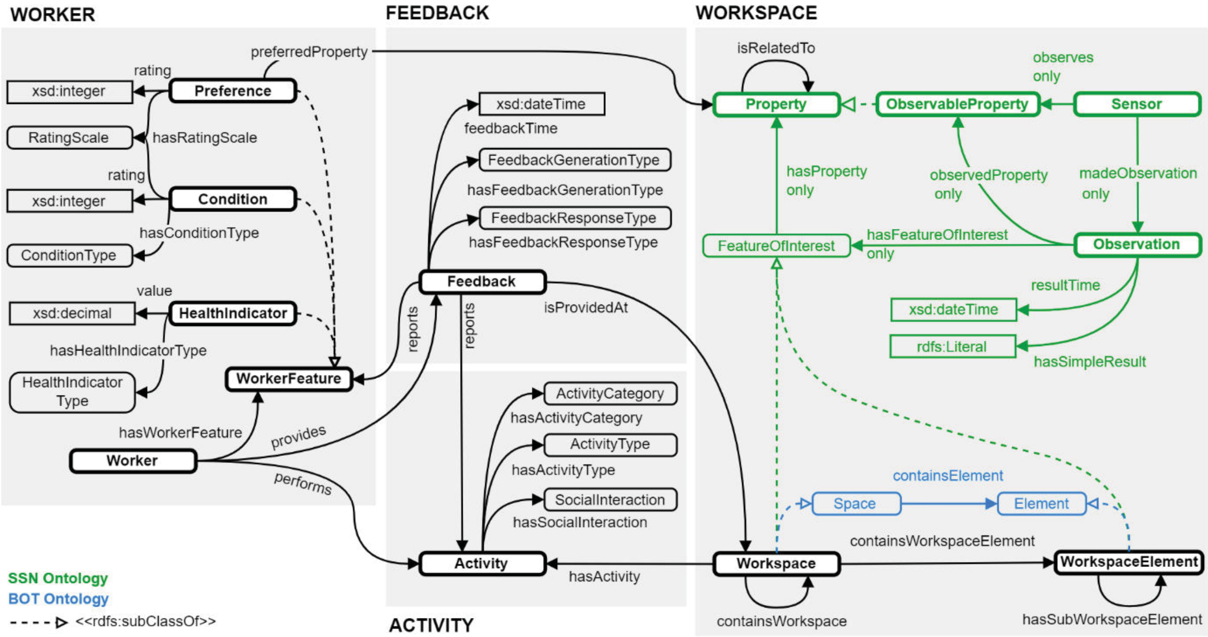


Fig. 3 Overview of the Occupant-centric Workplace Management Ontology (WOMO)

4.4.1. Workspace

The topological representation of the workplace is based on the two core concepts of workspace and workspace element. Each portion of space that can be physically or functionally identified within the workplace belongs to the `womo:Workspace` class (subclass of `bot:Space`). This applies to rooms or parts of a room but also to workstations, intended as the spatial entities where work is performed and which may contain the necessary equipment. Building elements, furniture and equipment are included into the `womo:WorkspaceElement` class (subclass of `bot:Element`).

The relations among the described entities are expressed by three object properties - `womo:hasWorkspace`, `womo:containsWorkspaceElement` and `womo:hasSubWorkspaceElement` – derived from the respective BOT properties. This allows for descriptions of workplace scenarios with different resolutions in terms of workspaces and elements, for example: an open-plan office containing an area dedicated to specific functions, in turn containing several workstations can be represented through interrelated `womo:Workspace` instances; the same applies using members of `womo:WorkspaceElement` for furniture that can include pieces of equipment.

The objective observation of workplace properties, carried out through deployed sensors, is addressed considering workspaces and elements as members of the `sosa:FeatureOfInterest` class. In this way, the concepts of the SSN ontology can be straightforwardly reused to represent the variable environmental conditions of workplace scenarios. For instance: the thermal quality (`ssn:Property`) of an office (`womo:Workspace`) can be characterized in terms of the air temperature (`sosa:ObservableProperty`) observed by a deployed thermometer (`sosa:Sensor`) through periodic measurements (`sosa:Observation`) of known time and value (`sosa:resultTime`; `xsd:dateTime`; `sosa:hasSimpleResult`; `rdfs:Literal`). The addition of the `womo:isRelatedTo` object property, whose range and domain coincide with `ssn:Property`, enables the semantic description of the influences occurring among different properties at two different levels of abstraction: between properties and observable properties (e.g. thermal quality – air temperature, relative humidity, etc); among observable properties (e.g. people count, noise level, CO_2 concentration, etc). In the first case, the easier comparison of a preference usually expressed for a `ssn:Property` (e.g. visual quality - prefer brighter) against the data point measured for the related `sosa:ObservableProperty` (e.g. illuminance) is enabled. For further details about the reused classes and properties, please refer to the BOT and SSN ontology documentation.

4.4.2. Worker, Feedback and Activity

Each employee, as an individual of the `womo:Worker` class, is related through the `womo:provides` object property to `womo:Feedback` instances generated either on request or voluntarily at known times (`womo:feedbackTime`). Besides holding the temporal information, from feedback are also drawn two other key relations via the properties `womo:isProvidedAt` and `womo:reports`. The former marks a contact point with the workspace domain, uniquely identifying where the feedback, along with the reported information, was provided. The latter connects the feedback to its contents: the specification of the `womo:Activity` performed and a set of `womo:WorkerFeature` for the worker's objective and subjective conditions.

Activity instances provide momentary information related to the use of a workspace and give context to the simultaneously collected worker features. Specifications of the category (e.g. work, break), type (e.g. solo work, meeting, etc) and social interaction (e.g. solo, couple, small group, etc) are therefore requested as part of the assessment and constitute individuals of the respective classes: `womo:ActivityCategory`, `womo:ActivityType`, `womo:SocialInteraction`. Dedicated object properties connect activity instances to the related worker and workspace (`womo:performs, womo:hasActivity`).

The collection of worker-related information is achieved via a set of worker features reported by the feedback. For this purpose, three subclasses are defined: `womo:HealthIndicator`, for data points of objective worker physical parameters (e.g. heart rate); `womo:Condition`, for the evaluation of subjective self-perceived conditions (e.g. focus); `womo:Preference`, for the evaluation of subjective experience of the surrounding environment (e.g. visual quality). While health indicators collected via wearables are meant to hold s simple value information (`xsd:decimal`) and to be related to a certain `womo:HealthIndicatorType` (e.g. heart rate), when asking the workers for subjective ratings, different survey strategies calls for different rating scales. A more comprehensive assessment of workplace performances could require more questions but reduce the response options (e.g. thermal quality three-point scale: prefer cooler – OK – prefer warmer). Otherwise, for specific enquiries, more nuanced responses could be provided for fewer features. For these reasons, both preferences and conditions can be represented in relation to customizable scales (`womo:RatingScale`). Similarly to health indicators, conditions are specified through their relation to members of the `womo:ConditionType` class. Instead, each preference refers to a certain `ssn:Property` through the `womo:preferredProperty` relation, making it the third contact point between the building and the occupant domains.

Concluding with the feedback, other metadata are provided through their relation to instances of dedicated classes: `womo:FeedbackGenerationType` (e.g. scheduled, random, voluntary, etc) and `womo:FeedbackResponseType` (e.g. responded, postponed, cancelled, etc). Moreover, while each feedback reports a maximum of one activity, no limitation is intended for the number of distinct worker features that can be reported at one time. Nonetheless, it should be stressed that the quality of the subjective data collected heavily relies on minimizing the survey fatigue, for which shorter survey completion time along with fewer and simpler questions are recommended.

Although not represented and discussed for readability reasons, for all the properties reported in Fig. 3 the inverse can be provided, e.g.: `womo:isPreferedAs` to link `ssn:Property` to `womo:Preference`.

5. DEMONSTRATION

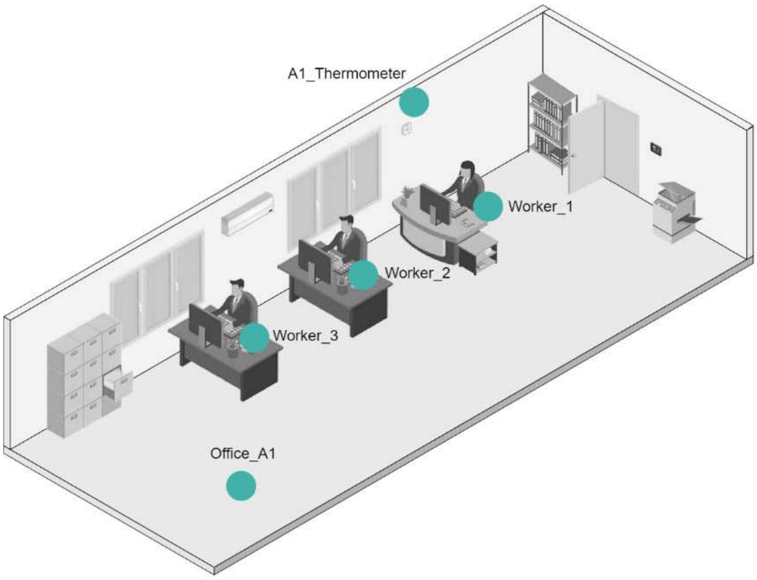
The evaluation of the proposed concept is carried out for a use case related to workplace performance assessment (see §4.2). The goal is to assess how a certain workspace has been perceived by its occupants in respect of a certain property, and further retrieve insights from the measurement of a related observable property.

Regarding the test scenario and criteria reported in Fig. 4 a test dataset has been generated and used to populate the ontology in order to respond to the following two competency questions (CQ):

- CQ1: *How has office A1 been perceived for thermal quality in the last week?*
- CQ2: *Which air temperature has been preferred in office A1 in the last week?*

A sample extract of the classes and properties considered in the use case is reported in Fig. 5. For readability reasons, only one instance for each class is represented in the diagram, although multiple shall be accounted for workers, feedback, preferences and observations.

CQ1 is addressed by querying for all the preference instances related to the desired workspace's property, A1_ThermalQuality, that are reported in feedback provided in the desired period. As discussed above, to this extent the returned data provides information on the environmental performance of the workspace regardless of the availability of sensor data.



Class	Instances
womo:Workspace	Office_A1
womo:Worker	Worker_1; Worker_2; Worker_3
womo:Feedback	FBK_0001;...; FBK_0150 *5 Feedback per worker per day for 2 weeks (10 working days)*
womo:Preference	PRF_0001;...; PRF_0150 *1 Preference per feedback*
womo:RatingScale	ThermalQuality_3points
sosa:Sensor	A1_Thermometer
ssn:Property	A1_ThermalQuality
sosa:Observable Property	A1_AirTemperature
sosa:Observation	OBS_0001;...; OBS_0090 *9 Observations per day in 9:00-18:00 range for 2 weeks (10 working days)*

Fig. 4 Test scenario and dataset

Further insights can be obtained by addressing CQ2. In this case, the preferences of interest are the ones with a neutral rating ("0" - OK) according to the assumed three-point scale. For each compliant preference, based on the feedback time in which they are reported, a temporally close observation of workspace air temperature is retrievable. Neutral ratings are therefore returned along with variable measurements of the observable property of interest for further analysis and interpretation (e.g. preferred temperature range and mean value).

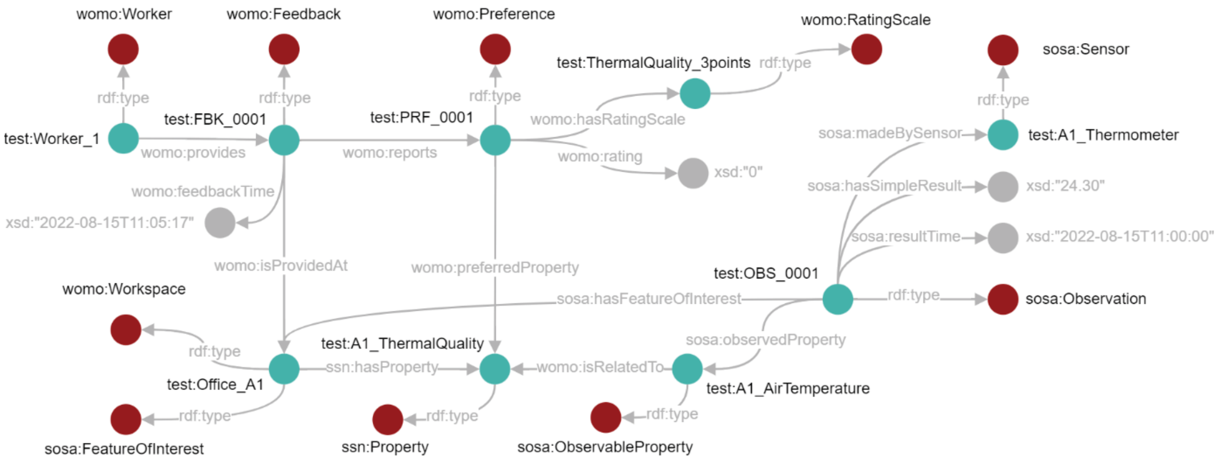


Fig. 5 Sample entities and relationships for the use case

6. CONCLUSIONS

This work presents the concept of an ontology intended to support the implementation of occupant-centric approaches for the management of indoor workplaces with the purpose of improving workers' well-being and productivity through the extraction of insights from the contextual interpretation of building data and worker data collected with the EMA method.

The identification and specification of three key knowledge domains has been provided for a coherent semantic characterization of an indoor workplace, namely: occupant, building and activity. On this base, the ontology conceptualization comprising the definition of its scope and purpose, general requirements, core concepts and relations, has been carried out. In this regard, four conceptual modules were distinguished (i.e. worker, activity, feedback and workspace) while two acknowledged ontologies were evaluated and reused for the description of the building domain (i.e. BOT and SSN). Eventually, the last objective set at this initial development stage has been achieved with the implementation and evaluation of the ontology concept in a demonstrative use case for the assessment of the thermal quality of a workspace.

However, in view of the broader goal of this research, further efforts are required to address the emerging limitations. First, the core ontology modules need to be extended with additional concepts and relations to provide a more detailed description of the workplace system, which in this form doesn't suit real managerial scenarios. In turn, this will comprise also the evaluation and possible reuse of other ontologies for specialized purposes, e.g. PROV[5] for the interchange of provenance information related to the worker-generated data. Likewise, a closer relation shall be drawn between the workspace domain concepts and the corresponding entities considered in the IFC schema. Furthermore, additional use cases will be defined and tested in a real-world workplace case study, hence comprising a larger dataset, especially in terms of temporal data (e.g. observations, feedback). The ongoing developments in this direction will be the subject of future contributions.

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