

Giving building users a voice: an AI-assisted approach

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Abstract—This paper reports on the initiation of a research effort to create versatile digital twins of building users, whose virtual agency would enable them to vocally express responses to prevailing conditions, articulate needs, and display disposition to adaptive behavioural actions. To this end, the conceived methodological approach involves the synthesis of methods in *i)* environmental sensing, *ii)* theories of human perception, cognition and behaviour, *iii)* advanced computational modelling, and *iv)* socially responsible artificial intelligence. The paper provides an overview of the elements and architecture of the proposed environment for the generation, enactment, and utilisation of building users' digital twins and focuses on related ontological developments. The two main use cases of this environment are to assist involved stakeholders involved in *a)* the design and construction of new buildings and *b)* the operation and retrofit of existing buildings.

Keywords—building users; digital twins; AI; perception; behaviour; building design and operation

I. INTRODUCTION

This paper reports on the state of a bi-national research initiative, which aims at providing deep cohesive support for creation and upkeep of built environments conducive to healthy and productive human occupancy. To this end, the envisioned approach involves the synthesis of methods in *i)* environmental sensing, *ii)* pragmatic theories of human perception, cognition and behaviour, *iii)* advanced computational modelling, and *iv)* socially responsible artificial intelligence. Specifically, the objective is to create versatile digital twins of building users, whose virtual agency enables them to vocally express perceptual responses to prevailing conditions, articulate needs, and display dispositions to behavioural (e.g., adaptive) measures that would bring about favourable indoor-environmental conditions.

The digital twins of building users are intended to serve as agentic representations of occupants, capable of providing empathic, vocalized insights into how indoor-environmental conditions are perceived and evaluated. In particular, they are intended to capture the manner in which occupants' experiences shape expectations of the built environment and how their behavioural dispositions evolve to meet their needs. Furthermore, these digital twins are envisioned as a critical source of input for stakeholders engaged in the AI-assisted design and operation of buildings, including engineers, architects, health professionals, and end users. By enabling more nuanced understanding of occupant experience and behaviour, the digital twins can support correspondingly more responsive, human-centred decision-making throughout the building lifecycle.

The proposed system architecture entails digital twin models of occupants and the elements needed to provide those with required operational information, that is indoor environment (specifically data regarding indoor air quality, as well as thermal, visual, and acoustic conditions) and affordance (i.e., those features of buildings, which accommodate occupants' functional requirements, including buildings' environmental control systems for heating, cooling, ventilation, and lighting). The two main use cases of the proposed framework pertain to *i)* the design and construction

processes of new buildings, and *ii)* the operation and retrofit of existing buildings.

Section II of the paper describes the motivation and background of the research. Section III outlines its aims and approaches. Sections IV and V present the envisioned system architecture and the implementation process respectively. Section VI provides concluding remarks pertaining to the project limitations and future steps.

II. MOTIVATION AND BACKGROUND

People spend most of their lives in indoor environments (Klepeis et al., 2001). As such, buildings critically impact people's health, comfort, well-being, satisfaction, and productivity. Children in Kindergartens, pupils in schools, students in universities, workers in offices and factories, families in homes, patients in hospitals, and seniors in care facilities, are all continuously influenced by the indoor-environmental quality (IEQ) in buildings (Al horr et al., 2016). Certain observations can be made when considering building design and retrofit phases: Frequently, design workflows display a linear character devoid of systematic iteration cycles and designers receive virtually no feedback from future occupants whether their design fulfilled their most important task, that is to create adequate spaces for human occupancy. This underlines the critical necessity of providing dedicated feedback loops for designers such as post occupancy feedback questionnaires, whose potential is recognized but not broadly utilised (Elsayed et al. 2023). Currently, building designers and operators can deploy building performance simulation tools that involve fairly detailed representations of buildings' geometry, construction, and systems, but entail relatively low-resolution models of building users devoid of feedback from earlier designs. This circumstance is in many instances responsible for failure in achieving energy and IEQ targets in building design and retrofit projects.

In this context, attention must be paid to the contradiction between *i)* the enormous significance of IEQ in shaping and nurturing human life in view of health, comfort, well-being, and productivity, and *ii)* the efforts to put building design and operation approaches on a rigorous and robust scientific

grounding (Dimitroulopoulou et al., 2023). Consequently, scientific research in the IEQ field must further enhance measures to situate building occupants' needs as the main concern of all those stakeholders responsible for the design, construction, and operation of buildings (Wu et al., 2023). The urgent need for scientific and technological advance in this direction becomes abundantly clear, when considering the increasing complexity of contemporary buildings, which integrate a wide range of advanced environmental control technologies alongside sophisticated sensing, automation, and control systems.

Over the past decades, substantial progress in sensing, actuation, and control technologies has significantly enhanced the capacity of buildings to monitor, predict, and optimize their performance, thereby reinforcing the need for continued innovation and systematic integration of these systems. The so-called smart built environments have been suggested to have the capacity to dynamically respond to the needs and preferences of their occupants and enhance the state of their health and comfort, while simultaneously optimizing buildings' energy and environmental performance, which is a major contributor for achieving the goals of the EU 2030 climate and energy framework.

In this context, the primary interacting elements are people, buildings (bricks), and building information systems (bits). Past efforts have indeed made progress in bridging the gap between bits and bricks, leading to the emergence of modelling tools and a wide range of sensing, actuation, and control systems for buildings. These developments have improved the ability to monitor, predict, and optimize buildings' performance, thereby reinforcing the incentives for continued innovation and systematic integration of these systems.

Confronted with the dual complexity of human experience and increasingly sophisticated building technologies, it is of utmost importance to equip relevant stakeholders with timely, empathic, intuitive, and intelligible information to support evidence-based design, operation, maintenance, and use of buildings that genuinely accommodate human requirements. Despite significant technological advances, a critical aspect of intelligent environments remains insufficiently addressed, namely the genuine inclusion of the human component. Deep consideration of human requirements is still insufficiently embedded in building design and operation processes. Occupants still lack effective and intuitive means of communicating with buildings and their underlying information systems, a disconnect driven by inadequate interaction interfaces, overly generic occupant models that fail to capture individual preferences and behaviours, and the limited availability of personalized optimization and decision-support services. Consequently, buildings may meet narrowly defined technical performance criteria, yet fall short of deep integration of human requirements (Shi et al., 2019).

The urgent need for scientific and technological advance in this direction becomes abundantly clear, when considering the increasing complexity of contemporary buildings, which integrate a wide range of advanced environmental control technologies alongside sophisticated sensing, automation, and control systems. Confronted with the dual complexity of human experience and increasingly sophisticated building technologies, it is of utmost importance to equip relevant stakeholders with timely, empathic, intuitive, and intelligible information to support evidence-based design, operation,

maintenance, and use of buildings that genuinely accommodate human requirements.

Traditionally, building design has been guided by clearly defined functions and a relatively narrow set of target occupant groups. Offices, homes, schools, and commercial spaces are typically conceived as distinct environments with stable patterns of use, allowing designers to optimize spatial layouts, environmental controls, and operational strategies for predictable activities and user profiles. Comfort standards and building performance criteria have been therefore often developed based on assumptions about "stereotypical" and frequently reductionist occupant archetypes, which in many instances reflected limited demographic diversity in terms of gender, age, health status, cultural background, or working patterns.

In recent years, however, the boundaries between different types of environments—most notably between work and home—have become increasingly blurred. The rise of remote and hybrid working models, flexible learning arrangements, shared living-working spaces, and digitally mediated activities have led to the emergence of multifunctional environments. These spaces are expected to support a wide range of tasks, schedules, and occupant needs throughout the day, often accommodating users with very different expectations and comfort requirements. As a result, traditional design approaches that rely on fixed assumptions about function and user groups are rendered less adequate.

At the same time, growing evidence suggests that conventional comfort ranges and operational strategies have been conventionally calibrated to serve specific cross-sections of the population that are not necessarily representative. For example, several studies have shown that thermal comfort standards in office environments were largely derived from data collected from young male occupants, leading to temperature setpoints that may not adequately reflect the comfort needs of women and elderly groups (van Hoof et al., 2017). Similar concerns have been raised regarding accessibility, indoor air quality sensitivities, neurodiversity, ageing populations, and cultural differences in environmental preferences.

Ensuring comfort and well-being for all occupants has therefore become an increasingly important objective in building design and operation. Addressing the related challenges requires more adaptive, data-driven, and human-centred approaches that recognize variability in occupant needs rather than relying on one-size-fits-all assumptions. This shift highlights the need for new frameworks and tools that can support inclusive decision-making, enable responsive building systems, and ultimately create indoor environments that perform effectively for all user groups.

Currently, we are witnessing rapid advancements in AI technologies, with breakthroughs in areas such as Large Language Models (s) and Machine Learning (ML). These innovations have transformed AI solutions from experimental tools into practical applications delivering substantial value. Despite this growth, most contemporary AI models remain predominantly based on statistical and sub-symbolic approaches, which limits their ability to reason about and internalize real-world logic and domain constraints.

In the built environment domain, many AI applications primarily rely on technical and operational data streams, while nuanced occupant experiences, preferences, and subjective comfort perceptions are less frequently integrated

in a structured and scalable manner (Aghaei et al., 2025; Yan et al., 2023).

As a result, the deployment of AI solutions in complex real-world environments such as smart built environments, cannot rely on data-driven models alone. Instead, they must be complemented by logical components and hybrid-AI approaches (Sheth et al., 2023) that provide explicit contextual knowledge about the environment and users. Such approaches may include human-in-the-loop systems or meticulously designed digital twins of real-world entities such as buildings and occupants, which can guide and augment numerical methods employed by AI and LLM models. By integrating symbolic reasoning and domain knowledge, these hybrid systems are better equipped to address the inherent complexity, uncertainty, and safety requirements of real-world applications.

III. AIMS AND APPROACH

As alluded to before, the objective of the research initiative is to provide deep cohesive support for creation and upkeep of built environments conducive to healthy and productive human occupancy. This is targeted via the creation of versatile digital twins of building users, which can serve as agentic representations of occupants, capable of providing insights into how indoor-environmental conditions are perceived, how occupants' related expectations are formed, and how behavioural patterns have emerged. As such, these digital twins can provide critical information for engineers, architects, health professionals, and end users throughout the building lifecycle.

In pursuit of this objective, the research effort hypothesizes that AI technologies can be utilized in two distinct ways to support the generation of occupants' digital twins. On the one hand, AI enables the capture and representation of occupant characteristics that have traditionally been difficult to articulate, measure, or model, thereby supporting the development of richly detailed occupant digital twins. This capability can be facilitated through a range of applications, including pattern recognition, machine learning-based inference, and advanced data analytics, which can identify behavioural trends, preferences, and context-dependent comfort needs from heterogeneous data sources. On the other hand, occupant digital twins can be used as derivatives of a structured library of personas that represent individuals or occupant groups as multidimensional profiles.

These profiles may take the form of quantitative vectors derived from empirical data or prompt-based approximations that encode relevant human attributes such as personality traits, behavioural tendencies, ethical perspectives, comfort preferences, and socio-cultural values. By formalizing these characteristics into computationally usable representations, a "persona space" can be generated and systematically integrated into generative AI workflows.

Occupants can be given a virtual voice by developing an advanced array of theory-informed, data-driven user profiles or "personas" that are designed to accurately represent human needs, preferences, and behaviours in the context of built environments. Given a multidimensional persona space, each persona can be embedded into occupants' digital twins in various cyber-physical solutions, thus facilitating meaningful interactions with both building systems and occupants. In addition, the persona space can support advanced generative

AI applications by enabling the selection and representation of relevant occupant types in different operational scenarios.

Embedding occupant persona representations into generative AI applications, such as LLM, simulation agents, or image and scenario generation tools, enables outputs to be conditioned on distinct sets of human characteristics rather than relying on generic or implicitly averaged assumptions about users. In this way, generative models can produce context-sensitive insights, recommendations, or design alternatives that better reflect the needs, expectations, and lived experiences of diverse occupant groups. This capability is particularly relevant for decision-support, participatory design processes, building operation strategies, and human-AI interaction scenarios such as conversational AI within the built environment domain.

Importantly, the underlying premise is that many aspects of human values, preferences, and behavioural patterns are implicitly encoded within the representation spaces of large-scale generative models. However, systematic methods for explicitly structuring, selecting, and operationalizing such human-centred representations remain limited. In application domains such as the built environment where performance outcomes are closely tied to human comfort, well-being, and equity, this dimension of generative AI remains largely underexplored. Thus, embedding structured occupant personas into generative systems offers a promising pathway to improve the inclusiveness, responsiveness, and societal relevance of AI-enabled design and operational practices. The approach is projected to be impactful at multiple levels:

- At the occupant level, more responsive and human-centred building operation can be facilitated, leading to measurable improvements in thermal comfort, indoor air quality, and overall wellbeing, while reducing the prevalence of sick building syndrome and enhancing occupants' cognitive performance and productivity in workplaces.
- At the building level, independent of the building type (e.g., residential, commercial), the occupants can be provided with an effective and meaningful "voice" in shaping their environments. For instance, in educational environments, improved and continuously optimized Indoor Air Quality (IAQ) can support healthier learning conditions for children, whose safe and secure growth represents the highest obligation of any society.
- At the professional level, designers, engineers, and facility managers could be provided with actionable, evidence-based insights into human-building interactions, thereby enhancing design quality, supporting performance-driven decision-making, and reducing the gap between intended and actual performance of buildings.
- At a national level, the approach can contribute to addressing a critical societal challenge at the intersection of public health, energy efficiency, and the built environment by advancing human-centric solutions for healthier, more resilient buildings. This multi-level approach can also provide the potential to inform standards, guide policy, and improve performance across diverse building types and populations.

IV. GENERAL SYSTEM ARCHITECTURE

The realization of the research objectives requires an interdisciplinary approach that integrates the study of indoor-environmental conditions with theories of human perception and behaviour. This combined perspective enables a more comprehensive understanding of how physical building parameters interact with occupant experiences, preferences, and actions. Whereas each of the proposed system's constituents require specific innovations, the central innovative contribution lies in their integrative synthesis so as to construct effective and communication-enabled digital twins of building occupants. The general architecture and elements of the required environment for this purpose is briefly described in Figure 1. The abbreviations used in this Figure are listed in Table 1. As mentioned before, the realization of the system architecture requires the deployment of multiple advanced technologies, including environmental sensing needed to generate the IEQ matrix (M_{IEQ}), computational simulation needed to generate the building's digital twin (DT_{BU}) and the respective virtual IEQ data stream (V_{IEQ}), as well as artificial intelligence resources and tools including large language models (AI_LLM).

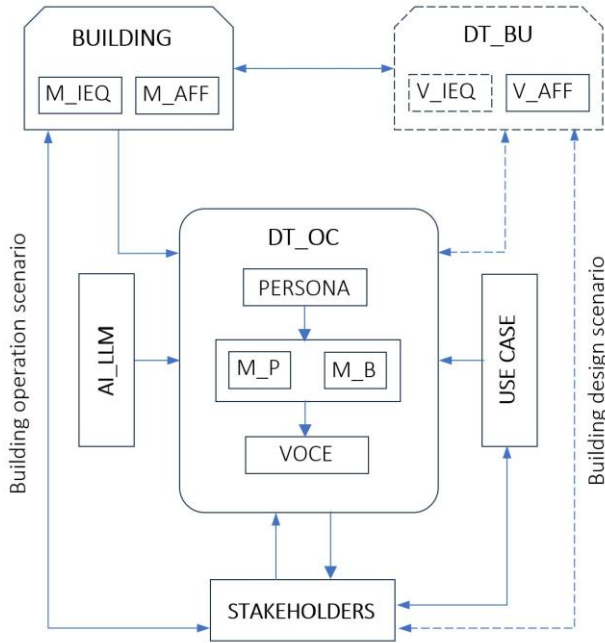


Fig. 1. Schematic illustration of the architecture and key constituents of the Viva-Voce environment.

Table 1. Abbreviations used in Figure 1.

Symbol	Meaning
M_{IEQ}	IEQ (Indoor Environmental Quality) matrix
M_{AFF}	Affordance matrix
DT_{BU}	Digital twin of building
V_{IEQ}	Virtual IEQ matrix
V_{AFF}	Virtual affordance matrix
DT_{OC}	Digital twin of occupants
M_P	Models of perception
M_B	Models of behavior
VOCE	LLM-powered vocalizer

To better understand this architecture, it is useful to distinguish between the structure of the digital twin model for building occupants (DT_{OC}) and the elements needed to provide DT_{OC} with required information and the entities and processes that enable its application. Required information includes, in case of a real building, information on the building's IEQ (M_{IEQ}) and affordance (M_{AFF}).

IEQ-related data streams (M_{IEQ}) is a constitutive part of required observational data. The importance of IEQ stems from the fact that modern populations spend the vast majority of their lives indoors, making the quality of those environments a critical determinant of public health and productivity (Dimitroulopoulou et al., 2023, Trounce et al., 2025, Engineer et al., 2021, Králiková et al., 2016, Hassan, 2024). The approach to operationalization of IEQ can be described in terms of a matrix of stimuli affecting occupants' perception and behaviour. As such, IEQ is part of an overarching ontology (see Table 2), which relies on advancing previous work in this area (Mahdavi and Taheri 2017, Mahdavi et al. 2023). This "umbrella" ontology represents a well-formed schema for building monitoring, encompassing a number of key data categories (i.e., occupants, indoor-environmental conditions, external conditions, control systems and devices, equipment, and energy flows). Data gained via sensors and other sources (e.g., simulation-based virtual sensors, human agents) in the above categories can be structured in terms of values, sources, and actors. In this context, M_{IEQ} specifically encompasses the previously outlined four domains pertaining to indoor air quality, as well as thermal, visual, and acoustic conditions.

Both measurable physical variables and purported health and comfort implications have been associated with the aforementioned IEQ domains. Examples of the former include, for IAQ, particulate matter, VOCs (volatile organic compounds), CO_2 (Carbon Dioxide), and ventilation rate, for thermal comfort, temperature, humidity, and air movement, for visual quality, illuminance, and daylight factor, and for acoustics sound level, frequency spectrum, and reverberation. As to health and comfort related ramifications of shortcomings in these domains, relevant studies point to respiratory ailments, thermal discomfort, loss of concentration and productivity, physiological stress responses, eye strain, and task performance decline.

In the schema depicted in Figure 1, affordance (M_{AFF}) denotes those features of buildings, which accommodate occupants' functional requirements, including buildings' environmental control systems for heating, cooling, ventilation, and lighting. In case of the digital twin of a building (DT_{BU}), respective virtual data streams apply (i.e., V_{IEQ} , V_{AFF}): Whereas data for V_{IEQ} can be generated via building performance applications, virtual affordance data are obtained through digital representation supported by BIM (Building Information Modelling).

The functional core of the system architecture is the DT_{OC} application, whose main utility is the representation of building users and processes related to their perception of indoor environments and their disposition to adaptive actions. There are a number of approaches in the relevant scientific field to explain and describe human perceptions of a given indoor environment. High-level explanatory theories have been categorized as *i)* Psychophysics, *ii)* Human Ecology, *iii)* Ecological Psychology, *iv)* Biosemiotics, *v)* Cybernetics, and *vi)* Cognition (Mahdavi, 2020).

Table 2. Proposed elements of a building monitoring ontology including pertinent data categories and sub-categories.

External conditions	Hygro-thermal data
	Radiation data (including light)
	Acoustics
	Air quality
Indoor conditions	Thermal
	Visual
	Acoustics
	Air quality
Control systems/devices	Heating/cooling
	Ventilation
	Lighting
	Equipment
Equipment	Appliances
	Electrical equipment
	Safety/security equipment
	Transportation
Energy	Heating/cooling
	Ventilation
	Lighting
	Equipment

It is important to keep in mind that, for a number of decades, building performance assessment processes, including energy efficiency and adequate IEQ, have relied on computational modelling. However, early practices in indoor building energy and comfort simulations adopted a reductionist (schedule-based or rule-based) approach to the representation of buildings' inhabitants. More recently, efforts have been undertaken to enhance the representational realism of inhabitants in building modelling. These efforts have been motivated in part by pointers to the potentially important role of occupants' behaviour (OB) on energy use. In fact, the "energy performance gap" phenomenon (i.e., discrepancy between a priori prediction of energy use on the one hand and the actual energy use on the other hand) has been suggested to be at least partially caused by the absence of high-resolution behavioural models in modelling applications. Recently, several detailed and dynamic models have been introduced to quantify the dynamics of occupants' presence, movement, and behaviour within indoor environments, including interactions with different building systems (e.g., window opening, thermostat setting changes, lighting switch) as well as adaptive comfort-restoring actions (e.g., change of clothing level, posture, and activity) (Ahmed et al., 2023). As such, researchers have embarked on collection and classification of theories (Heydarian et al., 2020) and compilation of a library of OB models for building performance simulation applications (Deme Belafi et al., 2019).

In the present effort, one of the key supporting methods involves the use of personas, which can be applied in interactions with LLMs to guide and condition model behaviour in generative AI use cases. These personas enable more context-aware and user-centred outputs across both the design and operational phases of a building's lifecycle. In the context of LLM applications, personas are defined as structured representations of users that condition model behaviour, influencing aspects such as tone, linguistic style, preferences, decision-making tendencies, goals and constraints, as well as awareness of situational context. While personas can be generated synthetically by leveraging diverse perspectives within LLMs to create synthetic user data (Ge et al., 2024), thus offering a scalable and cost-effective

approach, such methods often rely on heuristic generation techniques. The limited precision of these approaches can result in systematic biases that propagate to downstream applications (Li et al., 2025). Therefore, in the present context, the emphasis is on deployment of data collection methods to capture occupant information, enabling the representation of multi-dimensional attributes and supporting a more accurate and reliable characterization of occupant profiles. Figure 2 illustrates the persona construction workflow and highlights the key scenarios in which personas are applied.

Building upon past progress in this area (Mahdavi et al., 2022), an initial ontological basis for the realization of the multi-dimensional conceptual space of occupants' attributes has been developed (see Figure 3). Development of personas relies on multiple data sources that characterize users within the context of a specific built environment. The representation of people in buildings, along with the diverse dimensions of user modelling, has been studied in the past. Starting from the aforementioned ontology of occupants' attributes, the present project adopts state-of-the-art semantic models to systematically capture both occupant-related and building-related data. Occupant-related data can be broadly grouped into three main categories:

- The first category includes static or slow-changing attributes, such as demographic characteristics, age range, gender identity, profession, cultural background, and language. This type of information can often be reused across different personas and contextual environments.
- The second category comprises behavioural and preference data, which evolve through users' interactions with their surroundings and can be progressively enriched over time. To this end, the context information on the building's IEQ (M_IEQ) and affordance (M_AFF) can be leveraged as previously discussed. Instances of this second category include the use of environmental controls or repeated actions taken by occupants in various comfort-related situations within a specific built environment.
- The third category consists of high-frequency contextual data that change rapidly and therefore require real-time access and analysis to assess occupants' current status. These may include anonymised occupant-related sensor data, relevant for capturing mobility patterns, activity states, heart rate, stress levels, or sleep cycles, as well as built environment data streams, including noise levels and lighting conditions. Note that the generated personas in this category do not represent identifiable individuals. Rather, they represent aggregate persona archetypes and are thus privacy-preserving.

Together, these inputs help dynamically adapt and refine personas based on the occupants' immediate context. Subsequent to data acquisition, relevant features are represented as embedding vectors using techniques tailored to the specific data types. For example, demographic attributes may be captured through direct or categorical encoding, while time-series encoders are applied to sensor stream data. In addition, more advanced methods, such as transformer-based encoders or graph embeddings, are used to model complex relationships and contextual dependencies. The synthesis of these different data components facilitates the construction of

persona vectors, that is the numerical representations of user profiles inferred from data and used as conditioning signals in subsequent interactions with LLMs.

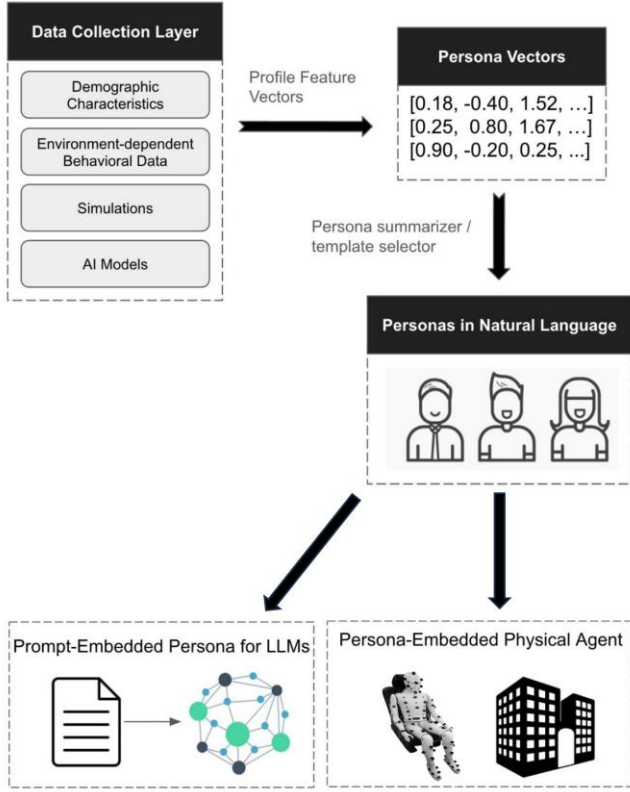


Fig. 2. Schematic overview of the persona construction workflow.

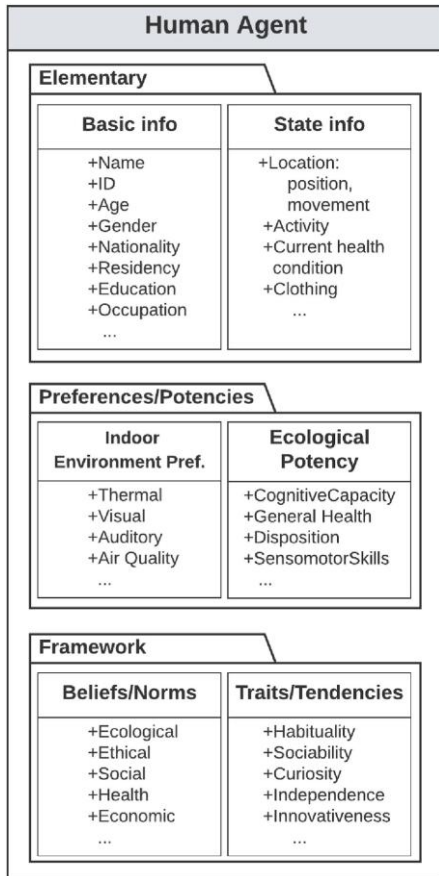


Fig. 3. Ontological basis for the multi-dimensional space of occupants' personas.

The persona vectors are then utilized by persona summarizers or template selectors to generate textual persona descriptions. These descriptions can be applied in a variety of scenarios, such as prompt injection into LLMs for building design or building operation processes, or integration into persona-embedded physical agents, including robots, humanoids, or other human-machine interfaces, to facilitate interactions with occupants and the built environment.

Finally, as the system architecture illustration of Figure 1 illustrates, the two main use case groups encompass *i)* the operation of existing buildings, and *ii)* the design of new buildings. Note that the emphasis on AI-assisted high-resolution representations of occupants incentivises greater attention to the specification of user profiles and their needs in the building design process in early stages. Such needs are better understood with respect to certain building typologies (e.g., elderly care facilities, schools). In cases with less concrete profile specifications, existing occupancy data bases can be utilized at the starting point (Dong et al., 2022a, Huebner and Mahdavi, 2019, Kjaergaard et al., 2020). Information thus obtained can be successively enhanced and carried over to the operation phase while maintaining an iterative refinement, for instance via continuous learning regimes.

V. IMPLEMENTATION PROCESS

The initial step in the project concerns IEQ and affordance matrices and establishes the foundation of the effort by defining actual and virtual IEQ parameters, organizing them into structured IEQ matrices, and developing corresponding models of building affordances. To ensure the robustness of the data processing strategy, a compact and transportable sensing unit is developed to dynamically capture a matrix (M_{IEQ}) of key indicators of indoor-environmental quality (IEQ) in thermal, visual, acoustic, and air quality domains. Whereas the assembly of this unit uses existing sensing and monitoring technologies, it relies on an original ontologically structured foundation (Mahdavi and Wolosiuk, 2019). Simulation-powered construction of digital twins of buildings (DT_BU) facilitates the generation of a virtual instance of IEQ sensing unit (V_{IEQ}). To obtain a virtual IEQ matrix, dynamic multi-domain simulation methods can generate IEQ-related data streams that can be calibrated using actual monitored data (building operation use case) or later on supplied to predictive models of human perception and behaviour (building design and retrofit use cases).

In the next step, data streams pertaining to the indoor environment's IEQ matrix and affordance (already generated either actually or virtually in the previous step) are fed into human perception and behavioural models to create the occupants-in-the-room model and predict what they experience, how they feel, and what adaptive actions they are considering. Hence, perceptual and behavioural modelling engines developed at this point can be integrated, in a third step, into the digital twin frameworks, which focus on collecting and integrating relevant data to construct occupant persona vectors, resulting in digital twins of both building occupants (personas) and buildings themselves. Demographic data sources are deployed to generate occupants' personas, which represent composite profiles of building occupants, including their age, gender, state of health, education, cultural background, preferences and attitudes, and belief system.

These personas serve as the identity-constituting background for the realization of DT_OC, whose predicted perceptual and behavioural processes can be tested under controlled conditions involving real participants' response to the identical indoor-environmental conditions.

As to the architecture and elements of the digital twin of the occupants (DT_OC), the processes involved in human perception, cognition, and behaviour are of course highly complex. In fact, it is exactly the recognition of this complexity that guides the selected modelling strategy for realization of DT_OC. As such, the focus is, operationally, on those features of human response to indoor environments that are directly relevant to decision-making processes targeting occupants' health and comfort. Such decisions pertain to the IEQ conditions (e.g., ambient temperature, illuminance and luminance levels, fresh air volume flows), as provided via M_IEQ or V_IEQ, as well as to the indoor environment's specific affordance, as represented by M_AFF or V_AFF.

Building information (IEQ, affordance) and occupants' profiles (personas) provide the requisite information required for the core functionality of the digital twin of occupants (DT_OC), which is afforded by two foundational modelling engines. Whereas the first engine (M_P) serves the prediction of occupants' IEQ experience (sensation, perception, evaluation), the second engine (M_B) is dedicated to the prediction of occupants' disposition to adaptive behaviour (mainly interaction with buildings' control devices), which is assumed to result from occupants' experience of the prevailing conditions as well as changes in their internal (physical and mental states).

M_P uses, as input, information about personas and prevailing IEQ conditions (M_IEQ or V_IEQ). It generates, as output, values of key IEQ constructs (e.g., sensation, satisfaction, acceptability), numerically expressed in terms of the corresponding metrics. This engine relies on a compound streamlined assembly of multiple predictive models in key IEQ domains (Zhao et al., 2021). M_B uses, as input, *i*) information on occupant's personas, *ii*) description of indoor environment's specific affordance, and *iii*) output of model M_P. The output of M_B includes computed probabilities of the occupant's adaptive actions, that is the type and frequency of the occupant's interactions with the building's environmental control systems. In this case too, the modelling engine functions on the basis of an operationally unified assembly of multiple human-system interaction models (Dong et al., 2022b).

Specific affordance or ecological valency (Mahdavi et al., 2021) is understood here as the availability and implementation features of buildings' control devices (e.g., windows, shades, luminaires, radiators) and their controllability (e.g., user interfaces such as thermostats, dimmers, and other actuators). The creation of the models of affordance of given spaces is aided by the existing utility of building information modelling (BIM) applications.

The final developmental project step focuses on AI-based linguistic communication and leverages the digital twins developed in the previous step, together with specifically designed personas, to enable conversational AI scenarios. This key element of DT_OC functionality lies in its capability of direct linguistic communication with presumed stakeholders. To this end, the development of an LLM-powered vocalization module confers to the DT_OC the capacity to engage in real-time interlocution with various

stakeholders and verbally express its needs, perceptions, views, evaluations, levels of satisfaction or discontent, as well as conceivable behavioural options (e.g., control actions, adaptive adjustments). The intention is to test and validate the functionality of this module in actual settings under participation of individuals and groups representing different stakeholders. Such settings and participants planned to include, for instance, educational buildings (with educators and children/students as stakeholders) and office buildings (with occupants, visitors, and facility managers as stakeholders).

VI. CONCLUDING REMARKS

This paper presented the scope and initial output of a recently initiated bi-national research effort, focused on the provision of deep human-centric support for the building design, construction, operation, and retrofit processes. To this end, the core objective is to create versatile digital twins of building users, whose virtual agency would enable them to vocally express responses to prevailing conditions, articulate needs, and display disposition to adaptive behavioural actions. These digital twins can be instantiated as the digital operating system of physical devices within existing buildings, or realized, as computational agents, within simulation-based digital twins of buildings.

A methodologically-layered approach is adopted to achieve the project's objectives, involving a synthesis of environmental monitoring technologies, persona-driven computational agents capable of emulation of perception and behaviour processes, building information modelling and building performance simulation, and integration of AI and LLM utilities.

The ongoing status of the project implies certain limitations due to its current stage of implementation. As reported in the paper, certain aspects of the project are well advanced, including the state-of-the-art assessment, ontological developments pertaining to building monitoring and persona generation, and the design of the architecture of the envisioned project platform. Ongoing and future steps are expected to provide a fully function prototype of the occupants' digital twins capable of processing real and simulated matrix of environmental conditions and surrounding's affordance to acquire perceptual attitudes and behavioural dispositions that can be, among others, verbally communicated to the stakeholders involved in the building planning and operation processes.

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