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OTTO: Outline of an Occupants Theory-Tailored Ontology for building performance simulation

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Abstract

Early building performance computing practices adopted a reductionist attitude to inclusion of occupants in simulation models. More recently, efforts have been made toward more realistic representations of occupants in simulation. The present contribution argues that high-resolution occupant models must be grounded on a more robust ontological basis, which requires, in turn, a deeper theoretical understanding of the relevant domain, that is human requirements and behavior. To this end, a pragmatic theory of occupants' control-oriented actions in buildings is outlined. Furthermore, this high-level theory's relevance for ontological developments is exemplified via a derivative representational scheme, labeled as an occupants theory-tailored ontology ("OTTO").

Highlights

- The standing of occupants in simulation models is discussed.
- A pragmatic theory of occupant behavior in buildings is outlined.
- An ontological schema for a detailed representation of occupants' presence and actions in buildings is introduced.

Introduction

The present contribution addresses the need for advances in theory-driven ontological developments toward detailed representations of occupants in building performance simulation (BPS) models. Data schemes of existing BPS applications do cover basic representations of inhabitants. More recently, these representations have been further developed to adopt more sophisticated (e.g., probabilistic) formalisms. Hence, the potential for emulation of realistic patterns of occupants' presence and actions in buildings has been augmented. Nonetheless, further improvements in this area are needed, pertaining to theoretical foundations, data ontologies, and of course actual empirical information on occupants' actual behavior (Mahdavi 2021). To this end, there is a need to support ontology development efforts aided by high-level behavioral theories that go beyond rule-based data-driven black-box schemes and adopt instead models that benefit from physiologically and psychologically grounded first principles.

Building's general geometry, structure, and construction typically do not go through significant changes over their life cycle of the building. On the other hand, buildings' control elements and devices (e.g., windows, shades, technical systems for indoor-environmental control) do routinely and intentionally undergo dynamic state changes not only to respond to changes in external boundary conditions (i.e., weather conditions), but also to accommodate the dynamics of occupants' requirements. This implies the importance of including, in BPS models, appropriate representations of occupants. In other words, there is a need for representational solutions that can effectively map occupant-driven dynamic changes in the state of buildings' adjustable control devices. Such changes might be brought about by inhabitants' direct actions (for instance when a window, a blind, or a light switch is manually operated), or through automated control systems control, which nonetheless can be assumed to operate based on occupants' preferences. Consequently, simulation models must take physiological, psychological, and social drivers of occupants' behavior into consideration. In practice, these drivers are rarely considered explicitly. Frequently, simple schedules are deployed to represent occupants' patterns of presence in buildings, together with likewise simple rules to map their comfort preferences and their control-oriented actions. Less common are time series based on probabilistic distributions and high-resolution representations of occupants as individuals.

Note that the argument is not to suggest that all past reductionist practices in representation of occupant actions are somehow unreasonable. There has been a wide range of resolution levels in representation of occupants in simulation models, from simple schedules and rules to agent-based modeling (ABM) (Malik et al. 2022a, Berger and Mahdavi 2020). The choice of the proper level of abstraction must indeed take the purpose of the performance query into account (Gaetani et al. 2016, Malik et al. 2022b, Mahdavi and Tahmasebi 2016).

As such, the existing occupant data schemes may adequately cater for purposes of those simulation scenarios involving simple benchmarking via aggregated performance indicator values. But the situation is different in those cases, where a more detailed study needs to include the influence of occupants' characteristics, attitudes, and behavior on the performance of buildings. For the latter kinds of studies, one would not only need reliable empirical data on occupants' behavior (Mahdavi 2020, 2016), but also versatile ontological classes that can formally capture such behavior (Mahdavi et al. 2021a,

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2021b, 2022). A source of complexity thereby is the multitude of parameters that can affect occupants' behavior, including occupants' physiological and psychological requirements and preferences, and the social context. This underlines the aforementioned significance of occupant-centric theories of perception, evaluation, and behavior. Such theories could, in turn, provide the basis for formulation of ontologies beyond existing solutions (Balaji et al. 2018, Chandra-Putra et al. 2021, Chávez-Feria et al. 2020, Hong et al. 2015a, 2015b, Luo et al. 2022, Mahdavi and Taheri 2017, Mahdavi and Wolosiuk 2019, Mahdavi et al. 2021a, 2022, Rasmussen et al. 2017, 2020).

In this context, the key objective of the present paper is to outline a systematic path from a high-level behavioral theory (of occupants' control-oriented actions in buildings) to a versatile occupant behavior ontology. To this end, the elements of a recently developed ontology (OTTO: occupants theory-tailored ontology) are presented, which cover key factors affecting occupants' behavior, including physiological and psychological needs and preferences, outdoor conditions, buildings' layout and amenities, affordance of outdoor spaces, and multiple organizational and social circumstances. The proposed ontology is explicitly derived based on a high-level explanatory theory of occupants' perception and evaluation of – as well as their behavior in – built spaces. The paper provides a description of the categories entailed in the proposed ontology.

About occupant behavior models

The choice of a suitable occupant model depends on the type of performance query (Gaetani et al. 2016, Malik et al. 2022b, Mahdavi and Tahmasebi 2016). For highly detailed queries involving, for instance, representation of occupants as agents, existing ontological frameworks would have to be refined (D'Oca et al. 2017, Mahdavi 2021). In a previous study, we analyzed instances of control actions by different occupants in different situations. This analysis highlighted the multi-layered complexity of even the simplest control action performed by an occupant. It also provided insights regarding necessary ontological and theoretical developments. Specifically, the analysis implies that at least four types of affordances perceived by occupants must be ontologically represented:

i) Buildings' spatial layout and amenities are entities with which occupants are either assumed to be familiar, or need to familiarize themselves once inhabiting a new environment. Building Information Modeling (BIM) (ISO 2018a) is ontologically equipped with the physical entities in this category, but not the respective agent-specific views.

ii) Building components and systems can be also ontologically mapped in BIM. Nonetheless, agent-specific perceived affordances of these entities are insufficiently captured in existing ontologies.

iii) Indoor-environmental conditions can be mapped via simulation, which in turn provide the basis for the estimation of occupants' responses via comfort models. Existing challenges in this category are not so much ontological. Rather, they pertain to the reliability of comfort models and the multi-layered nature of human behavior. The latter is not only propelled by perception of discomfort, but conditioned also by other values (e.g., energy and environmental consciousness).

iv) The presence of multiple occupants in the same physical settings and the related psychological and social circumstances represent a challenge for behavioral models and requires further advances both in domain knowledge and in ontology development.

To address a still existing gap between behavioral theories in human sciences (Heydarian et al. 2020) and technical applications in engineering domains, Mahdavi et al. (2021a, 2021b, 2022) put forward a pragmatic theory to support ontology development regarding occupants control actions in buildings. Given the limited space of the present paper, the theory can be illustrated here only in a highly compact form (see Figure 1 and Table 1). Whereas the theory cannot be empirically verified at this stage, it has been examined in view of its plausibility, applicability, and scalability via extended reasoning involving demonstrative control scenarios (i.e., operation of windows, shades, lamps, etc.) (Mahdavi et al. 2021a). The theory suggests that, at the most fundamental level, control actions are motivated by the perceived deviation of existing conditions from preferred ones, whereby preferences could be very different among different agents and they can also vary over time. Actions might be also initiated habitually. They may also be delayed or not executed at all due to deferral mechanisms or social considerations.

A scheme for representing occupants

Certain independent variables in the proposed behavioral theory can be accommodated through existing ontologies of IFC (ISO 2018b) and BIM, including buildings' geometry, construction, spatial layout, functional organization, furniture, equipment, appliances, operable elements (e.g., windows, blinds), and environmental control systems (Costa et al. 2016). What is still needed is ontological progress with regard to the currently rather rudimentary representation of occupants in BIM and BPS, including their ecological potency and their perception of the surrounding world's affordances. As such, *i)* physical spaces of the building must be mapped to respective occupants' conceptions as spaces or zones that afford various opportunities through their specific functional attributes; *ii)* control devices must be mapped to respective interfaces that occupants can recognize and operate; *iii)* physical indoor-environmental conditions must be mapped to subjective perception of quality (e.g., comfort, well-being).

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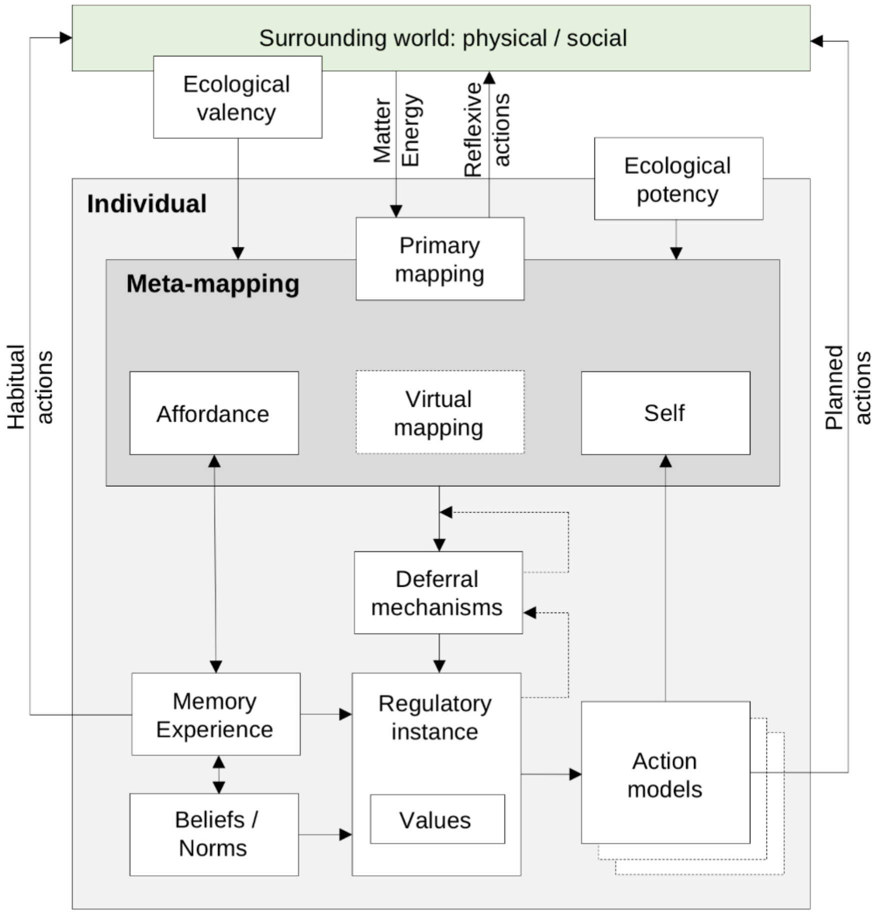

Figure 1: Schematic representation of the constituent elements of the pragmatic theory of occupants' control-oriented actions in buildings (based on Mahdavi et al. 2021a, with modifications).

The preceding discussion suggests that detailed representation of occupants' characteristics, requirements, and behavior in BPS necessitate a multi-layered ontological schema, which can facilitate the definition of ontologically structured information toward prediction of occupants' behavior. Figure 2 illustrates, in a compact form, the key features of such a schema, which entails six categories.

Three of these categories ("elementary", "preferences/potencies", and "framework") directly relate to occupants. The elementary category pertains to identification and general classification of occupants. It has two sub-categories, namely "basic information" and "state information". The framework category accounts for occupants' beliefs, character, and needs. It entails the sub-categories "beliefs/norms" (including ecological, ethical, personal, social, and economic values) and "traits/tendencies" (including psychologically relevant characteristics). This latter category focuses on the occupants' stated or assumed general preferences in terms of the thermal, visual, auditory, and air quality condition. It also covers the occupants' ecological potency (e.g., cognitive capacity, health disposition, and sensorimotor skills).

The fourth category ("affordance") pertains to occupants' perception of buildings' ecological valency. It represents occupants' real-time perception of indoor-environmental conditions as well as the discerned spatial and technical opportunities (e.g., control options) for improving those conditions. The affordance category entails two sub-categories. The "comfort perception" subcategory may be computationally estimated based on comfort models, which in turn may obtain, as input, BPS-generated indoor-environmental data. The "resources" subcategory accounts for the fact that the ontology must represent occupants' awareness of the conditions in buildings' spaces/zones as well as the availability and utility of control devices, and systems. BIM and BPS can provide objective data regarding both conditions and systems. But it is also necessary to represent occupants' awareness of these in terms of perceived affordances.

The fifth category ("behavior") covers types of occupant behavior assumed to influence buildings' performance

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Table 1: Explanations of the key concepts of the behavioral theory (see Figure 1 and remarks in text).

Term	Definition
Individual	Human agent (inhabitant)
Surrounding world	Surrounding world refers to the objective world around the human agent, consisting of physical entities, forces, and fields as well as social and cultural context. In a large fraction of people's life, buildings (specifically, indoor environments) constitute their surrounding world.
Ecological potency (EP)	EP denotes the human agent's physical and cognitive capabilities in dealing with the surrounding world. EP is influenced by inhabitants' physical and mental health and mobility, which are relatively stable over time, as well as other attributes such as the levels of attention, concentration, and arousal, which can rapidly change over time.
Ecological valency (EV)	EV denotes the totality of the surrounding world's attributes as relevant to the human agents. Considering buildings as the immediate segment of the inhabitants' surrounding world and focusing on control-oriented actions, EV can be interpreted with reference to the availability and utility of buildings' amenities and services such as directly accessible outdoor areas (e.g., balconies, terraces, gardens), furnished indoor spaces, appliances, equipment, lighting, and HVAC.
Primary mapping	The primary mental process of representing the relevant segment of a human agent's surrounding world.
Affordance	The surrounding world's objective EV is represented in terms of its subjective "affordance", which denotes perceived opportunities (e.g., food, shelter, control possibilities, context for interaction with other human beings) as well as recognized potential risks and threats. Affordance can be associated with means of indoor-environmental control such as windows, blinds, radiators, and fans. Whereas EV of a given setting can be assumed to be the same for all inhabitants, affordances can (and often do) differ from inhabitant to inhabitant, given differences in EP, including level of knowledge (of the control means' functionality) and awareness (of the control means' availability).
Meta-mapping	Meta-mapping refers to the inhabitant's awareness of his/her own self and the awareness of this self's situatedness in the physical world. Meta-mapping is a prerequisite of planned actions, as it allows human agents to reflect on their past and present states and anticipate their possible actions and the implications of these actions for their future states.
Experience and knowledge	The repository of experience and knowledge facilitates the categorization of perceived needs and the detection of the affordances. This repository contributes to the contextually appropriate evaluation and selection of behavioral options.
Beliefs and norms	The repository of beliefs and norms qualifies, shapes, and constrains the space of the behavioral options available to inhabitants, for instance, based on ethical considerations, environmental awareness, and social considerateness. The nature of beliefs and norms (and the strength of their influence) may evolve over time and can be overridden by other drivers (e.g., the opportunistic temptation to exploit momentary advantages).
Regulatory instance	The regulatory instance represents, in the behavioral theory, an abstract construct that captures the functionality of the inhabitants' central (executive) unit responsible for conceiving and executing control-oriented actions.
Values	Behavior is influenced by the value-driven assessment of the agent's current state with regard to alternative future states that could be preferable. The most basic (biological) value is the agent's immediate survival, but there are other "higher-level" values such as health, comfort, satisfaction, pleasure, and productivity. Aside from these "primary" values, behavior is also influenced by further kinds of values, such as economic, ecological, socio-cultural, and ethical values.
Virtual mapping and action models	Before actions are executed, they may be virtually enacted by the agents in terms of "action models", thus assessing their potential toward achieving the desired states. This process is supported by the perceived ecological valency (affordance) of the environment, the repository of knowledge and experience, and the supervisory role of beliefs and norms.
Deferral mechanisms	The notion of deferral mechanisms refers to the circumstance that planning and execution of actions that could be expected under ordinary conditions may in certain situations be delayed due to factors such as inhabitants' momentary distraction or excessive cognitive load.
Habitual actions	Successful past actions may be engrained over time into the repository of experiences as habitual patterns. Given fitting circumstances, these patterns can be enacted in terms of habitual actions.
Reflexive actions	Inhabitants' biologically and physiologically driven responses to specific stimuli from the surrounding context.

(specifically, energy use and indoor-environmental conditions). The behavior category entails two subcategories. The subcategory "adaptive behavior" pertains to adapting clothing, activity, and location. The "interactions" subcategory pertains to control actions (e.g., operation of devices, equipment, and appliances).

The last category ("zone conditions") pertains to the objective (i.e., quantitatively expressible) state of the indoor-environmental conditions (e.g., thermal, visual, acoustical, air quality) to which the human agents are exposed.

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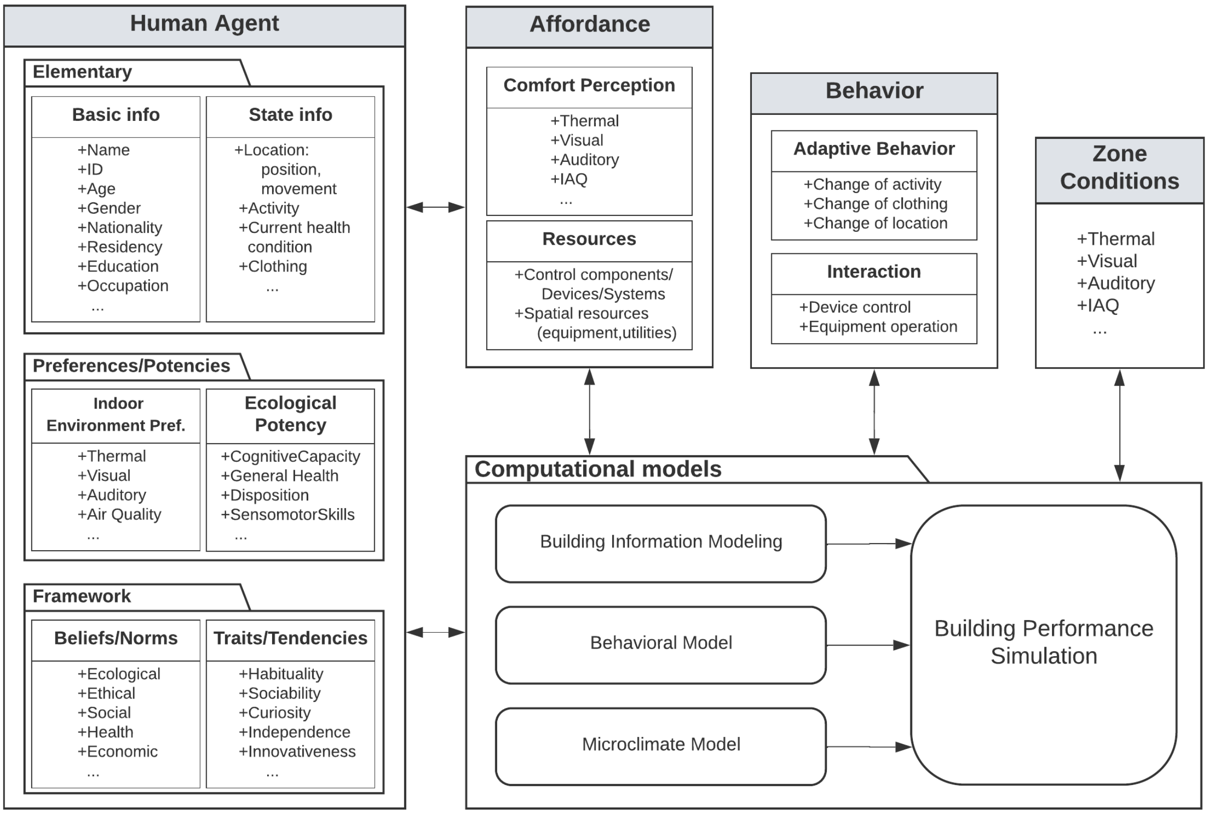

Figure 2: The main elements of the proposed Occupants Theory-Tailored Ontology (OTTO).

Conceptualization of ontology

The proposed ontological schema undoubtedly requires further developmental work and implementation efforts to become part of the mainstream ontological repertoire of BIM and BPS. One of the initial steps in this process is to utilize the elements of the proposed schema toward a preliminary ontology conceptualization. An initial instance of such a conceptualization is depicted in Figure 3, which displays the logical relationships between the previously discussed constituent elements of the ontology. Specifically, this conceptualization illustrates concepts as classes and the relations between the main concepts in terms of object attributes as data type properties. This results in an OWL-type representation of the model (Ontology Web Language).

The namespace "otto" refers to the proposed ontology's elements. Following the principle of ontology reuse, a number of concepts related to the buildings (e.g., control devices and systems, equipment, building elements and components, as well as building zones and spaces) can be linked to other existing building ontologies such as Brick Schema (Balaji et al. 2016, 2018), The Smart Application REFerence (ETSI 2023) or Building Topology Ontology (Rasmussen 2017, 2020).

As mentioned before, the proposed model and respective conceptualization, which focuses on behavioral considerations, should be viewed as the initial phase of an ongoing effort. Consequently, the depth of the specification of the attributes of the entailed concepts is at this time not at the same hierarchical level. Hence, in order to satisfy high-resolution implementation requirements (e.g., ABM), further iterations would be necessary.

A note on category attributes and their dynamics

Occupant-related categories (i.e., elementary, framework, preferences/potencies) and their attributes can be seen as rather stable over time. This means that the occupants' information could be qualitatively described as relatively persistent or static. This does mean that the relevant attributes would be immutable. They may indeed evolve through learning processes. However, qualitatively speaking, they would change on a rather slow pace. Notwithstanding this qualification, realistic modeling of occupants' control behavior must consider the real-time dynamics involved. As such, the ontological categories must entail variables that specifically capture transient circumstances as exemplified in the following:

- Present state of physical and mental health.
- Present physiologically relevant activity (e.g., metabolic rate) and psychologically relevant state (e.g., cognitive load).
- Contextual awareness of the building's ecological valency in terms of perceived affordances.

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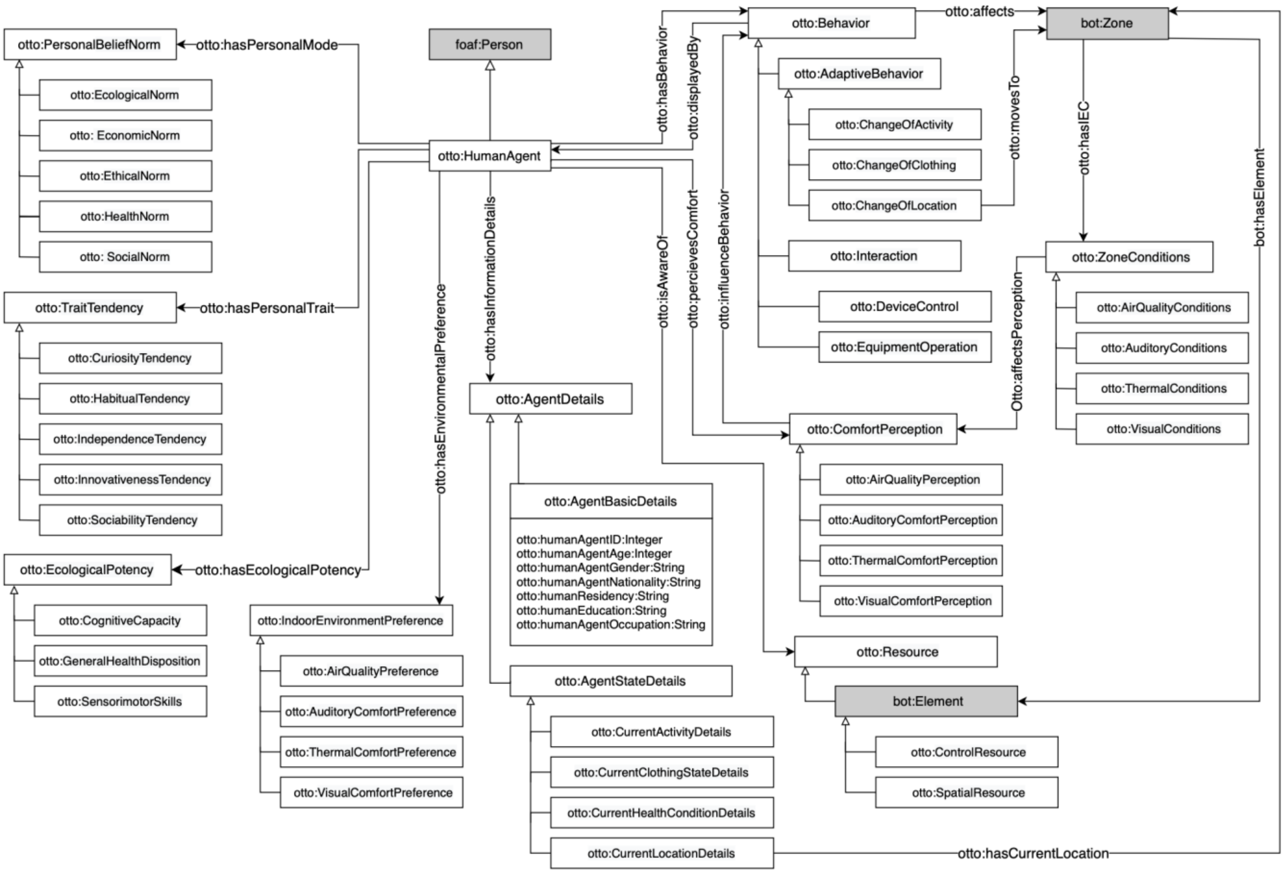

Figure 3: Conceptualization of OTTO.

As to the last variable in this list, it is important to recall that the effective affordance is not only a function of ecological valency as objectively given, but also the occupant's awareness of and familiarity with the availability, categories, states, and interfaces of the indoor-environmental control systems of the building. Furthermore, affordance pertains not only to the knowledge of available control means of control, but comprises also the perception of prevailing indoor-environmental circumstances.

This is an essential point, as the prediction of an occupant's behavior at any specific temporal instance requires the knowledge of the present indoor-environmental conditions at that temporal instance. As previously suggested, the discrepancy between the occupants' preferences and the prevailing indoor-environmental conditions can be viewed as the main driver of control-oriented actions (Mahdavi et al. 2021a). Note that the available BPS methods and tools have the capability to properly capture the dynamics of indoor-environmental conditions. Moreover, the representational requirements of variables relevant for this purpose are well understood and already covered by the existing ontologies (see, for instance, Mahdavi and Taheri 2017, Mahdavi and Wolosiuk 2019; Wolosiuk 2021). As such, they need not be treated here in detail.

Concluding remarks

The work presented in this paper was conceived as a contribution toward more versatile representations of occupants in BIM in general and BPS in particular. As such, the ingredients of the proposed ontological scheme were meant to offer a suitable foundation for systematic high-resolution representations of occupants in computational applications. As alluded to previously, there is no single valid fit-for-all level of representational resolution for all kinds of simulation-assisted performance queries. It is thus important to remember the present contribution's objective, which was to address the ontological requirements of highly detailed occupant models, such as those implemented via ABM. The successful application of such fine-grained formalisms requires individually customizable and very dynamic representational formats.

The appraisal of past research and development in this area points toward the necessity of further ontology-related efforts, lest progress is slowed down due to ad hoc, uncoordinated, and insular fixes in occupant modeling. What is needed is systematic collaboration toward ontologically robust, consistent, and interoperable solutions.

Needless to say, the presented state of affairs with regard to "OTTO" is far from being final. Considerable

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additional work is needed to work out the fine details of ontology such that it can be implemented in common BIM and BPS applications. For one thing, certain "OTTO" categories and the variables they entail are insufficiently operationalized. To make progress in this area, two kinds of developments would be needed. The first kind is related to coverage and completeness criteria. This is not so much about deep conceptual challenges, but involves practical matters relevant to the implementation of ontology-compliant data structures, which would necessitate the extension and refinement of the elements of each of the embedded categories in the proposed scheme (see Figure 2).

The second kind of required effort concerns the concrete operationalization of category elements in terms of variables with quantitative values. This applies, specifically, to elements in the framework category (beliefs/norms, traits/tendencies), preferences/needs category (indoor-environmental preferences), and affordance category (perceived IEQ). A common candidate for this purpose involves the adaptation of qualitative scales. Thereby, the difficulty is not so much the assignment of numeric scale values to inherently qualitative categories, which can be accomplished, for instance, via ordinal scales. Rather, the real challenge is the logically clear, consistent, and scientifically grounded mapping process, whereby the numeric scale values can be suggested to sensibly express the semantic nuances in qualitative concepts.

To address these challenges, two complementary strategies may be promising. The first strategy involves the continued efforts to extend and refine the categories and variables of the proposed ontology and to scientifically substantiate their operationalization. The second strategy involves detailed ontology-compliant BPS-embedded occupant models (for instance, using ABM formalism) that could help generating concrete data (i.e., predictions of occupants' type and timing of control actions) and comparing such data with observational data from real buildings. In this way, computational predictions could be compared with real (monitored) data, providing thus an appropriate basis for the assessment and improvement of the fidelity and reliability of occupant behavior models.

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