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Toward a theory-driven ontological framework for the representation of inhabitants in building performance computing

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ABSTRACT

Building performance computing focuses primarily on physical processes in buildings. As such, early practices in building simulation adopted a reductionist approach to the representation of buildings' inhabitants. More recently, efforts have been undertaken to enhance the representational realism of inhabitants in building modeling. However, progress in this area requires a robust ontological foundation, which in turn requires a theoretical understanding of the relevant domain. Based on the appraisal of past efforts, this paper identifies a gap between behavioral theories and occupant representations in building models. Consequently, a high-level occupant behavior theory is introduced and its relevance for ontological developments is illustrated through a derivative representational scheme ("otto": occupants theory-tailored ontology). The established link between behavioral theory and the derivative data schema is suggested to provide the necessary conditions for the development of a comprehensive ontological framework toward representation of inhabitants' presence and behavior in computational building models.

1. Introduction

The key premises of the present contribution may be summarized as follows: *i)* simulation models need to account for building inhabitants, and *ii)* further theory-driven ontological developments are necessary, in case highly detailed representations of inhabitants are deemed necessary. The first premise is generally undisputed. Key building performance indicators including energy efficiency, environmental impact, and indoor-environmental conditions are influenced by inhabitants' requirements and the patterns of their presence and behavior in buildings [1–3]. Simulation-based derivation of the values of such indicators must thus include inhabitants in simulation models. The second premise may need more elaboration. Existing building performance simulation applications can be argued to already possess data schemes covering more or less basic representations of inhabitants. Recent efforts have further developed these schemes so as to account for more detailed models of inhabitants [4]. However, the respective solutions still lack sufficient empirical basis, sound theoretical underpinnings [5,6], and robust ontological frameworks [7,8]. This implies the need for further research and development in this area, and represents as such the motivational background of the present contribution. Thereby, a major gap in the existing ontology development approaches is the absence of a continuous process starting from underlying high-level, comprehensive, and transparent behavioral theories that go beyond rule-based data-driven schemes and facilitate thus the transition to more scalable ontologies. In other words, the key objective of the present contribution is to demonstrate the need for a general-purpose occupant-centric ontological schema that is derived, in a transparent and tracible manner, from an underlying high-level be-

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havioral theory. The continuity implied in this theory-to-schema mapping is suggested to provide a more consistent and scalable working process for the development and implementation of occupant models in building performance assessment applications.

A systematic treatment of the representational matters concerning buildings' inhabitant should perhaps start with a brief reflection on building simulation models in general. The nature and scope of these models can be viewed from different angles [9]. Given the basic fact that the performance of buildings unfolds over time, one potentially fruitful perspective involves the consideration of the various elements of the simulation models in view of the level of dynamics involved. Certain components of a simulation model may be fairly static, whereas other components are highly dynamic. The consideration of the latter is obviously of critical relevance when simulating transient phenomena. Of course, for building (particularly thermal and visual) simulation, the par excellence instance of transient phenomena pertains to the microclimatic boundary conditions (i.e., weather, solar radiation, etc.) [10]. But these phenomena are not at the center of the present discussion. For one thing, these external boundary conditions can be treated as purely physical phenomena with no involvement on the part of inhabitants. Moreover, when modeling the performance of a specific building, the influence of microclimatic circumstances is modeled, in most instances, in a one-way manner: Whereas the building's performance is assumed to be influenced by external conditions, the microclimate is not commonly assumed to be influenced by the building, or a possible influence is assumed to be small enough to be negligible. Note that, strictly speaking, this is not the case: Buildings do influence their immediate surroundings, and large agglomeration of buildings can influence the urban microclimate [11–13]. Should such influences constitute the subject of inquiry (for instance, when analyzing the potential of urban heat island mitigation measures), insights can be gained via co-simulation of the pertinent processes at multiple levels, including individual buildings, neighborhoods, and whole urban districts [14,15].

As the transience of external boundary conditions is purely physical and uninfluenced by inhabitants, we can turn our attention back to the discussion of other dynamic processes that need to be captured in a simulation model. Short of retrofit and remodeling cases, a building's general shape, geometry, morphology, and basic construction does not change over the life cycle of the building. These aspects could be considered as fairly static and, with few exceptions, do not require for consideration of dynamic state changes in the simulation process: Whereas physical material properties such as the thermal conductivity and surface albedo of building envelope components are given in fix values in most routine simulation studies, they could – and, in detailed studies, should – be assumed to be subject to change. Such change may be simply the consequence of material aging and deterioration, or due to interrelated physical processes (e.g., impact of humidity accumulation in materials on their thermal conductivity). On the other hand, there are certain building elements and devices that do routinely and intentionally undergo distinct and consequential state changes. Obviously, this cannot be ignored in the simulation process. For instance, windows and shades could be opened, closed, or brought into intermediate states. Likewise, buildings' technical systems for indoor-environmental control are subject to dynamic changes of their states, which allows for the modulation of mass and heat transfer intensities.

These preceding observations clearly explain why it is important to include, in building performance simulation models, adequate representations of inhabitants: Dynamic changes in the state of buildings' adjustable building components control systems influence buildings' performance and they are essentially due to inhabitants. Changes might be brought about by inhabitants' direct actions (for instance when a window, a blind, or a light switch is manually operated), or via automated control systems that nonetheless are supposed to operate based on inhabitants' assumed or explicitly stated preferences. It is at this juncture, that a purely physical simulation process must integrate effects originating from and shaped by physiological, psychological, and social drivers of inhabitants' actions. A study of past practice reveals various levels of reductionism in consideration of these drivers. Simulation models display a wide range of detail levels in capturing the effects related to inhabitants, starting from simple schedules and rules all the way to agent-based modeling [16]. It has been argued that the choice of a proper level of abstraction should depend on the nature of the performance query and the purpose of simulation [17–19].

As alluded to before, the existing data schemes regarding occupant-related simulation parameters may sufficiently cater for purposes of basic simulation scenarios that target simple benchmarking and generate aggregated performance indicator values. But the same does not apply, when, for whatever reason, a more in-depth study is to be conducted to explore the impact of inhabitants' attributes, attitudes, and behavior on buildings' performance. Such highly-detailed studies might not be always necessary, but assuming they would be, two preconditions apply. One is of course the availability of empirical information about how and why people behave in specific ways [5,20], and the other is computationally useable ontologies for the formal expression of inhabitants' patterns of presence and behavior in buildings [8]. Note that inhabitants' behavior may be affected by multiple factors, including physiological and psychological needs and preferences, outdoor conditions, buildings' layout and amenities, affordance of outdoor spaces, and various organizational and social circumstances. The formidable complexity involved in these matters strongly implies the necessity for further efforts to effectively integrate high-resolution representations of inhabitants in performance simulation models. Specifically, explanatory theories of inhabitants' perception, evaluation, and behavior are needed, which, in turn, can support the formulation of robust and versatile ontologies that go beyond existing solutions [6,21–30].

The present contribution is motivated mainly by this need. It introduces a high-level behavioral theory of occupants' control-oriented actions in buildings. Furthermore, the utility of this theory for ontological developments is illustrated through a derivative representational scheme, which we label as "otto" (Occupants Theory-Tailored Ontology). The established continuity between a general-purpose behavioral theory and the derivative data schema represents the key contribution of the effort and is suggested to provide the necessary conditions for the development of a comprehensive ontological framework toward representation of inhabitants' presence and behavior in the built environment.

Note that the proposed theory is not suggested to represent a predictive model of human behavior. Nor is it suggested to have been validated – or even could be validated – in a manner that physical theories can be, in principle, validated. Rather, the theory is suggested to offer a consistent framework for behavioral narratives that allow for systematic definition of entities and classes in pertinent ontological schemes. Consequently, the categories inferred from the proposed theoretical framework are suggested to offer an adequate formalism for representation of a large class of control-oriented user actions in building, despite the potential semantic variations in interpretation possibilities pertaining to the motivational field of human behavior. However, the fact that the theory is not suggested to provide, at this stage of the inquiry, empirically testable predictions, does not imply that one cannot question the utility of the theory as the underlying platform for ontological developments. A straight-forward way to falsify the purported utility would be to show examples of reasonable behavioral narratives that cannot be formally accommodated within the derived ontological scheme. Our experiences so far point to a good coverage and relatively robust performance of the theory-driven scheme. The logical features underlying the structure of proposed high-level theory are suggested to account for the ontological classes necessary for behavioral representations. As such, the validity of the theory and the scalability of the schema cannot be suggested to have been conclusively demonstrated, and developments in future may well require, further adjustments to the theory and extensions to the schema.

2. About past efforts

Building-related existing data models and ontologies categorize and structure relevant information related to, for instance, construction components, building systems, and equipment. Note that, in the domain generally referred to as building information modeling (BIM) [31], the terminological distinctions between concepts such as models, schemes, and ontologies are not always defined precisely and consistently. For instance, mention of ontologies may be at times in a manner closer to the philosophical connotation of the word [32] and at other occasions in a more specific sense of reusability of schematic material [33]. The common general thread among these interpretations is the recognition of the importance of information organization. Whereas schemes with hierarchically defined classes and their relationships are primarily geared toward introduction of fundamental structure in a domain's informational resources, more specific views of ontology exploit their potential in cumulative multi-player model and code development. However, even this rudimentary semantic umbrella does not cover the interpretative variety and terminological ambiguity in the field. For instance, IFC (Industry Foundation Classes) [34], given its organization in terms of nested class objects with structured attributes and its inherent object-based inheritance hierarchy, could be arguably suggested to have an ontological character. Nonetheless, it is typically referred to as a data model. On the other hand, BRICK [21] is frequently labeled as a schema, even though it is formalized in ontological terms. Our perspective in this discussion, which is expressed in the “ontological framework” phrasing, focuses on the potential of ontologically structured information regarding fundamental building-related entities and processes for advanced downstream applications [35] such as building performance simulation.

As emphasized already in the introduction section of the present paper, it is also necessary to integrate detailed information on occupants in these schemas. Moreover, it appears necessary to develop extended ontologies and new schemes to support occupant-centric building design and operation. The existing data models and ontologies related to the built environment may fit different building life cycle stages. This aspect influences, together with a schema's primary scope, the choice of the kinds of occupant-related information that must be included in such models. For example, the aforementioned IFC refers to a data schema and file format used for creating digital descriptions of the built environment and related management and scheduling processes. Hence, it is mostly dedicated (but not limited) to the building design and construction phases of the building life cycle. This standardized information representation, is intended to facilitate seamless data exchange by different actors of the building process. This representation can be used in a variety of BIM-related software for modeling, managing, or simulating the built environment. The IFC data schema includes definitions of over 1000 entities, enumerations, and measure types that constitute the schema, namely the resource, core, interoperability, and domain specific architecture layers. Following the schema's specification, the real-world objects and actions such as building construction elements, building systems, construction schedules, or cost estimates are abstracted into entities with required and optional attributes, properties, and relationships to other entities [36]. The occupant representation in this data schema circles around an actor involved in the building project and carries, as such, certain basic information including name, address, contact details, and assigned role with regard to the relevant property [37].

Unlike IFC, which is considered an industry-standard data model for the construction and management process, the gbXML [38] is considered the industry standard schema for sharing information between BIM software and analysis tools. It is used to link a building construction model and related information (i.e., 3D and 2D geometry, construction elements and material properties, space boundaries, internal and external equipment, lighting systems and control) with building performance simulation tools. Therefore, the representation of the occupant in this scheme is a logical consequence of the types of occupancy-related information used by these simulation tools. For instance, in many routine thermal simulation applications, the representational focus lies in occupants' contribution to the internal heat gains, which is captured in terms of the occupancy count and associated occupancy schedules.

Most of the existing schemas and ontologies related to the operation phase of the building life cycle address the occupant-related information in a rather basic manner. For example, in the ontologies that cover sensor networks, internet of things, and smart homes such as SAREF [39], DogOnt [40], or the ontologies that cover building automation and monitoring such as Project Haystack [41]; Brick Schema ([21,42], occupant-related information is mostly limited to occupancy state, as recorded by an occupancy sensor, positioned in a specific location. Another example of the circumstance is the BuildingSync schema [43] (used to standardize energy-audit related data) whose extent of the occupant-related information is limited to personal and contact details.

The above-mentioned schemas face certain challenges when dealing with advanced high-resolution and dynamic building performance simulation applications (such as those involving agent-based modeling). These applications require the detailed representation of occupants' patterns of presence and behavior in buildings.

An instance of a schema that explicitly focuses on occupants is the occupant behavior XML (obXML) schema [24,22]. The obXML is an implementation of the DNAS framework [23,44,45]. As such, it attempts to capture occupants' energy-related behaviors in buildings. The four main DNAS framework components are: i) the Drivers of occupants' behavior (relevant environmental factors); ii) the Needs (both physical and non-physical) such as personal comfort requirements; iii) the Actions, i.e., any type of interaction with systems to satisfy needs; iv) the Systems, i.e., building's environmental control systems that can be interacted with. The schema allows to establish an occupant entity with basic information (name, age, gender, etc.), situate an occupant in a spatial context (building, space), and assign details regarding the aforementioned drivers (e.g., environment – indoor temperature). The drivers trigger needs (e.g., physical – thermal – ISO adaptive comfort), which in turn determine the probability of occupants' interaction with relevant building systems (e.g., Thermostat) [35].

The recent expansion of the DNAS framework [28], motivated by ABM-oriented application scenarios, provides a more detailed description of the occupants. This framework introduces four additional categories of occupant-related details, namely i) Socio-economic (census-related information); ii) Geographical location (information category that can help associate occupants with a location-specific energy use or comfort needs); iii) Subjective values (personal traits that might influence the probability of performing energy-related actions), and iv) Activities (relevant in case of needs not related to personal comfort but related to energy use). It is conceivable that further development of and additions to frameworks of the DNAS type would expand the level of coverage and degree of resolution with regard to behavioral scenarios. The question remains though, that if ontological development strategies in this area could obtain a higher level of efficiency and robustness if they would be grounded on explicit behavioral models, rather than on partial – e.g., questionnaire-based – datasets of stated opinions. The contention is that once a model discloses logical relationships underlying occupants' behavioral manifestations, these relationships can be deployed toward development of general-purpose ontologies, instead of relying on an ad hoc foundation that would not offer a compass for consistent amendments.

As the preceding brief review suggests, the importance of progress in the area of occupant-centric representations in BPS has been recognized and related efforts have been undertaken. However, as the last instance in the above listing suggests, there are multiple unresolved issues that pertain both to the aptitude of the underlying behavioral theories and the ontological translation of these theories to sufficiently versatile data structures for ABM. The relative stagnancy of computational representations of occupants in BPS has not been so much due to paucity of formalisms or data, but is rather mostly a consequence of insufficient progress in theory-driven schema development efforts. In other words, major qualitative progress appears to necessitate that ontological development processes establish continuous mapping processes from the logic of behavior theories to specifics of data scheme entities. Another way to look at this challenge would be to recognize that most existing efforts in this area (a number of which were alluded to in the previous appraisal above) display a partial bottom-up approach, in that ontological solutions are sought for existing occupant-related data requirements of simulation models. This approach leads to an incremental – and frequently ad hoc – set of adjustments when extensions of such data requirements are deemed necessary. This approach may be capable of fixing emerging problems on a short-term basis. However, making top-down use of the compass of a general-purpose theory of behavioral patterns (instead of starting with legacy input data formats of existing simulation models) is more likely to keep the ontological development on a consistent track, and thus making it more effective in the long run.

Given this state of affairs, the effort and approach described in the present contribution is not suggested to provide a finalized ontological solution for the existing gaps. Hence, substantial additional work will be necessary to operationalize the proposed ontological framework and translate it into implementation-ripe code [7]. This would require, as in other similar areas of development, iterative, cumulative, and collaborative efforts. Rather, the objective here is the paradigmatic initiation of a systematic effort toward theory-driven development of an ontological framework that can serve as the basis of detailed, consistent, and high-resolution representations of occupants in computational building performance assessment applications. Accordingly, we present in the remainder of this contribution a specific theory-driven approach toward the construction and implementation of an occupants theory-tailored ontology ("otto") that would cater to the informational requirements of advanced modeling applications (specifically, agent-based modeling) in building performance simulation.

3. Reflections on the nature and scope of inhabitants' behavior

As previously argued, the appropriate resolution level of inhabitants' models must be judged based on the nature of the performance query at hand [17–19]. Let us assume that there exist some queries that would necessitate modeling inhabitants in detail as perceiving and acting agents. This raises an immediate question: Do we have, from the computational modeling standpoint, the necessary ontological means? The preceding review of the state of the art (see section 2) implies that ABM efforts in this area cannot fully rely on the existing ontological frameworks to sufficiently capture the representationally necessary detailed information on human agents' attributes, attitudes, and behavior. One way to weigh, not only the effectiveness of the available schemes, but also to specify the features of the necessary ones, is to develop and refine ontological frameworks based on their capacity to formally capture the salient aspects of inhabitants' behavior.

To further elaborate on this point, consider a list of selected typical instances of different control actions by different inhabitants in different settings (Table 1). The assumption is that these actions influence the respective buildings in view of energy and/or indoor-environmental performance. Table 1 cites the actions, elaborates on the context in which they were taken, and includes a number of observations about possible motivation and reasoning. Most importantly, the illustrative cases in this Table provide pointers to ontologically relevant requirements. A first point of this listing is to highlight the multi-layered (contextual and motivational) complexity underlying even the most seemingly trivial control actions performed by inhabitants. More importantly, these illustrative cases exemplify, pars pro toto, the factors and circumstances behind inhabitants' behavior, and can thus help us examine two key questions. First,

Table 1
Illustrative selection of inhabitants' (referred to as P1 to P7) actions, together with note on context and explanatory observations.

Case	Action	Context	Relevant observations
C_I	P1 opens windows for cross-ventilation, and moves to an outdoor space.	Action occurs after P1 arrives home in the evening of a summer day.	Upon arrival, P1 feels that the rooms are somewhat warm and stuffy. After opening the windows for ventilation, P1 walks out into the shaded back garden to sit and enjoy a drink.
C_II	P2 turns on the air-conditioning for cooling.	Action occurs after P2 arrives in his apartment in the evening of a summer day.	Upon arrival, P2 feels that the rooms are overheated, and seeks an immediate cooling effect of air conditioning (P2's apartment does not have outdoor spaces).
C_IIIa	P3 switches the light on, opens the window, and turns down the thermostat.	Actions occur after P3 arrives Monday morning in a double-occupancy office; a co-worker (P4) is already present in the office.	P3, who generally prefers cooler conditions, does not consult the subordinate co-worker before his actions (social competence is not P3's strength).
C_IIIb	P3 closes the window and turns up the thermostat.	Actions occur after P3 arrives in the office Thursday morning; a co-worker (P4) is already present in the office.	Recuperating from a flu, P3 still feels weak and cold, hence he reverses P4's prior actions (P4 had previously opened the windows and adjusted the thermostat anticipating P3's usual actions).
C_IV	P4 opens the blind and switches off the light.	Actions occur after P4 arrives in a double-occupancy office after lunch, and notices P3 (the superior co-worker) is not present.	P4 is an energy-conscious individual: Given P3's absence, she seizes the opportunity to open the blinds and let the daylight in, making thus electrical light unnecessary.
C_V	P5 opens the windows to close them again after 15 min.	Action occurs after P5 arrives in the morning of a winter day in her single-occupancy office.	P5 is not indifferent to energy wasting, and the room does feel neither warm nor stuffy, but P5 has a habitual preference for fresh air, even if the cold air produces a momentary thermal discomfort.
C_VI	P6 moves from one room to another room in the same building.	Action occurs mid-day, when P6 leaves her shared office and moves to a – currently vacant – meeting room.	P6 finds the thermal and acoustic conditions increasingly uncomfortable, a temporary move to the cooler and quieter meeting room functions as a successful adaptive measure.
C_VII	P7 takes off his jacket and turns on the desk fan.	Actions occur in the open-plan office after lunch early afternoon.	P7 feels conditions as rather hot, however opening the windows or changing the thermostat settings is not an option.

are we ontologically equipped to map such behavior onto respective repertoires of human agents, for instance, in building-related ABM applications? Second, do we have, at our disposal, a theoretical framework to explain inhabitants' manifest behavior that can facilitate respective narratives for ABM purposes?

With regard to the first question, a brief consideration of the illustrative cases of Table 1 can be instructive. This table entails a selected number of actions by inhabitants in indoor-environmental settings. Obviously, this list is not meant to be either comprehensive or exhaustive. Rather, it represents samples from a larger corpus of typical – control-oriented – inhabitants' actions and thus allows for the demonstration of circumstances that a general-purpose behavioral model would need to cover. Note that, in all cases included in this table (C_I to C_VII), the affordances perceived by the inhabitants must be represented. The set of these affordances may be divided into different constitutive categories. To this end, we can follow a logical analysis path and consider the categories of information required to generate the constitutive (physical) entities of a simulation model, that is the spatial layout and amenities, building components and systems, indoor-environmental conditions, and the presence of occupants. These categories are described in more detail in the following:

i) Spatial layout and amenities: In all cases of Table 1, inhabitants are assumed to be familiar with the spatial conditions. Specifically, in case C_I, the inhabitant P1 is aware of the utility provided by the accessible outdoor space. It can be assumed that people starting to live or work in a new environment must go through a learning and familiarization phase. There are many other cases, where inhabitants, instead of changing the conditions where they are, would move to another, indoor-environmentally distinct space that better suits their needs (see case C_VI). Note that BIM (Building Information Modeling) can provide an ontologically structured representation of the underlying physical (objective) aspects of this category, but not their agent-specific views. Likewise, performance simulation can reveal indoor-environmentally relevant differences among different rooms of a building, but sophisticated comfort models are needed to arrive at agent-specific views on the quality of these rooms. Note that the hypothesized combined effects of multiple environmental stressors (consider the thermal-acoustic exposure situation in case C_VI) further complicates the development of versatile comfort models.

ii) Building components and systems relevant to indoor-environmental control: In all cases included in Table 1, the assumption is that inhabitants are aware of existence, location, and functionality of control components and devices (including their user interfaces), such as windows, blinds, HVAC equipment, and user-based equipment (e.g., desk fan in case C_VII). Also, in this case, an extended BIM offers the ontological placeholders. However, agent-specific views (perceived affordances) of these entities require further ontological developments.

iii) Prevailing indoor-environmental conditions: In computational processes, values of relevant indoor-environmental performance indicators (e.g., temperature, relative humidity, illuminance) can be generated via simulation. Representation of such data is well understood. The translation of such objective indicators into subjective quality attribution is typically carried out based on psychologically and/or physiologically-based comfort models. As such, the main motivation behind most of the actions included in Table 1 is the perceived discomfort. Note that in this area, the challenges are not so much in the ontological realm: For instance, the distance to assumed comfort zones (i.e., the perceived level of discomfort) could be treated as the driving force behind inhabitants' control actions. Rather, the remaining challenges in this area pertain mostly to the reliability of comfort models and the availability of large-scale data for model validation. Moreover, in a number of instances (see, for example, the actions of P4 in case C_IV and P5 in case C_V), the behavior is motivated by factors other than the immediate perception of personal discomfort, for instance when inhabitants may be considerate of other people's needs or when other values (e.g., health, energy consciousness) override, at least on a short-term basis, immediate comfort considerations.

iv) Presences of other agents and gauging their standing and expectations: The presence of multiple human agents in the same physical domain complicates the formulation and application of behavioral models (see cases C_IIIa, C_IIIb, and C_VII in Table 1). Both the domain knowledge and the ontological developments in this area require further research and development work.

Regarding the second question above (availability of adequate theoretical models of inhabitants' behavior), a possible solution was proposed in previous research [6]. Thereby, we discussed the role and capacity of perception and behavior models to offer an explanatory framework for inhabitants' control-oriented behavior and hence guide respective ontological developments. A key motivation behind the theory was to work toward a framework that is capable of covering multiple scenarios of human behavior in buildings, as opposed to segments of customized theoretical regularities that would fit specific scenarios. Past review efforts have indeed provided the impression that a multitude of existing socially and psychologically relevant theories are conceived in a manner to provide conceptually fits to specific settings [46–54]. This circumstance is manifested in part in the diversity of the selected sub-sets of independent variables that cannot be simply synthetized in terms of a more general-purpose theory [55]. Note that the theoretical framework put forward in this paper is not suggested to be either exhaustive in coverage or fully operationalized. Nonetheless, it provides a suitable testing ground for the viability of the behavioral narratives it can generate. Specifically, the theory provides a basis for the construction and examination of an ontological framework for the computational representation of the kinds of control-oriented actions exemplified in Table 1. The outline of such a theory is provided in the following section of this contribution (section 4). The derivative ontological schema is presented in section 5.

4. Outline of a behavioral theory

As argued previously, ontological developments of human agents' representations in building performance simulation can benefit from an underlying theoretical framework. However, there is arguably still a gap between the multitude of behavioral theories in human sciences [55] on the one side and technical applications in engineering domains on the other side. To address this issue, Mahdavi et al. [6] introduced a pragmatic theory that is suggested to provide an adequate conceptual scaffolding for the development of ontologically robust models of control-oriented human behavior in buildings. The intellectual background and roots of the theory cannot be covered here in exhaustive detail, as it involves a selective synthesis of a number of preceding conceptual developments [5,56–63]. Moreover, a more detailed description is provided in previous publications [6,8]. Hence, the theory is presented here in a terse fashion, using the simplified schema of Fig. 1 and the explanatory remarks of Table 2.

The theory distinguishes between the human agents and their surrounding world. Whereas the former is characterized by its "ecological potency" (EP), i.e., the human agent's physical and cognitive capabilities in dealing with the surroundings, the latter is characterized via its "ecological valency" (EV), i.e., the totality of the surrounding world's attribute as relevant to the human agent(s) interests, needs, and requirements. The theory assumes that the surrounding world (specifically, its EV) is mentally mapped in terms of a primary representation of the affordances [56,57,61]. The cognitive process involves also a kind of meta-mapping [64], resulting in the representation of the agent's "self" and his/her awareness of situatedness in the environment. The agent's mind entails a history of "experience and knowledge", which facilitates the detection of the affordances and contributes to the evaluation of behavioral options. Moreover, the agent can be assumed to be conditioned by a set of "beliefs and norms", which can constrain the space of these behavioral options. Human agents' conscious behavior serving short-term and mid-term regulatory functions may be suggested to be influenced by the value-driven assessment of the agent's current state with regard to alternative future states that could be preferable [65]. Note that, actions are not always triggered by the desire to leave negative (e.g., painful and uncomfortable) states behind. Actions can be also motivated by the promise of transitioning to positive (satisfying, pleasurable) states [6].

Before actions are executed, they may be virtually enacted by the agents, thus assessing their potential toward achieving the desired states. This process is supported by the perceived affordance, knowledge and experience repository, and beliefs/norms supervision. Actions could be "habitual", i.e., automated versions of previously conscious behavior, or they could be "reflexive", i.e., mostly biologically driven responses to specific stimuli. The theory also postulates the notion of "deferral mechanisms", which denotes delaying or abandoning the planning/execution of actions due to factors such as distraction or cognitive occupation.

The proposed theory has not been operationalized to the degree that would render it amenable to empirical testing and falsification. However, the theory's basic applicability and scalability could be examined and demonstrated via a large set of practical human-building interaction scenarios (operation of windows, blinds, luminaires, and thermostats) of the kind exemplified in Table 2 and analyzed in the context of corresponding thought experiments [6]. The outcome of the thought experiments demonstrated that, while reports of inhabitants' actions on their own do not yield insight into their underlying logic, combining these with information regarding both the ecological potency of the occupants and the ecological valency of their offices facilitates the formulation of plausible explanatory narratives, that could support ontology development efforts.

The theory views control actions mainly as the consequence of the perceived discrepancy between the existing conditions and the preferred (value-driven) ones. Given the dependence of these preferences on agents' ecological potency, they are subject to considerable inter-individual variance and can change over time. Control actions without a conscious regulatory intention may be in the habitual category. The need for engaging in an action may not be acted upon due to social and cultural circumstances as well as individual beliefs and norms. The execution of actions may be also delayed or even abandoned due to the aforementioned "deferral mechanisms". The theory also highlights the importance of perceived affordance in conceiving and executing control actions. As suggested before, the proposed high-level theory of control-oriented human behavior in buildings was motivated by the need for a more de-

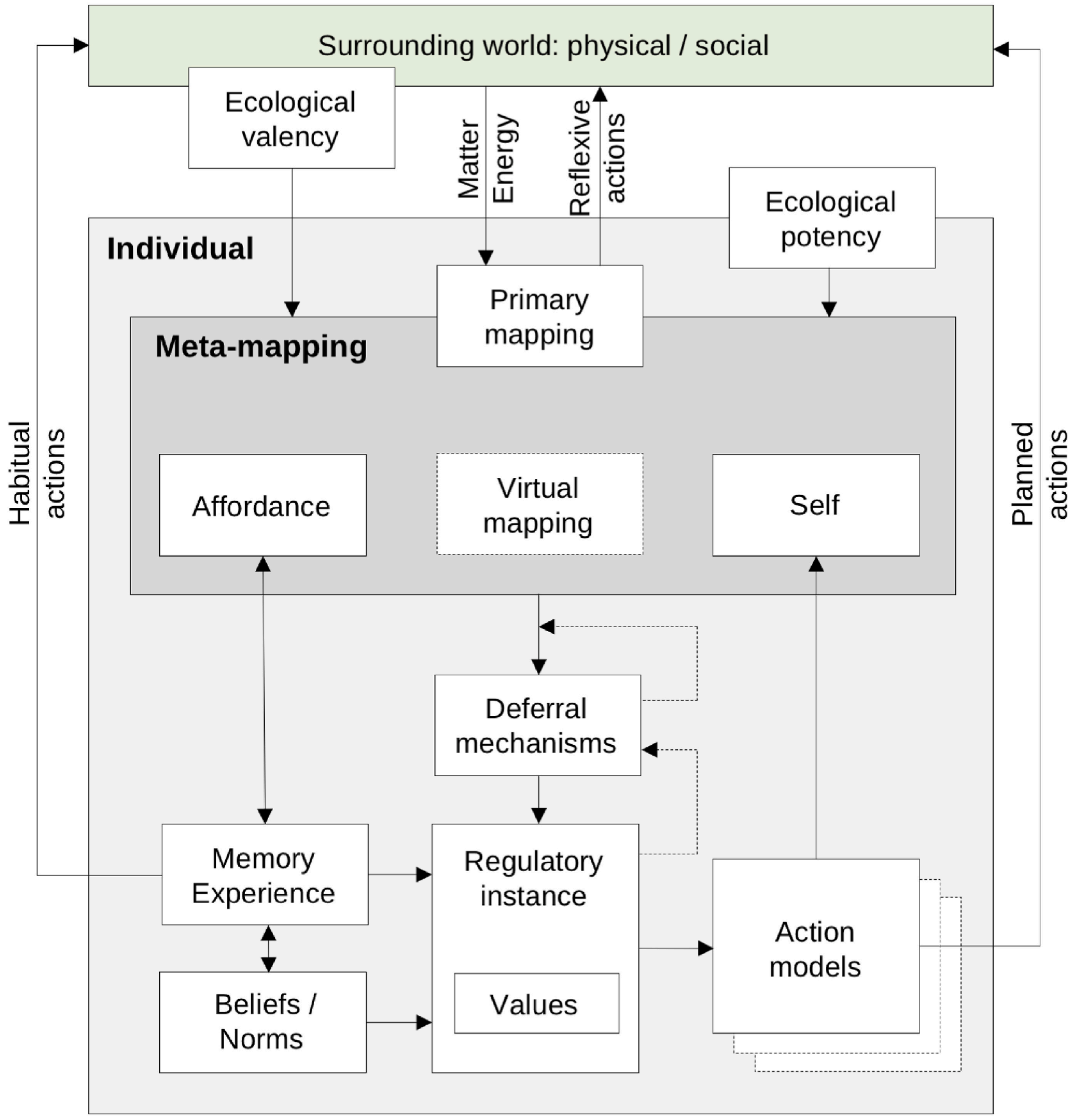

Fig. 1. Schematic representation of the constituent elements of the pragmatic theory of occupants' control-oriented actions in buildings (based on [6]; with modifications).

tailed, dynamic, and realistic representation of inhabitants in building performance simulation, or, in other terms, the need for a general ontology of occupants' control-oriented behavior in buildings.

5. An ontological scheme for the representation of inhabitants

5.1. Introductory remark

Certain ingredients of the behavioral theory [6] discussed in the previous section can be captured via existing ontologies and need not be treated here in detail. For instance, to represent the physical aspects of the built environment (the relevant segment of the surrounding physical world), there exist mature computational solutions in terms of IFC and BIM applications [31,34]. As such, BIM can capture the physical components of the surrounding world's ecological valency, which cover:

i) Building geometry and construction;
ii) Spatial layout and functional organization;
iii) Furniture, equipment, and appliances;
iv) Operable building components (e.g., windows, blinds, doors);
v) Buildings' environmental control systems (including all involved equipment, networks, terminals, actuators, sensors, etc.).

Table 2
Explanations of the key concepts of the behavioral theory (see Fig. 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, terrasses, 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.

However, as previously argued (see sections 1 and 2), the representation of human agents in BIM and BPS can benefit from advancing the state of ontology development in this area: The existing representations of human agents and their attributes (specifically, the attributes of their ecological potency) are still rather rudimentary. Likewise, current representations of the agents' surrounding world in terms of the above-listed physical entities cannot explicitly address agents' perceptions of these entities, that is, their affordances. Consequently, ontologically speaking, the proposed methodological approach can effectively respond to the need for mapping the elements of the ecological valency entities into corresponding or "mirror" classes of individually operative affordances. This implies that:

a. Indoor and outdoor spaces associated with a building need to be mapped to the inhabitants' conceptions of these spaces as spaces or zones affording various opportunities (working, regeneration, interaction with others) with specific functional and environmental attributes;
b. Control devices and systems of a building need to be mapped into respective interfaces (manual, mechanical, digital), whose affordances can be recognized by inhabitants such that they can be operated and thus bring about desired changes in the indoor-environmental conditions;
c. Physical information on the indoor environment needs to be mapped into subjective assessments of the level of comfort and acceptability.

From these observations, we can conclude that multiple layers of ontologically structured information must be provided to the "regulatory instance" element of the schema (see Fig. 1), which is expected to support computational predictions of agents' behavior. It is thus necessary to explore how information in these layers can be ontologically structured.

5.2. Elements of the ontology

The preceding discussion underlines the importance of having, at our disposal, a multi-layered ontological schema to represent salient information on inhabitants' attributes and requirements in the context of building performance simulation. Fig. 2 provides a

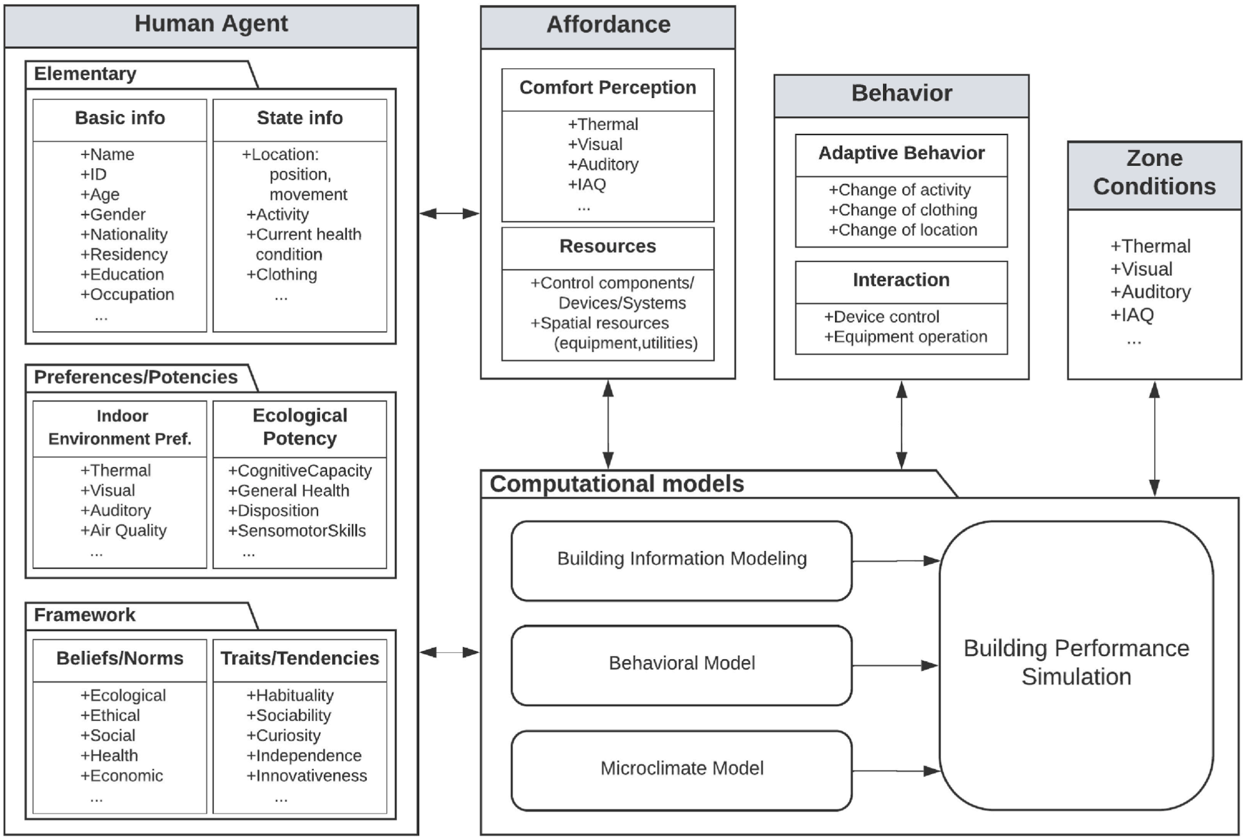

Fig. 2. Illustrative depiction of the elements of an ontological scheme to facilitate the structured representation of human agents in building performance simulation.

compact overview of the key elements of a proposal for such a schema. The schema is organized around five components or categories. Three of these categories are directly related to human agents (inhabitants), referred to here as the "elementary" category, the "preferences/potencies" category, and the "framework" category. Most items in the elementary categories (particularly the basic information items) are typically present in general data input schemes for building-related performance assessment applications and hence need not special explanation. However, the item "current health condition" in the sub-category "state information" (see Fig. 2) already exemplifies a time-dependent derivative of the "ecological potency" concept in the theoretical framework (see Fig. 1). Detail modeling – using, for instance, ABM formalism – of a scenario such as the one depicted in case C_IIIb (see Table 1) requires information regarding P3's ecological potency (an attribute coined in the theoretical framework) which is then mapped to the ontological scheme as an item in a sub-category of the ontological schema. Note that, viewed as a more general – mid-term and long-term – trait, health state, along with attributions such as cognitive capacity and sensorimotor skills are explicated entailed in the sub-category ecological potency of the preferences/potencies category (see section 5.4 for further reflections on the dynamics of the category attributes).

The fourth category, namely the "affordance" category (see Fig. 2), represents a central instance of the aforementioned theory-to-ontology mapping. It pertains to inhabitants' view of the buildings' ecological valency and is a key consequence of the meta-mapping process postulated in the theoretical framework (see Fig. 1). As such, it entails two sub-categories: The "comfort/perception" sub-category represents inhabitants' real-time perception and evaluation of indoor-environmental conditions. Representations of multiple illustrative scenarios in Table 1 relies on the ontological mapping of this theoretically established perceptual process (see, for instances P1 in case C_I, P2 in case C_II, P6 in case C_VI, and P7 in case C_VII). The "resources" sub-category represents what is seen as recognized opportunities in the built environment toward improving the perceived conditions. The previously discussed theoretical framework (see section 4 and Fig. 1) suggests that the value-driven differentiation between as-is (perceived) and desired conditions constitute the general motivational field for conceiving and implementing control actions. However, this process unfolds in the context of perceived opportunities. These opportunities may involve spatial resources (e.g., outdoor spaces, differently conditioned spatial zones) as well as means of adjusting indoor-environmental conditions (e.g., buildings' control elements, devices, and systems). The latter set of opportunities represent both a key concern of the theoretical framework (see section 4 and Fig. 1) as expressed in terms of perceived ecological valency or affordance and a derivative component of the proposed ontological schema (see Fig. 2). Inhabitants' awareness of indoor-environmental opportunities often correlates with the familiarity of the user interfaces of control devices and systems. From this perspective, buildings can be categorized in view of the degree to which they provide control possibilities to the inhabitants. However, the degree to which inhabitants can utilize such possibilities depends both on the quality of the provided device user interfaces and the inhabitants' knowledge about their existence and functionality. The “resources sub-category” in the “affordance category” provides the principle ontological vehicle for modeling purposes (see section 5.2.4. and Fig. 2). Related issues have been addressed in more detail in previous publications [66].

Finally, the fifth category of manifest behavior pertains to the different kinds of inhabitants' actions, which are assumed to be of relevance to buildings' performance and are meant to be predicted in the course of behavior modeling. Instances of such behavior include adaptive behavior (e.g., change of clothing, activity, location) and interaction behavior (e.g., operation of control elements/devices and use of equipment/appliances). Note that, when representing inhabitants' control-oriented actions in building performance simulation, different levels of detail can be implemented. As it has been discussed in other studies, the appropriate level of resolution may be suggested to be a function of the relevant performance query [17–19]. Inhabitants' presence and actions may be represented in terms of simple schedules or rules, or in terms of advanced stochastic formalisms. The point is that, whereas a detailed ontological vessel can be simplified to capture scenarios with low level of detail, the reverse is not true. Hence, application scenarios involving stochastic routines or ABM are more likely to require correspondingly detailed theoretical assumptions and derivative ontological schemes.

The elements of the ontological scheme are further elaborated upon in the following (sections 5.2.1. to 5.2.5.). The conceptual relationship of these elements to the deployment of computational models and the bi-directional of information flows are also schematically indicated in Fig. 2.

5.2.1. The elementary category

The elementary category entails types of information about agents that serve the purposes of identification and general classification. Certain items in this category may serve as proxies for more specific information, which can be distilled, for instance, from demographic repositories or from the typology of the buildings the agents occupy at a given point in time. This category can be assumed to encompass two sub-categories:

- The sub-category “basic information” refers to a fairly standard component of the ontologies concerned with human agents. This sub-category entails items such as IDs (Identifiers), as well as the agent's name, gender, nationality, and date of birth (DoB). This sub-category can also include information on the agents' educational background (including technical skills), occupation, and location/residency.
- The sub-category “state information” refers to dynamic variables that pertain to the agent's state in view of location (position, movement), activity, clothing, and current health condition.

5.2.2. The framework category

The framework category is postulated to account for the fact that inhabitants' conscious decisions are not made in a vacuum, but are influenced by human agents' beliefs, character, and needs. Accordingly, two sub-categories in the framework category appear to be specifically relevant to the case of human agents' control-oriented actions:

- The sub-category “beliefs/norms” pertains to psychologically and socially relevant beliefs, convictions, and norms. This sub-category includes ecological values (attitudes toward energy, greenhouse gas emissions, environmental protection) and partially related ethical values, personal values concerning health consciousness, self-discipline, social values (courtesy, fairness, hierarchy), and economic values (relevant, for instance, to the monetary consequences of actions).
- The sub-category “traits/tendencies” pertains to the agents' behaviorally relevant psychological traits and tendencies. Expressed in qualitative terms of bipolar scales, instances of attributes in this sub-category include: strong versus weak habit development tendencies, extrovert versus introvert, proactive versus reactive, curious versus disinterested, leader versus follower, and innovative versus uninventive.

It is worth mentioning the standing of these two ontological sub-categories anticipated implicitly in the broader context of the underlying theoretical framework, as this can provide yet another argument for the essential role of the theory-to-ontology mapping approach. As illustrated in Fig. 1, the regulatory instance responsible for inhabitants' planning of conscious behavior is activated by a value-driven gradient (e.g., perceived versus desired conditions) and consequently generates the behavioral option space (corpus of possible actions with the potential to resolve the gradient). From the behavioral theory perspective (see section 4), the aforementioned two sub-categories can be interpreted as performing a filtering function in the emergence of the corpus of actions. Roughly speaking, the “traits/tendencies” acts as kind of a priori filter, preventing certain (logically conceivable) options to be generated in the first place. The “beliefs/norms” sub-category acts as a kind of a posteriori filter, excluding certain generated options from the final candidate set for execution, despite the agent's awareness of their existing potential.

5.2.3. The preferences/potencies category

Agents' behavior can be influenced by different sets of preferences, depending on the applicable behavioral domain. Moreover, agents' ecological potency constraints the scope of possible behavioral manifestations. Given the present concentration on indoor-environmentally relevant control behavior, the sub-category of specific IEQ (Indoor-environmental quality) preferences and needs is of essential importance. The focus of this category lies in the inhabitants' stated (or derived) general preferences in terms of the thermal, visual, auditory, and air quality conditions in buildings. Items in this category are as such directly – perhaps even causally – relevant to inhabitants' emergent control-oriented behavior. Inhabitants of buildings can of course have preferences and needs in other areas, including accessibility, ergonomics, information technology, amenities, etc. The ecological potency sub-category covers agents' cognitive capacity, general health disposition, and sensorimotor skills.

5.2.4. The affordance category

A central question concerning inhabitants' control-oriented behavior concerns the motivation behind and the means for control actions. Discussing this point provides also a further useful case in point for the illustration of the previously postulated need for the critical relevance of the theory-to-ontology mapping approach pursued in our contribution. In our discussion of the cornerstones of the proposed general-purpose behavioral theory (see section 4 above), we argued that control-oriented actions are frequently motivated by the perceived discrepancy between prevailing and preferred conditions. The means, on the other hand, can be suggested to be the recognized affordance (a derivative of the surrounding environment's ecological valency). Accordingly, the affordance category must address inhabitants' perception of indoor-environmental conditions, and the spatial and technical opportunities they have at their disposal. These observations imply the representationally relevant need for the following two sub-categories:

- Comfort perception: Physical conditions in indoor environments can be computationally emulated (i.e., using simulation) based on information on the building and context. Subsequently, this information must be fed to the appropriate comfort models to approximate inhabitants' perception of IEQ. Note that existing comfort models are typical single-domain (e.g., thermal, visual, acoustic, air quality) [67–69]. Ongoing work toward the formulation of multi-domain models has not yet produced practically deployable tools [70].
- Resources: Inhabitants may identify two types of opportunities for improving IEQ. We can refer to these as adaptive versus active. Whereas the former pertains to the inhabitants themselves (e.g., change of clothing, change of activity), the latter involves the exploitation of the available spatial and technical resources. Specifically, inhabitants may make use of buildings' control components, devices, and systems or they could seek alternative spatial zones (if available). Representationally speaking, the ontology must account for human agents' awareness of the distinct spaces/zones in the building (including their conditions) as well as their knowledge of the availability and effectiveness of the said control components, devices, and systems (including their user interfaces). In this case too, BIM and BPS can provide objective information on ecological valency. However, agents need to be aware of the existence and functionality of the related entities in terms of perceived affordance. Given the fact that the proposed theoretical framework naturally accommodates the relevant affordance category, the mapping process to the respective ontological categories can be supported in a manner that is methodologically systematic and operationally scalable.

5.2.5. The category of behavior

In the process of computing the values of a number of occupant-centric dependent variables, ontologically structured information about human agents and their environment (that is, for the purpose of the present discussion, indoor spaces) may be viewed as the relevant independent variables. Focusing on the basic building performance categories of energy use and indoor environment, the computation aims at predicting agents' behavioral manifestations in terms of two sub-categories. The first sub-category of "adaptive behavior" includes change of clothing, change of activity (e.g., transitioning from working on a computer to a face-to-face meeting), and change of location (e.g., entering or leaving a building, or moving from one space to another). The second sub-category of "interactions" includes performing a control action (e.g., changing the thermostat setting of the HVAC system, opening/closing a window, switching on/off the lights), operation of equipment (e.g., computers, electronics), and use of appliances (refrigerator, oven, etc.).

5.3. Conceptualization of ontology

The ontological elements described above facilitate the initial schematic conceptualization of the proposed ontology as depicted in Fig. 3. This figure visualizes the logical relationships between the constituent concepts of the ontology, which were referred to in detail in section 5.2. above. Specifically, the initial conceptualization of Fig. 3 depicts concepts as classes and relations between the main concepts in terms of object attributes as data type properties, which results in an OWL-type (Ontology Web Language) representation of the model. The namespace "otto" refers to the elements of the proposed ontology. In accordance with the principle of ontology reuse, a number of concepts pertaining to the built environment, such as control devices, control systems, equipment, building elements, as well as building zones and spaces can be linked to other established building ontologies such as Brick Schema [42], The Smart Application REFerence (SAREF) [39] or Building Topology Ontology (BOT) [29,30]. Note that, as alluded to before, the proposed model and respective conceptualization, which is strategically focused on behavioral considerations, must be seen as the initial phase of an evolving undertaking. Hence, the specification depth of the attributes of various concepts are currently not at an identical hierarchical level. Consequently, to accommodate implementation requirements related to applications such as agent-based modeling would require further iterations toward enhanced representational resolution.

5.4. A note on dynamics of category attributes

The categories related to inhabitants (elementary, framework, preferences/potencies) and their entailed attributes may be viewed as relatively stable over time. In other words, the respective information about agents could be qualitatively described as more or less persistent or static. These attributes are not suggested to be fixed, and some are subject to learning processes, but their rate of change can be suggested – again, qualitatively – to have a rather slow pace. However, the realistic modeling of inhabitants' control-oriented behavior requires the consideration of real-time dynamics involved. To this end, the ontological categories must accommodate variables specifically envisioned to capture transient circumstances. Instances of such variables may be listed as follows:

- Current (present) state of physical and mental health.
- Current (present) activity, which can refer to the physiologically relevant metabolic rate as well as to the psychologically relevant cognitive load.
- Contextual awareness, which corresponds to affordance, i.e., the agent's perception of the building's ecological valency.

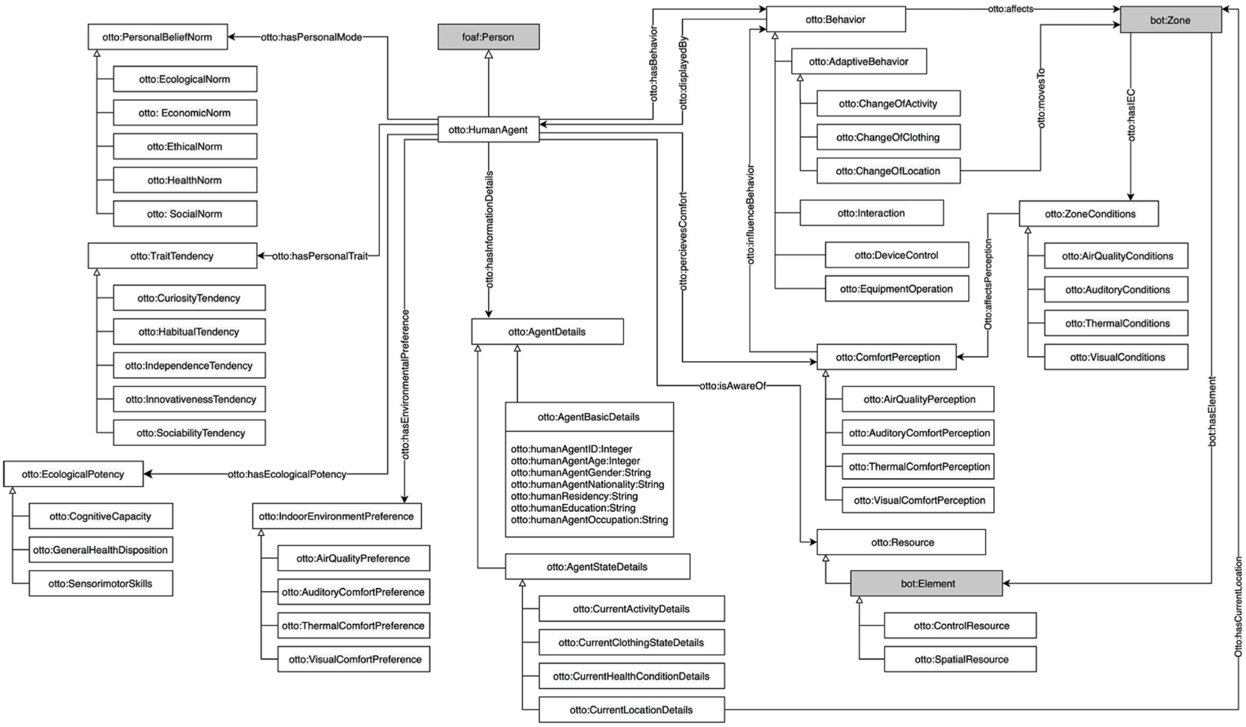

Fig. 3. Schematic conceptualization of the proposed ontology.

With regard to the last variable in the above list, note that the effective affordance is both a function of objectively available ecological valency, and the agents' knowledge of and experience with the existence, types, states, and interfaces of the building's indoor-environmental control systems. Moreover, the affordance is not limited to the knowledge of available means of control in a space, but includes also the perception of actually prevailing indoor-environmental conditions. This point must be taken into consideration since the prediction of an inhabitant's behavior at any specific point in time necessitates the knowledge of the prevailing indoor-environmental conditions at that specific time. It was noted previously that the mismatch between the agent's preferences and the prevailing conditions can be seen as the primary driver of control-oriented actions [6]. However, existing methods and tools in BPS are already in a position to capture the dynamic behavior of indoor-environmental conditions. Moreover, the ontological requirements for the representation of the respective variables are well understood (see, for instance Refs. [26,27,36], and do not require separate treatment in the present discussion.

6. Concluding remarks

The research and development work presented in this paper was intended to contribute to ongoing efforts toward more versatile representations of buildings' inhabitants in building information modeling in general and in building performance simulation in particular. To this end, we proposed an ontological schema whose elements are suggested to provide a proper basis generating well-structured representations of human agents in building-related computational applications. As it is the case with all classes of independent variables involved in building performance computing, one cannot postulate an absolutely valid fit-for-all level of representational resolution for simulation models. Existing occupant-related input data categories can be suggested to accommodate basic (aggregate-level) building performance queries. As such, the present contribution's focus was rather more on high-resolution models of inhabitants that would be appropriate, for instance, for agent-based modeling applications. A meaningful deployment of such applications requires individually customizable and highly dynamic representational formats. A review of the past efforts in this area implies the need for further ontological developments. Despite recent progress, the review of existing data schemes of the representation of inhabitants in simulation models suggest that such schemes represent, to various degrees, rather insular and ad hoc solutions, rather than frameworks that would effectively provide interoperability, consistency, and systematic collaboration. We argued that a fundamental contributor to this state of affairs concerns the insufficiently articulated high-level behavioral models that could act as the conceptual compass for developing adequate and scalable data schemes pertaining to the role of inhabitants in building-related computational applications.

To address this circumstance, we described the main features of a theoretical framework that was derived based on concepts in human ecology and cognitive science. The purpose of this theoretical framework is not to provide specific predictions of specific control-oriented actions by buildings' inhabitants. Rather, the objective was to provide the basis for generating the conceptual entities that could accommodate various narratives concerning inhabitants' behavior in indoor environments. The behavioral theory has been shown to successfully and flexibly capture a representative set of such narratives. Hence, ontological categories can be derived from the theoretical model, and the robustness of the model can be in turn tested based on how well it can account for the manifestation of inhabitants' behavior. As such, the methodology adopted by the contribution has led to the demonstration of a systematic theory-to-ontology mapping process. The resulting ontological scheme and its components were described and a partial conceptualization effort was presented and discussed. Note that the structure of the proposed high-level behavioral theory is arguably robust enough to cover rival lower-level – more detailed – explanatory ideas about the physiological, psychological, and social background and triggers of behavioral manifestations. Hence, derivative ontological categories and classes need not be substantially modified every time new data and findings from specialized disciplinary research emerge. For instance, revised ideas about the preferred ranges of indoor-environmentally relevant independent variables do not essentially alter the theoretical postulate, that larger deviations of as-is conditions from as-desired conditions increase the probability of control-oriented behavior. Likewise, technological developments in building control systems and their interfaces can be reflected in the operationalization of already existing affordance-related categories in the ontological schema.

The presented results are of course far from final: Considerable further developmental work is necessary to work out the details of ontology and render it ripe for implementation in BIM and BPS applications. Ongoing work in the implementation of the proposed ontological schema in agent-based modeling scenarios suggest that certain categories in the ontology (and the variables they entail) are not yet fully operationalized. Future progress in this area can be suggested to require two main types of efforts. One type pertains to the completeness or coverage requirements. This does not necessarily represent a fundamental intellectual challenge. Rather, practical issues emerging from the implementation of ontology-conform data structures may require extension and refinement of the items entailed in each of the categories of the proposed scheme (see Fig. 2). These refinements may be suggested to be of a linear nature, thus not requiring a fundamental rethinking of the underlying theoretical framework. The second type of needed work pertains to the actual operationalization of category items in terms of quantitatively expressible variables. This applies specifically to items such as beliefs/norms and traits/tendencies (framework category), indoor-environmental preferences (preferences/needs category), as well as perceived IEQ (affordance category). To this end, a frequently adopted approach involves the employment of qualitative scales. The challenge herein is not per se in the mapping of qualitative categories onto numeric values of a scale. Such mappings are indeed quite common, for instance, in psycho-physical research pertaining to human perception and behavior. Rather, and similar to many other areas that involve numeric scales, the challenge is to demonstrate the logical consistency (and the scientific reasoning underlying) of the process through which nuances in a specific category are mapped onto a numeric scale.

It would be perhaps most promising to address the considerable scope of these challenges via two parallel and complementary strategies. The first strategy shall pursue the progressive theory-driven extension and refinement of the proposed ontology's categories and variables on the one hand and explication of the scientific logic behind their operationalization on the other hand. As part of this strategy, an ongoing activity involves the preparation of an explicit declarative document involving the principles and rules that would warrant the theory-to-ontology mapping continuity as a formal and scalable process. The second strategy shall involve the ontology-conform computational implementation of agent-inclusive simulation models toward generating data (i.e., predicted types and timing of occupant actions in buildings) that could be compared with empirical (observational) data. Generation of such data based on data from real buildings facilitates the comparison of the predictions of the behavioral models with monitored data, providing thus the necessary condition for as well as the most effective means to improving the fidelity and reliability of such models.

Author statement

Ardeshir Mahdavi: Conceptualization; Formal analysis; Investigation; Methodology; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing., Dawid Wolosiuk: Conceptualization; Formal analysis; Investigation; Methodology; Software; Visualization; Writing - review & editing., Christiane Berger: Formal analysis; Investigation; Methodology; Software; Roles/Writing - original draft; Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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