A Pragmatic Theory of Occupants' Indoor-Environmental Control Behaviour

Mahdavi, Ardeshir; Bochukova, Veselina; Berger, Christiane

Published in:
Frontiers in Sustainable Cities - Urban Energy End-Use

DOI (link to publication from Publisher):
10.3389/frsc.2021.748288

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Mahdavi, A., Bochukova, V., & Berger, C. (2021). A Pragmatic Theory of Occupants' Indoor-Environmental Control Behaviour. *Frontiers in Sustainable Cities - Urban Energy End-Use*, *3*, 1-15. Article 748288. https://doi.org/10.3389/frsc.2021.748288

frontiers in Sustainable Cities

ORIGINAL RESEARCH
published: 25 November 2021
doi: 10.3389/frsc.2021.748288

Check for updates

A Pragmatic Theory of Occupants' Indoor-Environmental Control Behaviour

Ardeshir Mahdavi[1], Veselina Bochukova[1] and Christiane Berger[2]*

[1] *Building Physics and Building Ecology, Technical University Wien, Vienna, Austria,* [2] *Department of Architecture, Design and Media Technology, Aalborg University, Aalborg, Denmark*

Computational tools for building design and operation support entail fairly detailed representations of buildings' geometry, construction, and systems. Recent efforts aim at enhancing, in these tools, the relatively less developed models of building users. Thereby, one of the key challenges concerns the fit between the nature and level of needed support (e.g., performance queries) on the one hand and the required or appropriate resolution of the applied occupant model on the other hand. Some queries involving aggregate performance indicator may be sufficiently served by simple models of occupants' presence and actions in buildings. Detailed queries, however, may necessitate the implementation of high-resolution dynamic occupant representations. Methods to generate an occupant model may be fully data-driven, or they may be based on explicitly stated causal theories of human behaviour. However, there is not necessarily a sharp boundary between these approaches: Regularities harnessed by data-driven methods often reveal an implicit theoretical feature, as they are key to mapping processes from independent variables (model input) to dependent variables (manifest behaviour). Causal methods, on the other hand, need data to both develop and calibrate occupant methods. In this context, the present paper introduces the outline and main elements of a pragmatic theory of control-oriented human behaviour in buildings. The theory is suggested to inform the efforts towards construction of occupant models in computational applications related to building design, operation, and evaluation. Specifically, it can systematically guide the formulation of occupant-related ontologies and their instantiation in computational applications.

Keywords: behavioural theory, indoor environment, occupant actions, computational models, ontology

OPEN ACCESS

Edited by:
Marilena De Simone,
University of Calabria, Italy

Reviewed by:
Jiying Liu,
Shandong Jianzhu University, China
Saber Khoshdel Nikkho,
Affiliated Engineers, Inc, United States
Andrea Gasparella,
Free University of Bozen-Bolzano, Italy

****Correspondence:***
Ardeshir Mahdavi
amahdavi@tuwien.ac.at

Specialty section:
This article was submitted to Urban Energy End-Use, a section of the journal Frontiers in Sustainable Cities

Received: *27 July 2021*
Accepted: *01 November 2021*
Published: *25 November 2021*

Citation:
Mahdavi A, Bochukova V and Berger C (2021) A Pragmatic Theory of Occupants' Indoor-Environmental Control Behaviour. Front. Sustain. Cities 3:748288. doi: 10.3389/frsc.2021.748288

INTRODUCTION

In the past, the representation of building users in applications such as building information modelling (BIM) and building performance simulation (BPS) has been arguably rather reductionistic. Accordingly, a number of recent research efforts have been concerned with the resolution of representations of building users in simulation models. The aim of these efforts could be termed as the search for a robust approach to human information modelling (HIM) (Mahdavi, 2020b, 2022). However, there is still a lack of conclusive understanding of the scope and format of adequate occupant-related computational representations. Whereas it is generally agreed that the resolution of occupant-related representations must match the nature of the performance queries, there are no definitive methods available to identify the fitting levels of resolution (Mahdavi and Tahmasebi, 2016). Some queries involving aggregate performance indicators may be sufficiently served by simple models of occupants' presence and actions in buildings (e.g., presence schedules or rule-based approximations of occupants' actions). Detailed queries, however, may necessitate the implementation of high-resolution and dynamic occupant representations, for instance, *via* agent-based modelling.

Methods to generate an occupant model may be fully data-driven, or they may be based on explicit causal theories of human behaviour. However, there is not necessarily a sharp boundary between these approaches: Regularities harnessed by data-driven methods often reveal an implicit theoretical feature, as they are key to mapping processes from independent variables (model input) to dependent variables (manifest behaviour). Causal methods, on the other hand, need data to both develop and calibrate occupant methods.

There is of course a vast body of research and associated findings concerning human beings' perception and behaviour. Decades of studies in fields such as biology, physiology, psychology, neuroscience, human ecology, and sociology have generated much detailed knowledge about various facets of processes involved in how environments are perceived and assessed by human beings. These studies have also shed light on the nature of the processes involved in how people engage in interactions with the environment (Carpenter and Reddi, 2012; Yantis and Abrams, 2016). However, notwithstanding this formidable treasure trove of scientific output, there is a paucity of compact and coherent theories of human behaviour as relevant to the processes of perception and behaviour in built environments. This should perhaps not come as a surprise, given a number of obstacles, three of which are briefly addressed in the following.

First, these processes are utterly complex by nature. Arguably, even the—seemingly—simplest perceptual process (e.g., feeling draught in a room and linking that feeling with the state of an open window) and the most routine control action (e.g., closing an open window) require a vast machinery of sensorimotor and cognitive capabilities. The multitude of efferent and afferent neural elements in this machinery would have to be identified and invoked whenever a causal model is to explain or predict even the most basic instance of a perceptual process or a control action. To identify the model's salient independent variables (belonging to either the environment or the organism) amongst an extensive corpus of candidates that would have to be mapped to the end value of the model's dependent variable (e.g., a discrete manifest behaviour) represents a difficult challenge in and of itself. It would be even more difficult to come up with a generic procedure for such identification and mapping operations.

The second reason for the absence of a comprehensive explanatory model of inhabitants' behaviour is related to the first and is attributable to the well-known *divide et impera* approach common in the scientific process since at least nineteenth century. Scientific progress has been made mainly in that specific aspects and individual process of human perception and behaviour have been investigated within the confines of differentiated disciplinary domains. To aggregate and synthetize the respective results in terms of overarching explanatory theories suitable for practical applications is less likely to be seen and appreciated as the hallmark of modern scientific understanding in terms of specialised terminologies, ontologies, and investigation methods.

A final, third reason is also related to the first two. It is related to a specific and frequently wide divide between human and social sciences on the one side and to applied engineering domains on the other side. It is arguably in the nature of applied fields of design and engineering to look for rough and ready rules and prescriptions. Especially, by reverting to codes and standards, decision-making processes can be simplified and responsibilities—for instance, in view of possible liabilities—avoided. The distillation of domain knowledge down to codes and standards, however, does not necessarily represent a systematic and transparent process. The complexities, uncertainties, and—at times—inconsistencies of research result do not translate well into rigid code-based quality evaluation schemes involving, among other things, fixed minimum and maximum values of some designated design variable or performance indicator. It is thus not quite likely that any semblance of an implicit behavioural theory underlying domain knowledge would survive the standardisation process that results in common design and engineering codes and regulations.

These challenges underscore the need for further efforts towards formulation of accessible and practically applicable theories of human behaviour. Such theories have the potential to provide guidance, transparency, and structured reasoning in both fundamental scientific research and for applied engineering fields. They are necessary and relevant from the perspective of fundamental scientific research given their introduction of constructs that could be examined, confirmed, or falsified. But they can also support transparent methods to support design decision-making and operation optimization. Moreover, explanatory theories, with their demarcation of constructs, definition of dependent and independent variables, and description of causal relationships provide the requisite elements of domain ontology for the relevant field, that is, in this case, computational applications for building design and operation support.

Motivated by the above-mentioned observations, the present paper introduces the outline and main elements of a pragmatic theory of control-oriented human behaviour in buildings. We refer to this theory as pragmatic, in order to distinguish it from fundamental theories of human behaviour formulated in the more specialised domains of neuroscience or psychology. The proposed theory is referred to as pragmatic simply because it is primarily intended to inform current efforts towards construction of practical occupant models in computational applications related to building design, operation, and evaluation. A practically deployable theory of human behaviour has the potential to properly capture those aspects of human perception and behaviour that are relevant to building performance (e.g., energy efficiency, indoor-environmental quality). People's expectations and requirements mandate specific indoor-environmental conditions, and these very conditions are influenced by occupants' actions. The proposed theory is thus intended to facilitate a high-level mapping of perceptual and behavioural processes (Mahdavi, 2020a). Moreover, the theory is suggested to bear the potential to systematically guide the formulation of occupant-related ontologies and their instantiation in computational applications. An ontology can be seen as the necessary condition for a shared representation and operationalization of domain knowledge underlying, in the present case, computational models of people's perception of and behaviour in the built environments. Given the syntax character of the constitutive elements of the ontology, they may be developed and deployed in a manner that would be accommodating of a variety of theoretical expressions of the pertinent domain knowledge. The ontology developed on the basis of the proposed behavioural theory may be thus generally applicable, even if some of the theory's premises may be provisional, uncertain, or even mistaken.

The effort described in the present contribution is thus geared towards supporting the computational realisation of knowledge-based and ontologically promising models of occupants' presence, perception, and behaviour in buildings. Despite the wide scope of queries relevant to the building design and operation domain, it is conceivable that the multitude building information modelling and building performance simulation tools could all revert back to a common ontology, albeit with different takes in terms of coverage and detail. The proposed theory and a derivative ontology are not suggested to provide the ultimate solution to the formidable challenges discussed before. Rather, the objective is to offer the main features of an explanatory theory of people's control actions in buildings as well as the contours of an ontological approach for bridging the gap between high-level behavioural theories in human sciences and occupant representations in engineering applications.

THEORIES OF BEHAVIOUR AND THEIR APPLICATIONS

Introductory Remark

High-resolution representations of occupants in computational building models require more than the consideration of basic physical factors, such as occupants' emission of sensible and latent heat, and indoor air pollutants. Likewise, detailed representations would have to do more than simple rules and schedules in order to model occupants' interactions with buildings' environmental control systems. Especially the latter circumstance implies the need for consulting pertinent theories on human behaviour in general and their control-oriented actions in particular. A recent article attempted a review of a large number of behavioural theories assumed to be potentially relevant to people's behaviour in buildings (Heydarian et al., 2020). However, given the broad scope of this effort, it could not go into the details of the elements, logic, practical application potential, and ontologically relevant implications of each and every paper reviewed. Hence, rather than a longitudinal review, we focus here on four studies (Sections Energy Behaviour in Offices to Behavioural Changes in University Buildings), each of which includes references to a distinct behavioural theory. We reflect on the results of this examination of these studies (Section Reflections on Past Applications of Behavioural Theories in Building-Related Inquiries). Thereby, a key point of inquiry concerns the theories' potential to inform a shared ontological framework. Furthermore, we critically examine a previous effort to synthetize multiple theories as a basis for a common ontology of human behaviour in buildings. We conclude this chapter with an examination of implicit representations of human agents in common building analysis applications (Section Implicit Tool-Embedded Schemata).

Energy Behaviour in Offices

Lo et al. (2014) studied office energy-saving behaviours in four different organisations in the Dutch provinces Zuid-Holland and Limburg. Towards this end, they used an extended model of the Theory of Planned Behaviour (TPB; Ajzen, 1985, 1991; Fishbein and Ajzen, 2010), with perceived habit as an additional construct (**Figure 1**). The authors tested the reliability of TPB constructs and the relevance of the organisational context for predicting energy-saving behaviour. They examined actions by office workers regarding lighting and shading (i.e., switching off lights) and usage of appliances and electronics (i.e., printing and switching off monitors). The participants took part in an anonymous online survey concerning their energy consumption.

The TPB is an extension of the Theory of Reasoned Action (TRA, Fishbein and Ajzen, 1975; Ajzen and Fishbein, 1980). The TRA is aimed to predict volitional behaviours and suggests that a person's behaviour is determined by that person's intention to engage (or not) into an action. This intention is formed by the personal evaluation of the outcome of the considered behaviour, i.e., attitude towards the behaviour, and the personal perception of the social environment, i.e., subjective norm. The attitude towards the behaviour lies on the individual's previous knowledge and experience. The subjective norm mirrors the opinion of our significant others, whether they think we should perform the behaviour or not, and their behaviour in the past. The TPB introduces an additional construct to these of the TRA-the perceived behavioural control. This construct consists of the individual's judgment whether they are capable of performing a behaviour and in what extent or not capable at all, given resources, knowledge and skills. Some consider personal norm, i.e., our moral, as an additional construct of TPB, but it hasn't been officially introduced by Ajzen. After an intention is formed, this could result in performing a behaviour or not. It should be noted that not all intentions are implemented to an end, some become abandoned and other are being reconsidered since the physical and social environment is in constant change. If a behaviour is performed repeatedly, it eventually becomes a habit and is no longer involved in the described framework for forming a behavioural intention.

The particular study of Lo et al. (2014) combines the TPB constructs with habit and physical context to evaluate the collected survey data from the participants. Their findings suggest that everyday office energy-saving behaviour is significantly influenced by the physical context, e.g., organisation and availability of operational devices and electronic appliances.

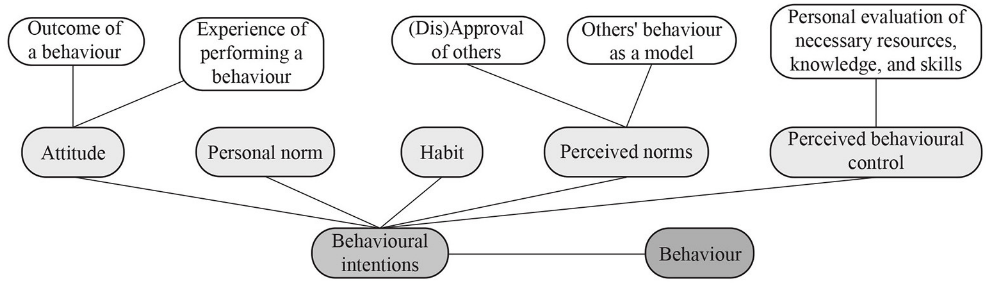


FIGURE 1 | Schematic illustration of the application of the theory of planned behaviour (based on Lo et al., 2014).

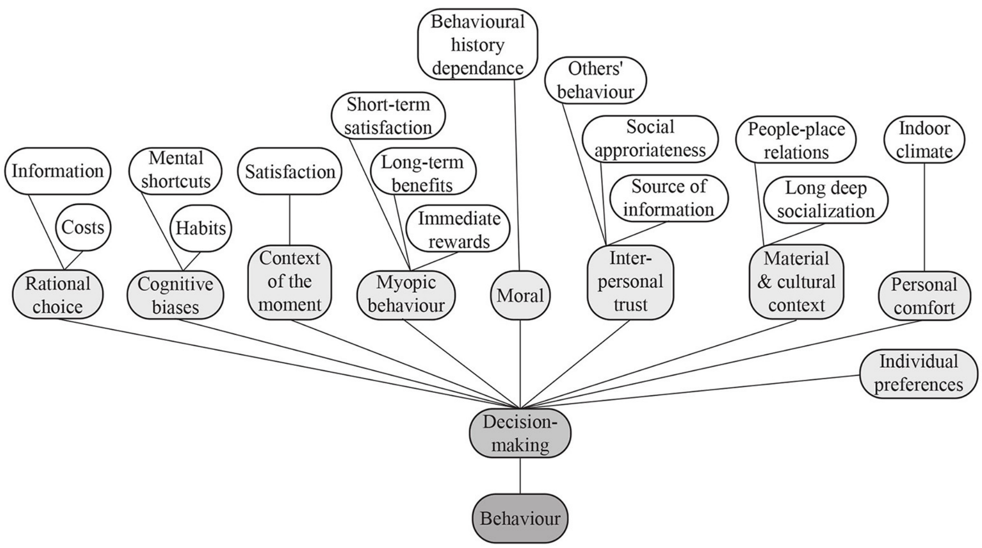


FIGURE 2 | Schematic illustration of the application of social practise theory and neoclassical economic theory (based on DellaValle et al., 2018).

Energy Behaviour in Social Housing

DellaValle et al. (2018) aimed to explain the gap between expected and actual energy performance of social housing buildings. To this end, a pre-retrofit survey was conducted among occupants. The collected data was analysed through the lenses of Social Practise Theory (SPT, Reckwitz, 2002; Shove et al., 2012) and Neoclassical Economic Theory (Simon, 1957, 1995) in order to identify the behavioural and social levers that would increase retrofit effectiveness (**Figure 2**).

The Neoclassical Economic Theory postulates that individual's decision-making process is based on rational choice, considering given information and costs. Behavioural economics add that mental shortcuts and habits support our choices, which then rely on cognitive biases. How far these will be considered in the decision-making process depends on the momentary context. Individuals are likely to demonstrate a myopic behaviour, considering the short-term satisfaction of their actions more valuable than the long-term benefit of these, as the first is closer in time. When investigating energy behaviour in social housing, this myopic behaviour is manifested, for instance, in the choice of electricity suppliers or devices. Our decisions are also affected by our moral norms. Individuals are usually tempted to be involved into immoral behaviour, even when we see ourselves as moral figures. Inconsistent behaviour could also be observed if the individual has been previously rewarded for a good behaviour, this typically results into a bad behaviour in another sphere. The social context of the situation is another important factor in the decision-making process. Interpersonal trust is formed by the behaviour of others', what they do and what they consider as socially appropriate behaviour, as well as their connexion to the individual making a decision. To conclude, through an economic lens of view, people's decisions and behaviour are affected by the momentary context and the cognitive biases it highlights.

The SPT is a group of theories previously announced by Bourdieu (1977), Taylor (1983), Giddens (1984), and others. Rules and norms, which are culturally and socially accepted, form social structures. An individual examines these social structures and learns what behaviour is previously recognised in the specific situation. The repetition of this behaviour eventually establishes a social practise, i.e., everyday action. SPT determines

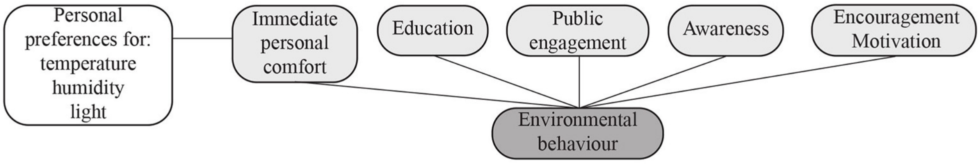


FIGURE 3 | Schematic illustration of the application of self-determination theory and maslow's hierarchal theory of needs (based on Al-Marri et al., 2018).

context (both material and social) as crucial for the decision-making process of an individual. Two main types of time-related context are distinguished: the one in which people grow up (long-deep socialisation) and the one in which they live (actual context). Examining these helps understand their energy-related behaviour and the potential to influence it. Social practises could be changed or newly formed, when new knowledge is collected. Both individual and group experience is needed, as well as understanding the need for change and the reason behind it, in order to initiate a social practise change. Housing energy use results from different practises (e.g., showering, cooking, heating), which satisfy the individual's preferences and bring about personal comfort. Understanding and investigating these everyday social practises is suggested to provide guidance towards more effective retrofit solutions.

Households, Behaviour, and Energy Use

Al-Marri et al. (2018) examined the energy consumption behaviour in Qatari households and the residents' views on renewable energy and sustainability. Two different methods were used to conduct the experiment: Quantitative data was collected from a survey among a large number of occupants and qualitative data was collected through interviews with energy experts. The participants' self-reported actions regarding windows opening and ventilation together with lighting and shading behaviour were investigated. To analyse and interpret the results, reference was made to the Self-Determination Theory (SDT, Ryan and Deci, 2000) and Maslow's Hierarchal Theory of Needs (Maslow, 1943) (**Figure 3**).

The SDT is a meta-theory that combines and develops previous findings and theories in the field of human motivation and personality. SDT defines intrinsic and extrinsic sources of motivation and their roles in individual's cognitive and social development, as well as in evolving individual differences. Personal interests, constant values, curiosity or care are intrinsic sources of motivation for performing a behaviour. These could be supported by extrinsic motives such as rewards, grades or others' opinion and support. SDT also focuses on the influence of social and cultural factors on individual's volition and initiative for a specific behaviour. SDT postulates that the individual's need for autonomy, competence, and relatedness are the three main psychological needs to satisfy while pursuing self-determination. These are directly associated with individual's motivation, quality of performance, persistence and creativity. Eventually SDT suggests that the individual's social context and its support (or more likely lack of support) for these three needs could have a strong impact on the individual's well-being.

Maslow's Hierarchal Theory of Needs is a psychological theory developed by Maslow (1943) and firstly introduced in his paper "A theory of human motivation." It distinguishes five levels of human needs and explains individual's motivation for performing a specific behaviour. The lowest level represents the physiological needs, the basic factors for a survival, such as air, water, food, rest, shelter, etc. The second level includes the safety needs: need for personal and financial security, need for health, wellness and safety against accidents. These two levels represent the basic needs. Once they are satisfied, an individual can move up to the third level, namely the social needs. Satisfying these needs involves having meaningful relationship with family, friends, and intimate partner, which create a sense of belongingness and acceptance in the individual. The fourth level introduces the esteem needs, which means need for accomplishment and respect. To gain self-esteem and feel worth it an individual needs others' appreciation and recognition of their behaviour. The last two levels described build the psychological needs. At the top of Maslow's Hierarchy are the self-actualization needs. These refer to the need of achieving one's highest potential, using creativity, talents and capabilities. Maslow suggests one other distinction of the levels of needs in his hierarchy. He calls the physiological, safety, and social needs deficiency needs. An individual is motivated to complete these in order to survive and avoid discomfort. The two highest levels: esteem needs and self-actualization are recognised as growth needs. An individual is motivated to satisfy these by a desire for personal development.

To conclude, both theories suggest that social engagement, awareness, and especially education, as well as motivation and encouragement could influence people's environmental behaviour and result into more sustainable energy consumption choices.

Behavioural Changes in University Buildings

Matthies et al. (2011) conducted an interventional experiment among university staff in 15 public university buildings in Germany. Different types of data were collected, including energy consumption, self-reported behaviour, and behavioural observation. Using the Norm Activation Model (NAM) (Schwartz, 1977; Schwartz and Howard, 1981), the information was analysed, an intervention program was developed, and

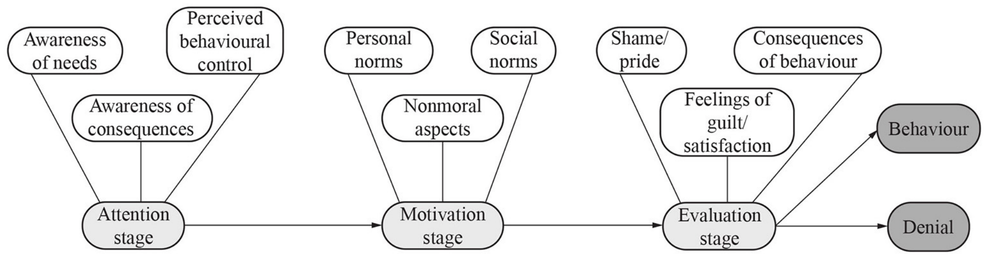


FIGURE 4 | Schematic illustration of the norm activation model (based on Matthies et al., 2011).

eventually behavioural changes regarding energy consumption were observed (**Figure 4**).

The NAM was proposed and developed by S.H. Schwartz and J.A. Howard in their works from 1977 and 1981. NAM is successfully and often used to explain prosocial, altruistic, and environmentally friendly behaviour. It distinguishes four stages of the decision-making process of performing or not a specific behaviour. The first stage, called the attention stage, is where the individual's perceived behaviour control makes them aware of their needs and of the consequences of the specific behaviour. In the second motivation stage personal and social norms, along with non-moral aspects (e.g., economical), are included in the decision-making process. During the third evaluation stage the collected information in the previous stages is being evaluated by the individual and the possible outcome of the specific behaviour is being judged. The fourth stage represents the individual's decision or denial to perform the specific behaviour. A denial of need, ability and/or control could be the reason why an individual denies performing the behaviour and this could result in a repetition of the four stages and reconsideration of the behaviour.

The NAM, as its name suggests, concentrates on the activation of personal norms. This was achieved, in the case of the specific experiment discussed here, through provision of information on environmental behaviour and its impact, together with rewarding techniques. NAM explains the conflict between personal norms and the social context. This sheds light on the question of why, in this case, fulfilling the expectations of colleagues and superiors leads to behavioural changes.

Reflections on Past Applications of Behavioural Theories in Building-Related Inquiries

The examination of the above instances of behavioural theory applications in building-related domains underline the previously voiced concerns. It could be argued that the theories themselves have not converged at a unified conceptual framework. This is in part understandable, as their development has been triggered by different contextual settings and different problem statements. Efforts to synthesise some of these theories into a unified framework have not been based on consistent and conceptually traceable steps. Rather, they appear somewhat *ad hoc* and eclectic in nature (D'Oca et al., 2017). It thus should not come as a surprise, when the applications of the theories, as exemplified in Sections Energy Behaviour in Offices to Behavioural Changes in University Buildings create a similar impression of disunity in concepts and constructs, and deviating layers of postulated causal relationships. These observations corroborate the perceived gap that motivated the top-down inquiry formulated at the outset of this contribution. The high-level behavioural theories and their applications in building-related settings have not resulted in comprehensive, consistent, and versatile ontologies towards shared representations of building occupants.

Note that somewhat comparable observations concerning the discontinuity of the approaches in sociology and engineering approaches have motivated some previous efforts in this area. For instance, an ontology was previously proposed to "represent energy-related occupant behaviour in buildings" (Hong et al., 2015a,b). At the theoretical level, a related effort proposed an "interdisciplinary framework for context and occupant behaviour in office buildings" (D'Oca et al., 2017). These efforts, while well-intentioned and useful, display also a number of limitations at both theoretical and ontological levels. Neither the choice of theories, nor the logic behind their synthesis are apparent. Rather, the framework leads to a questionnaire-based assessment of a fairly large number of variables suspected to influence occupants' adaptive actions. The conceptual and terminological haziness, already present to some degree in the original theories adopted, is further aggravated in the synthesised framework. A theory-driven ontology that is expected to effectively support high-resolution (e.g., agent-based) modelling of human behaviour in buildings arguably needs to be grounded on a more solid basis.

Implicit Tool-Embedded Schemata

As alluded to above, the bottom-up path involves the reverse-engineering of common building BPS applications. Thereby, the focus is on input requirements with regard to occupant-specific information.

Table 1 summarises core elements of occupant representations in typical BPS applications (Hong et al., 2018; Ouf et al., 2018). Aside from some basic information concerning the occupants' state (location, activity, clothing), these elements separately address passive and active effects of occupants on the indoor environment (Mahdavi, 2011). Passive effects mainly refer to the emission of sensible and latent heat, carbon dioxide, water vapour, and other substances.

TABLE 1 | Basic occupant-specific input categories in common BPS applications.

Basic state attributes of the occupants	Occupants' effects on the indoor environment	
	Passive effects	**Active effects**
Presence Metabolic Rate CLO Value	Sensible heat Latent heat CO_2/Pollutants/H_2O	Schedules Rules

Active effects refer to occupants' interaction with the buildings' indoor-environmental control devices and systems.

This brief observation reveals, from the ontological perspective, a number of gaps and inconsistencies in conventional occupant-related representations in common BPS tools. As such, different representational strategies are pursued with regard to passive and active effects. Passive effects are mapped to simulation zones. This is done, for instance, by specification of the number of occupants in each zone. To give an example, in this case, the people-related internal sensible heat gains are often expressed in area-related terms. For instance, people-related sensible heat gains are expressed in units of power per zone floor area (e.g., W.m^{-2}). Alternatively, people-related internal heat gains are computed by multiplication of the number of occupants with a (default) per-occupant power term (i.e., W.person^{-1}).

When representing active behaviour, even this rudimentary link to representation of occupants as individuals is absent. Instead, the operation of windows, blinds, and luminaires are captured in term of either schedules or rules applied to such devices. The resulting thermodynamic effects are, in case of thermal simulation, assigned to thermal zones. The schedules and rules may have been initially derived based on data or assumptions concerning occupants' behaviour. However, the implementation does not include necessarily an explicit ontological representation of the occupants as individual active agents.

OUTLINE OF A PRAGMATIC THEORY OF OCCUPANTS' INDOOR-ENVIRONMENTAL CONTROL BEHAVIOUR

Introductory Disclaimer

We examined, in the preceding sections of this paper, instances of building-related studies involving references to behavioural theories and implicit schema in typical computational building performance modelling tools. We also briefly considered recent efforts related to ontology proposals for representations of building occupants in energy analysis applications. These investigations have confirmed the initial conjecture formulated at the outset of this contribution: As far as representations of occupants are concerned, there is still a gap between the multitude of behavioural theories in human sciences on the one side and technical applications in engineering domains on the other side. Hence, to bridge this gap, there is still a need for appropriate intermediary theories and ontologies of human perception and (control-oriented) behaviour in buildings.

The specific high-level theory of people's indoor-environmentally relevant perceptual processes and control-oriented behaviour proposed here is not suggested to reflect a detailed scientific understanding of the salient aspects of the human behaviour. Major questions in this area remain unanswered, despite advances in the relevant disciplines including, but not limited to, psychology, cognitive science, and sociology (Donald, 2002). Rather, the proposed theory is intended to provide a compact yet plausible conceptual scaffolding that can serve computational applications for building design and operation support and requisite ontology developments. This disclaimer cannot be emphasised here enough, lest an unfortunate misunderstanding arises: We have no illusions concerning the formidable complexity of the human perception and behaviour processes. However, we argue that the deployment of even a highly simplified—but transparently stated—theory can contribute to the consistency of occupant representations in engineering applications. In the present case, the proposed theoretical construct is suggested to facilitate the development of ontologically cogent models of control-oriented human behaviour in buildings. Needless to say, only bench-marking of the resultant models against real world data can be the judge of the theory's performance in capturing the implications of human behaviour for buildings' performance.

Key Elements of the Theory

The theoretical concept proposed here can be described using the simple Mahdavi's schema depicted in **Figure 5**. This is a modified version of a previously introduced model (see Mahdavi et al., 2021). The theoretical basis of this schema takes inspirations from both previous forays in theoretical biology and human ecology (Uexküll, 1920, 1926; Knötig, 1992; Mahdavi, 1998a,b, 2016), cybernetics (Wiener, 1948; Ashby, 1956), ecological psychology (Gibson, 1979) as well as more recent work in cognitive neuroscience (Damasio, 2010).

The basic constituents of Mahdavi's schema are discussed in the following. The overall discourse domain is divided into the "individual" (in our case, a human agent) and the "surrounding world." The latter includes both physical entities and processes as well as social context and relationships. The concept of "ecological valency" (EV) refers to the totality of the surrounding world's attribute (resources, opportunities, risks, etc.) as relevant to the individual (or groups of individuals) (Knötig, 1992). As applied to indoor environment, the availability and quality of services and amenities can be viewed as reflective of its ecological valency. Such services include, in principle, anything from a space's furniture, appliances, power and data infrastructures, to indoor-environmental control devices for heating, cooling, ventilation, and illumination. This last category is of specific interest here, namely the equipment and devices (and their respective interfaces) for passive and active control of (thermal, visual, auditory, olfactory) conditions. As such, these are suggested to be constitutive of the indoor environment's EV as conceived in the present discourse.

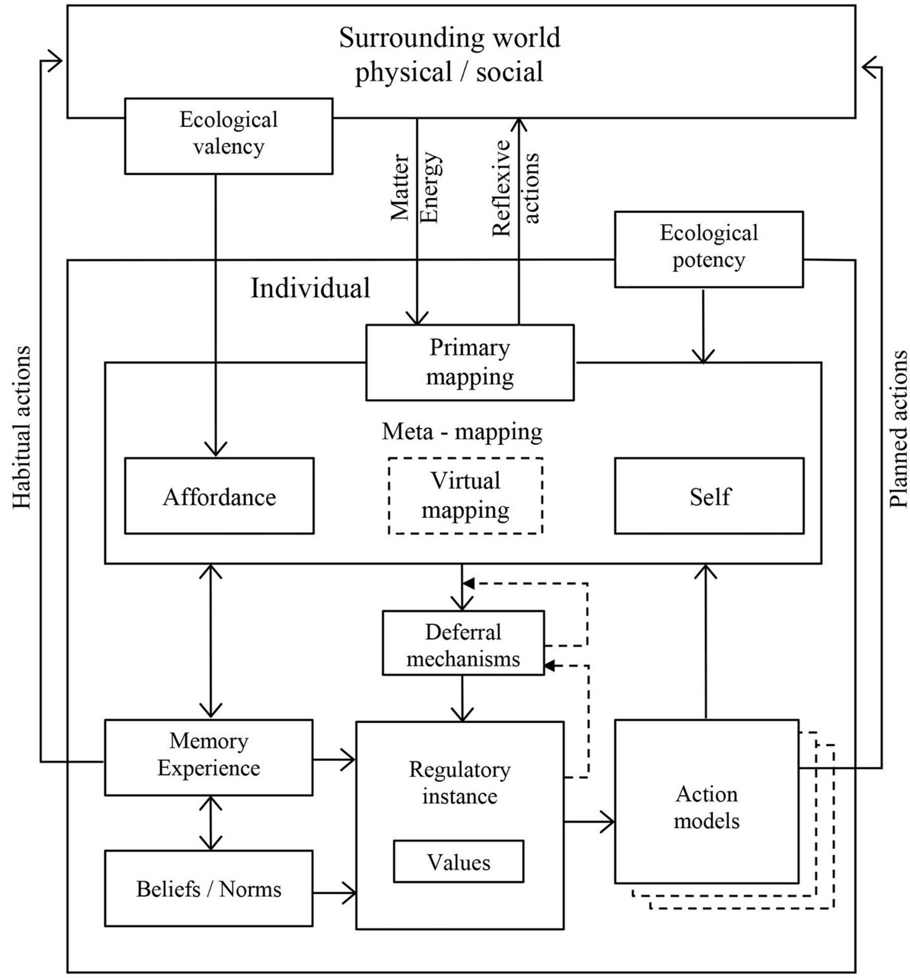
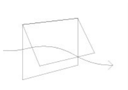
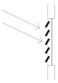
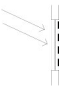
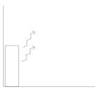
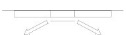
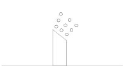
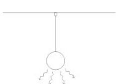
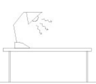
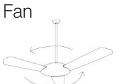
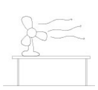


FIGURE 5 | Illustration of the main components of the Mahdavi's schema (Mahdavi et al., 2021).

On the other hand, the concept of "ecological potency" (EP) refers to the totality of the individual's physical (sensorimotor) and cognitive capabilities in dealing with his or her surrounding world (Knötig, 1992; Mahdavi, 1998a,b, 2016). Note that, attributes such as the individual's age, sex, physical and mental fitness, education, training, motivation, concentration, and experience are not identical with EP, but may be regarded as its basis. Some of these attributes such as occupants' overall health disposition, general mobility, and sensory aptitude are relatively stable over time, whereas others, including the level of arousal and attention, are more prone to short-term fluctuations. These latter inherently transient attributes make the prediction of actions and the times of their occurrence especially challenging, but may be addressed, at least formally, *via* adequate (for instance, probabilistic) modelling approaches.

While not entirely subtle from the epistemological standpoint, we expediently assume that both EV and EP are objective properties of the world. In fact, what is more relevant to a behavioural theory, is their cognitive representations. We suggest that the surrounding world is mapped in terms of a primary representation as the individual's "environment," or "Umwelt" in Uexküll's terms. This implies that, whereas individuals, at a specific point in time, may share the same surrounding world, they can have very different cognitive representations (environments) of it. Consequently, we assume that the ecological valency of the surrounding world is represented in individuals' environments in terms of its "affordance" (Gibson, 1979). But it is important to understand that we do not mean with affordance an innate attribute of entities in the individuals surrounding world. Rather, we interpret here affordance as the individual's perception of the surrounding world's ecological valency. Affordance denotes thus, in general, the recognised opportunities regarding nutrition, shelter, social inclusion, as well as various potential risks and hazards. Specifically, in the context of the present discussion, affordance may be attributed to various buildings' features and devices, when identified by occupants as means of indoor-environmental control. Illustrative instance of such control devices are included in **Table 2**. Thereby, the applicable functionality mode (i.e., mass and energy transfer process) are highlighted for the selected

TABLE 2 | Examples of control devices together with the main physical (mass and energy transfer) processes they modulate.

Devices	Radiative energy modulation	Lighting modulation	Convective energy modulation	Air flow modulation	Humidity control
Window 	○	○	○	✓	○
Exterior shades 	✓	○	–	–	–
Interior shades 	○	✓	–	–	–
Radiator 	✓	–	○	–	–
Radiant ceiling 	✓	–	○	–	–
Floor heating 	✓	–	○	–	–
Air diffusers 	–	–	✓	✓	✓
Humidifier 	–	–	–	–	✓
Illumination 	○	✓	–	–	–
Task lighting 	○	✓	–	–	–
Fan 	–	–	–	✓	–
Desk fan 	–	–	–	✓	–

In this table, "✓" denotes a primary process mode, "o" the secondary process mode (or side effect), and "–" no (or insignificant) influence (based on Mahdavi and Berger, 2019; modified).

devices (e.g., windows, shades, radiant elements, luminaires, and fans). To further clarify this point, we suggest that both the physical properties of surrounding world's ecological valency and the physical, physiological, and psychological realities of the individuals' ecological potency are observer-independent real-world properties. However, their cognitive representations as affordance or the individual's self-assessment of their capacities are subjective and observer-dependent. Note that an environment's perceived ecological valency (or its affordance) may be underdeveloped due to various reasons. Control features may be either entirely absent, or the respective control opportunities may not have been assigned to the occupants, but, for instance, reserved for some high-level control agency (e.g., a buildings central automation system). It is also possible that occupants are insufficiently aware of the presence and functionality of theoretically available control opportunities. Hence, the theory accounts for the presence of objective control opportunities, the occupants' principle access to such opportunities, and the resulting—behaviourally relevant—level of the environment's effective affordance.

The cognitive mapping process includes also the representation of the individual's "self." This implies a kind of meta-mapping process, expressing the individual's awareness of herself or himself and her/his presence in the environment. We label this cognitive model as the "self within the environment." The meta-mapping is assumed to be accompanied by the capacity to imagine and anticipate future states of the individual through time and space. Focusing further on the cognitive domain associated with an individual, we can make a number of additional assumptions. For one thing, the individual's mind is arguably not a tabula rasa, but entails a memory-based (historical) reservoir of "experience and knowledge." This repository can be assumed to inform the perception of the affordance and contribute to the anticipatory evaluation of behavioural options. Memory is the source of familiarity with characteristics of spaces as well as familiarity with technologies (devices, equipment, appliances) implemented in built environments. Levels of past experiences with the success and failure of behaviour can be assumed to be recorded in the memory and inform the evaluation of the prospects of planned—but not yet executed—actions.

Moreover, the individual can be assumed to be—at least to some extent—guided or conditioned by a set of "beliefs and norms," which can narrow the space of principle behavioural opportunities, for instance down to those deemed admissible or proper on, say, ethical grounds. Neither the nature of the beliefs and norms nor the degree of their influence on behaviour can be assumed to be immutable. Rather, they are subject to evolution over time and they be suppressed in circumstances dominated by other drivers, for instance in those cases when actions beneficial to others may be in conflict with perceived self-interest.

The above conceptual reflections facilitate the conception of a basic explanatory model of control-oriented behaviour. Thereby, it is important to note that we are concerned here more with manifestation of conscious behaviour geared towards short-term and mid-term regulatory functions, rather than behaviour with complex cognitive background targeting long-term planning agenda. We assume that the individual's control-oriented or regulatory behaviour is guided by the outcome of a process that involves the value-driven assessment and evaluation of its current state in view of possible distance to states that would be preferable. The preferable or desired state is the one that is—at the most basic (biological) level of values—oriented towards the individual's "survival." Seeking nutrition and shelter are basic yet vital instances of such behaviour. Higher-level expressions of control-oriented behaviour may be motivated by desire for physical or intellectual values associated with "health, comfort, satisfaction, pleasure, and productivity." Aside from these fundamental or first order values such as personal survival, health, satisfaction, and pleasure, individuals' behaviour is also influenced by further values that could be loosely referred to as second order. These values, as relevant to occupants' control actions and corresponding models, could involve economic (e.g., energy saving, monetary investments), ecological (e.g., expected environmental impact), socio-cultural (e.g., acceptance, compatibility, hierarchical relationships), and ethical values.

Note that, especially with regard to first order values, the motivational field behind the tendency to engage in control-oriented actions can involve not only rational but also emotional drivers. It has been argued (Damasio, 2010; Mahdavi, 2020a) that in living beings of a certain complexity (including humans), the transition from states that are less compatible with values to those that are more is typically rewarded with positive sensations (pleasure), whereas a move in the opposite direction may be punished in terms of negative sensations (pain). For instance, an organism rapidly losing heat in a thermal state far from equilibrium with the surroundings would experience a pleasurable feeling whilst moving to a warmer location. This suggests, however, that in order for an organism to experience pleasure, at least temporary departures from "optimal" states may be required. As long as they are not long-term and severe, such departures may not only provide the organisms short-term pleasurable experiences, but also play a positive role in the organisms' adaptive fitness. This can also shed light on the motivational field behind a specific class of actions, namely those that seem to be geared towards breaking states perceived as monotonous or dull. In other words, actions are not only triggered by the desire to depart from negative (painful and uncomfortable) states, but also actively pursue the promise of positive (pleasurable) states. To give a simple example, an occupant may close a window due to an uncomfortable sensation (e.g., draught or noise) or open it searching for a positive sensation ("freshness of air"), thereby tolerating—at least temporarily—temperatures much lower than what is typically considered to be comfortable. This discussion entails a significant corollary for the understanding of actions' motivational field. Whereas the intention to depart from value-negating (e.g., uncomfortable) states may explain a major share of people's control-oriented actions, their desire for positive experiences (resulting, for instance, from breaking an equilibrium state that is perceived as dull) may also trigger control behaviour.

Prior to execution, behavioural options may be assumed to be virtually enacted in terms of "action models." Thus, the potential of "planned actions" in achieving the desired state can be assessed in an anticipatory fashion. Actions are executed if such pre-screening promises success and reconsidered or revised otherwise. The entire process is, as alluded to before, informed and supported by the affordance (perceived ecological valency of the surrounding world), the memory-based repository of knowledge and experience, and the philtre-function of belief systems and norms. Actions that have been repeatedly successful in the past may become part of the repository of experience in terms of "habits" or "rituals" and be executed without prior explicit and conscious assessment of their ramifications. Note that "habitual behaviour" must be distinguished from "reflexive behaviour." Whereas the former entails "automated" versions of previously conscious behaviour, the latter denotes primarily biologically driven responses to specific stimuli and do not involve higher level cognitive (consciously planned) actions.

Note that, in certain circumstances, both the decision to make an action and the execution of an action may be delayed (see the "deferral mechanisms" in the scheme) or subsequently abandoned altogether. For instance, people might have, quasi in the back of their mind, a feeling that some aspect of the indoor environmental conditions is out of the desirable range. However, this background feeling may not lead to the formation of an action plan due to other factors, such as the individuals' cognitive loads (e.g., a phone conversation or completing an urgent task on the computer). These kinds of deferral mechanisms may also kick in, even in cases where people are fully aware of the nature and necessity of specific actions but still delay their execution.

Notwithstanding simplifications and shortcuts entailed, Mahdavi's schema (see **Figure 5**) is suggested to embody the minimum conceptual repertoire for the formation of an ontology that would address the core aspects of human behaviour as relevant indoor-environmental applications (e.g., interactions with physical elements and interfaces constituting the environment's affordance). It is important to reiterate that this model is not suggested to be a physiologically or psychologically detailed, accurate, or validated model of the human control-oriented behaviour. Specifically, a theory must be operationalized before yielding concrete predictions, and the proposed theoretical schema is not operationalized. What is suggested here is that the proposed theory entails, as opposed to existing previously discussed instances, the minimum ingredients necessary for a general-purpose ontology versatile enough to support the implementation of occupant behaviour models for engineering applications concerned with supporting the design and operation of built environments.

The utility and effectiveness of the proposed behavioural model for ontology development cannot be conclusively proven here as more implementation experiences with the operationalized theory's derivative models are needed. More importantly, the validity of the theory-driven predictions cannot be tested without systematic comparison with observational data. However, even though a proof of utility or a demonstration of validity cannot be provided here, aspects of the theory's applicability, scalability, and operationalization potential can be scrutinised. Specifically, explanatory stories of actual behavioural phenomena can be outlined based on the proposed theory and their plausibility can be examined. To this end, we consider in the following a number of scenarios concerning occupants' presence in indoor environments and behavioural manifestations of their control intentions in terms of their interactions with buildings' environmental control systems. With the aid of these scenarios, we can test the theory's principle explanatory potential, outline the required algorithmic procedures for fine-tuning of the implementation, and identify the ranges of required data for model instantiation.

THE EXPLANATORY RELEVANCE OF THE THEORY

As with any other theory, a formal validation of the proposed theory would require sufficient quantity of relevant empirical data. But the paucity of data on human behaviour in indoor environments is not the only or the most relevant reason why a formal validation of the proposed theory cannot be undertaken here and at this stage. As alluded to before, the high-level theory introduced in the present contribution is not intended to provide specific predictions of specific control actions under specific situations. Rather, the objective is to provide a general explanatory framework towards a more suitable perspective of occupants' control-oriented actions in indoor environments. The necessary conditions are not yet fulfilled for the proposed model to be operationalized in terms of computationally appliable predictive models. Specifically, extensive, adequate, and long-term observational data on human behaviour is not yet available. Such data would have to be obtained from richly documented indoor settings and occupant attributes. Nonetheless, the fact that a quantitative validation of the theory is not an option at this time, does not mean that we cannot probe its logical consistency and explanatory plausibility. This possibility is briefly explored in the remainder of this section with the aid of a simple illustrative thought experiment.

Consider Bob, Mary, Carlos, and Liang, four imaginary occupants of a likewise imaginary office building, located in the capital city of a Central European country. We are in the possession of a monitoring report recording their presence and their control actions over a period of a typical working day in late October. **Table 4** shows these actions with a 15-min interval resolution. Specifically, actions pertaining to the operation of windows, blinds, luminaires, and thermostat have been documented. **Table 3** shows these devices and actions considered for the purposes of the present thought experiment together with the respective codes of control actions.

The point of this virtual case study is to probe if the proposed theoretical framework can help us make sense of the observed actions of these four individuals. What was their motivational background? What was their purpose? Did they have a generalizable underlying logic? The idea is to use the example of the type and temporal pattern of the actions by these occupants over the course of a typical working day as they are reflected upon based on the proposed theory. Note that, as already alluded to before, the theory is not meant to prove anything. Rather, it is meant to provide a conceptual framework, the basis for a versatile ontology, and computational representations of occupants in terms of autonomous agents. Hence, the expectation is that the theory, ontology, and computational implementations would satisfy the necessary preconditions for the formulation of hypotheses (or explanatory stories) regarding occupants' control-oriented actions.

To go back to our thought experiment, it is obvious that the protocol of the recorded control actions on its own (see **Table 4**) does not yield an insight into their underlying logic. What if we had the possibility to obtain some information regarding both the ecological potency of the occupants and the ecological valency of their offices? Some basic information relevant to the former is summarised in **Table 5**. We also have some information regarding the latter. Specifically, we know that the offices are naturally ventilated, with a radiant heating system controlled *via* a thermostat in each room (located next to the office door). Bob

TABLE 3 | Overview of selected devices and their considered states.

		Devices			
		Windows	**Blinds**	**Luminaires**	**Thermostat**
Actions	Open/close	W_{OP}/W_{CL}	B_{OP}/B_{CL}	–	–
	On/off	–	–	L_{ON}/L_{OF}	–
	Increase/decrease	–	–	–	T_{IN}/T_{DE}

TABLE 4 | Monitoring protocol of occupants' control action over the course of a typical day in October (grey cells denotes presence in the office).

Time of the day	Bob	Liang	Carlos	Mary
9:00			T_{IN}	
				W_{OP}, L_{ON}
				W_{CL}
10:00				
	L_{ON}, W_{OP}, T_{DE}			T_{DE}, L_{OF}
			B_{CL}	
	W_{CL}			
11:00				
	B_{CL}			
				W_{OP}
12:00				W_{CL}
13:00				
		B_{OP}, L_{OF}		
14:00				
	T_{DE}			
15:00				W_{OP}
	L_{ON}			W_{CL}
		T_{IN}		
16:00				L_{ON}
		L_{OF}		
			B_{OP}	
17:00		L_{ON}, T_{DE}		
				L_{OF}
18:00				
		L_{OF}		

It is assumed that at the start of the day, prior to occupancy, all lights are off, all windows closed, all blinds open, and all rooms at a temperature of 22°C (daytime outdoor temperature on this day is assumed to be in the range of 14–18°C) (note that, for simplification purposes, all events/actions in this table are reported on a 15-min time interval basis).

and Liang share a spacious double-occupancy office with a large window facing the street, whereas Carlos and Mary have each their own smaller single-offices. Each office has a window with external blinds, luminaires (with an on/off switch located near the entrance), and a thermostat for heating radiators.

Can we use the framework of the proposed theory to utilise the ecological potency and ecological valency to formulate plausible conjectures with regard to the occupants' control actions? An illustrative attempt in this direction is represented in terms of the following four stories:

Bob's story: (10:15) Having strong habits, Bob switches the lights on, opens the window, and turns down the thermostat upon arrival. The presence of Liang does not deter him from these unilateral actions, as social competence is not his strength and as he considers her a subordinate. (10:45) Noticing the overtly cold draught due to the open window, Bob decides to close the window, despite his general preference for lower temperatures. (11:30) Given some vision issues and heightened glare sensitivity, Bob closes the blind. (13:15) Lacking concerns regarding energy saving issues, Bob does not turn off lights when leaving for lunch (14:15) Returning to office after lunch, Bob finds the office too warm and hence lowers the thermostat setting. (15:15) Having been concentrated on mail exchange on computer before, Bob suddenly feels the office has gotten too dark and turns on the lights. (15:45) Bob leaves the office not thinking about control issues.

Liang's story: (9:30) A combination of factors (new to the office, junior member) deters Liang from any control action upon arrival, aside from the fact that she does not find conditions overly uncomfortable. (13:45) Returning to the office after out-of-the office assignment and noticing the absence of Bob, and having some sense of energy conservation, Liang decides to open the blind and turn off the light, as she thinks energy would be unnecessarily wasted. She eats lunch at the desk. (15:45) Liang turns the thermostat up as soon as Bob leaves the office, having felt somewhat cold previously. (16:15) She turns the lights off before leaving for a short visit to a shop outside the office. (17:00) She switches the lights on after returning to the office, and finding the office warm enough, she turns down the thermostat. (18:30) Liang switches off the lights before leaving for the day.

Carlos's story: (9:00) Upon arrival, Carlos immediately turns up the thermostat, preferring warmer settings. (10:30) Carlos prefers to work on computer under dim light conditions. Noticing the increasing light level in the room, he closes the blind. Subsequently, he leaves his office twice, without operating any devices. (16:45) Carlos makes a pause during computer work and decides to open the blinds, partly because of the room getting darker, but more because of a sudden impulse to look out the window. (17:45) Carlos leaves the office without turning down the thermostat. Even though ecologically not insensitive, he has not developed a habit of considering his actions from the energy conservation point of view.

Mary's story: (9:15) Upon arrival, Mary habitually opens the window for fresh air and switches the lights on. Even though she

TABLE 5 | Illustrative summary of information relevant to the ecological potency of the four characters in the thought experiment.

Selected attributes relevant to occupants' ecological potency	Virtual occupants of the virtual office			
	Bob	**Liang**	**Carlos**	**Mary**
Age	57	26	35	29
State of health	Fair	Good	Good	Excellent
Thermal preference	Cool	Neutral	Warm	Warm
Visual preference	Neutral	Neutral	Dim	Bright
Ecological attitude	Weak	Moderate	Moderate	Strong
Habitual tendency	Strong	Moderate	Weak	Strong
Hierarchic standing	High	Low	Low	Medium
Contextual familiarity	High	Low	Moderate	Moderate
Social competence	Medium	High	High	Medium

finds the room somewhat cool, she does not turn up the thermostat. Aside from an impetus to save energy, she has adopted to the office situations by adjusting her clothing habits. (9:30) Mary closes the window. (10:15) Before leaving for a meeting in another building, Mary turns down the thermostat and switches the lights off. (11:45) Upon returning from the meeting and an early lunch break, Mary opens the window, to close it again a short while later. (12:00) Mary closes the window. (13:45) Mary leaves the office for an inhouse meeting. (15:00) Upon returning to the office, Mary repeats her short window ventilation ritual. (16:00) Finding the office too dim for her liking, Mary decides to switch on the lights. (17:00) Mary switches off the lights and leaves the office for the day.

This very simple thought experiment displays, in principle, the explanatory potential of the proposed framework theory. Elements of the theory allow for the formulation of explanatory stories about occupants' actions. Looking at the sample data of **Table 1**, together with the information of the ecological potency of the occupants and the ecological valency of the office, we can explore a few such stories. Control actions are suggested to result from perceived discrepancy between existing and preferred conditions, which in turn are derived from the individuals' values. These preferences are tightly related to individuals' ecological potency. As such, they are not only subject to considerable inter-individual variance, but may change over time, even in case of the same individual. Changes may occur both short-term (e.g., temporary illness) and long-term (e.g., due to the ageing process). Note that, routines and habits that have been acquired *via* long-term experiences with similar events and circumstances, may trigger actions without the conscious presence of the regulatory intention.

In a number of situations, people may not act on a perceived need to engage in a control action: This may be due to social and cultural considerations (e.g., asymmetrical socially relevant positions of the occupants in a shared office). Likewise, general attitudes and beliefs (e.g., environmental consciousness) have been found to influence control-oriented behaviour. Moreover, as implied by the concept of "deferral mechanisms" in the model (see **Figure 5**), a need may be also consciously or subconsciously pushed to the background, for instance if a person's momentary cognitive load is too high (e.g., when engaged in an urgent task) or he/she is engaged in a phone conversation or web meeting. More generally, engaging in control actions requires a certain level of familiarity with the environment's ecological valency. In other words, the affordance of the control devices must be transparent and rewarding to the individuals. Moreover, the prospect of engaging in interaction with control devices must be perceived as rewarding, in that the exertion involved in operating them must be gauged to be worth the expected benefit.

It is important to realise what is not suggested here. It is not suggested that the sample theory-driven explanatory stories told here are the "true" ones. Rather, these are meant to represent conceivable, logical, and plausible interpretation of the observations. As such, they provide the basis for examination and interpretation of empirical data. Ultimately, the validity of a theory can be gauged only on the basis of predictions it makes. The proposed pragmatic theory underlying Mahdavi's schema represents merely a first step in this direction. Derivative ontologies and subsequent computational (specifically, agent-based) models are expected to facilitate operationalized implementations of the theory that could be tested against observational data.

CONCLUSION

We presented the main features of a pragmatic theory of control-oriented human behaviour in buildings. The development of this theory and the associated schema was motivated by recent trends towards more detailed, dynamic, and realistic representations of occupants in computational building modelling in general and building performance simulation in particular (Yan et al., 2017). Efficient generation, refinement, and sharing of occupant models can benefit from a shared ontology. Systematic and robust ontologies benefit, in turn, from the prior availability of a versatile behavioural theory. Such a theory can specifically capture those aspects of human perception and behaviour that are relevant to building performance assessment and prediction. As such, the main objective of the presented theoretical effort has been to support the computational realisation of knowledge-based and ontologically streamlined computational models of occupants' presence, perception, and behaviour in buildings. The critical importance of this activity is further underlined by the insufficient utility of the multitude of existing behavioural models. Neither these models, nor the implicit occupant-related schemata in common computational building performance analysis tools fully address the requirements of high-resolution representations of occupants in computational building models.

The proposed theoretical framework is not at an operationalized stage amenable to yielding specific predictions of specific occupant actions. As such, it cannot be subjected to a direct empirically-based validation exercise. Nonetheless, a general examination of the proposed theory, conducted *via* a thought experiment, suggests that it can offer consistent and plausible narratives with regard to the background of and reasons for occupants' interactions with buildings' control devices. The proposed theoretical framework has been thus shown to cover the essential ingredients of a general ontology of occupants' control-oriented behaviour in buildings. Such an ontology is currently under development. Moreover, the proposed theory and the derivative ontology act as the reference framework for the agent-based representation and modelling of occupant behaviour and its impact on buildings' energy performance.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

AM was the primary author of this paper. He selected the topic of the inquiry and was also the main developer of the behavioural theory/schema presented in this paper. VB and CB participated in the development of the paper's structure, content, and visual material. They also contributed significantly to the review of the state of art regarding existing behavioural theories relevant to the contribution's focus (occupant control actions in buildings). All authors contributed to the article and approved the submitted version.

FUNDING

The authors acknowledge TU Wien Bibliothek for financial support through its Open Access Funding Programme.

ACKNOWLEDGMENTS

In the writing of this paper, the authors benefited from participation and related discussions in the IEA EBC Annex 79 activities.

REFERENCES

Ajzen, I. (1985). "From intentions to actions: a theory of planned behavior bt—action control: from cognition to behaviour," in *Action control*, eds J. Kuhl and J. Beckmann, J. (Berlin, Heidelberg: Springer), 11–39.

Ajzen, I. (1991). The theory of planned behavior. *Orgn. Beh. Hum. Decision. Proc.* 50, 179–221. doi: 10.1016/0749-5978(91)90020-T

Ajzen, I., and Fishbein, M. (1980). *Understanding Attitudes and Predicting Social Behaviour*. New Jersey: Prentice Hall.

Al-Marri, W., Al-Habaibeh, A., and Watkins, M. (2018). An investigation into domestic energy consumption behaviour and public awareness of renewable energy in Qatar. *Sustain. Cities Soc.* 41, 639–646. doi: 10.1016/j.scs.2018.06.024

Ashby, W. R. (1956). *An Introduction to Cybernetics*. London: Chapman and Hall.

Bourdieu, P. (1977). *Outline of a Theory of Practice*. Cambridge: Cambridge University Press.

Carpenter, R., and Reddi, B. (2012). *Neurophysiology: A Conceptual Approach*. London: CRC Press.

Damasio, A. (2010). *Self Comes to Mind: Constructing the Conscious Brain*. New York, NY: Pantheon books.

DellaValle, N., Bisello, A., and Balest, J. (2018). In search of behavioural and social levers for effective social housing retrofit programs. *Energy Build.* 172, 517–524. doi: 10.1016/j.enbuild.2018.05.002

D'Oca, S., Chen, C.-F., Hong, T., and Belafi, Z. (2017). Synthesizing building physics with social psychology: An interdisciplinary framework for context and occupant behavior in office buildings. *Energy Res. Soc. Sci.* 34, 240–251. doi: 10.1016/j.erss.2017.08.002

Donald, M. (2002). *A Mind So Rare: The Evolution of Human Consciousness*. New York, NY: W. W. Norton and Company.

Fishbein, M., and Ajzen, I. (1975). *Belief, Attitude, Intention and Behaviour*. Reading, MA: Addison-Wisley.

Fishbein, M., and Ajzen, I. (2010). *Predicting and Changing Behavior: The Reasoned Action Approach.* New York, NY: Psychology Press.

Gibson, J.J. (1979). *The Ecological Approach to Visual Perception*. Boston: Houghton Mifflin.

Giddens, A. (1984). *The Constitution of Society: Outline of the Theory of Structuration*. Berkeley: University of California Press.

Heydarian, A., McIlvennie, C., Arpan, L., Yousefi Jordehi, S., Syndicus, M., Schweiker, M., et al. (2020). What drives our behaviors in buildings? a review on occupant interactions with building systems from the lens of behavioral theories. *Build. Environ.* 179:928. doi: 10.1016/j.buildenv.2020.106928

Hong, T., Chen, Y., Belafi, Z., and D'Oca, S. (2018). Occupant behavior models: A critical review of implementation and representation approaches in building performance simulation programs. *Build. Simul.* 11, 1–14. doi: 10.1007/s12273-017-0396-6

Hong, T., D'Oca, S., Taylor-Lange, S.C., Turner, W.J.N., Chen, Y., and Corgnati, S.P. (2015b). An ontology to represent energy-related occupant behavior in buildings. Part II: Implementation of the DNAS framework using an XML schema. *Build. Environ.* 94, 196–205. doi: 10.1016/j.buildenv.2015.08.006

Hong, T., D'Oca, S., Turner, W., and Taylor-Lange, S. (2015a). An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs Framework. *Build. Environ.* 92, 764–777. doi: 10.1016/j.buildenv.2015.02.019

Knötig, H. (1992). "Some essentials of the Vienna School of human ecology," in *Proceedings of the 1992 Birmingham Symposium. Austrian and British Efforts in Human Ecology, Archivum Oecologiae Hominis*, Vienna, Austria.

Lo, S. H., Peters, G.-J., Breukelen, G., and Kok, G. (2014). Only reasoned action? an interorganizational study of energy-saving behaviors in office buildings. *Energy Effic.* 7:9257. doi: 10.1007/s12053-014-9254-x

Mahdavi, A. (1998a). Steps to a general theory of habitability. (Summer 1998). *Hum. Ecol. Rev.* 5, 23–30. doi: 10.1146/annurev.ecolsys.30.1.23

Mahdavi, A. (1998b). The human ecology of the built environment. *J. Southeast Asian Architect.* 3, 25–44.

Mahdavi, A. (2011). "The human dimension of building performance simulation. driving better design through simulation," in *Proceedings of the 12th Conference of The International Building Performance Simulation Association, Sydney, Australia*, eds V. Soebarto, H. Bennetts, P. Bannister, P.C. Thomas, and D. Leach, K16–K33.

Mahdavi, A. (2016). "The human factor in sustainable architecture," in *Low Energy Low Carbon Architecture: Recent Advances and Future Directions (Sustainable Energy Developments)*, eds A. Khaled and A. Al-Sallal (London: Taylor and Francis),137–158.

Mahdavi, A. (2020a). Explanatory stories of human perception and behavior in buildings. *Build. Environ.* 86:498. doi: 10.1016/j.buildenv.2019.106498

Mahdavi, A. (2020b). *Bringing HIM Closer to HER. Keynote presentation SimAUD 2020, Vienna, Austria, 25–27 May 2020*. Available online at: https://www.facebook.com/simaudconf/videos/788466515015683/ (accessed July 27, 2021).

Mahdavi, A. (2022). The trouble with "HIM": New challenges and old misconceptions in Human Information Modelling. *J. Build. Perform. Simul.* 14, 611–618. doi: 10.1080/19401493.2021.1990410

Mahdavi, A., and Berger, C. (2019). "An inquiry into the certification potential of built environments' affordance," in *Proceedings of the 13th REHVA HVAC World Congress CLIMA2019*. ed C. Lungu, 84.

Mahdavi, A., Bochukova, V., and Berger, C. (2021). "Occupant-centric ontology as a bridge between domain knowledge and computational applications," in *Proceedings of ECPPM 2021*. London: CRC Press.

Mahdavi, A., and Tahmasebi, F. (2016). The deployment-dependence of occupancy-related models in building performance simulation. *Energy Build.* 117:65. doi: 10.1016/j.enbuild.2015.09.065

Maslow, A. H. (1943). A theory of human motivation. *Psychol. Rev.* 50, 370–396. doi: 10.1037/h0054346

Matthies, E., Kastner, I., Klesse, A., and Wagner, H.-J. (2011). High reduction potentials for energy user behavior in public buildings: How much can psychology-based interventions achieve? *J. Environ. Stud. Sci.* 1, 241–255. doi: 10.1007/s13412-011-0024-1

Ouf, M. M., O'Brien, W., and Gunay, H.B. (2018). Improving occupant-related features in building performance simulation tools. *Build. Simul.* 11, 803–817. doi: 10.1007/s12273-018-0443-y

Reckwitz, A. (2002). Toward a theory of social practices: a development in culturalist theorizing. *Eur. J. Soc. Theory*. 5, 243–263. doi: 10.1177/13684310222225432

Ryan, R. M., and Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *Am. Psychol.* 55, 68–78. doi: 10.1037/0003-066X.55.1.68

Schwartz, S.H. (1977). "Normative influences on altruism," in Berkowitz, L., ed. *Advances in Experimental Social Psychology* (New York, NY: Academic), 221–279.

Schwartz, S.H., and Howard, J.A. (1981). "A normative decision-making model of altruism," in *Altruism and Helping Behavior*, eds J. P. Rushton and R. M. Sorrentino (Hillsdale: Erlbaum), 189–211.

Shove, E., Pantzar, M., and Watson, M. (2012). *The Dynamics of Social Practice: Everyday Life and How it Changes*. London: SAGE Publications Ltd.

Simon, H.A. (1957). *Models of Man; Social and Rational*. New York, NY: Wiley.

Simon, H.A. (1995). A behavioral model of rational choice. *Q. J. Econ*. 69, 99–118. doi: 10.2307/1884852

Taylor, C. (1983). *Social Theory as Practice*. Delhi: Oxford University Press.

Uexküll, J. (1920). *Theoretische Biologie*. Berlin: Paetel.

Uexküll, J. (1926). *Theoretical Biology* (D. L. Mackinnon, Trans.). New York, NY: Harcourt, Brace.

Wiener, N. (1948). *Cybernetics, or Control and Communication in the Animal and the Machine*. Cambridge: MIT Press.

Yan, D., Hong, T., Dong, B., Mahdavi, A., D'Oca, S., Gaetani, I., et al. (2017). IEA EBC Annex 66: definition and simulation of occupant behavior in buildings. *Energy Build.* 156, 258–270. doi: 10.1016/j.enbuild.2017.09.084

Yantis, S., and Abrams, R.A. (2016). *Sensation and Perception*. New York, NY: Worth Publishers.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.