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An interdisciplinary model for behaviour in residential buildings: Bridging social sciences and engineering approaches

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ABSTRACT

In this paper, we develop a comprehensive behaviour model for residential buildings that considers the diversity among households. While existing behavioural theories from social and psychological sciences have been used in building research, they often lack technical detail, contextual aspects, and focus primarily on behavioural change. The authors propose an interdisciplinary theoretical model that integrates insights from behavioural science and engineering dimensions. This model aims to link measurable drivers directly to energy outcomes, consider building-related contexts, and reflect the complexity of high-performance buildings.

The research consisted of the quantitative analysis of building monitoring data and the analysis of interviews using thematic analysis. The mix-methods approach allowed to obtain new insights into the relationship between the aspects that affect occupants' behaviour. An interdisciplinary model is developed based on the results from the analysis, existing theoretical models used in building research, and previous studies on occupants' behaviour. The model is intended to support the identification of occupants' behaviour drivers, inform user-centric and energy-efficient building design, enhance decision-making for building monitoring and simulations, and aid in various practical applications such as performance assessment and energy contracting.

1. Introduction. Energy performance gap in residential buildings

As buildings consume about 40 % of the energy produced worldwide, building regulations and policies continue to tighten to improve the energy performance of buildings. New buildings and buildings that undergo a large renovation must comply with building envelope and systems requirements or with a minimum energy performance. As an outcome, buildings recently constructed or renovated have more airtight envelopes and efficient heating and ventilation systems, which in theory reduce their energy consumption. However, research has shown that there are large differences between the expected and actual performance in these types of buildings [1,2]. In reality, energy consumption of similar buildings varies by up to a factor of two [3,4]. This gap affects the implementation and upscaling of low carbon technologies (i.e. due to uncertainties in the return of investments) and can greatly affect the building occupants' quality of life (e.g., fuel poverty due to rising energy prices, poor indoor environment due to lack of ventilation or high/low indoor temperatures). Furthermore, rebound effects can affect the carbon emission reduction targets on National and Regional levels [5].

The so-called *building performance gap* [6–9] has been attributed to both technology-related and occupant-related factors. The technology-related aspects include faults in the building envelope (e.g. sealing around window frames and doors in low energy dwellings) or in the HVAC systems (e.g. failing sensors, inadequate heating and cooling setbacks, forgotten overrides, incorrect pressurisation), as well as poor building commissioning. These aspects can be considerably improved or avoided through the use of building performance tests such as co-heating tests, air permeability tests, and infrared thermography, and through proper commissioning of the building during construction, as well as follow-ups after the delivery of the buildings [10]. Monitoring building performance during construction activities and Post-Occupancy Evaluation play an important role in the fine-tuning of the buildings. In this regard, a wide variety of methods exist and although

Abbreviations: DNAS, Drivers, Needs, Actions, Systems; E-B, Environment-Behaviour; ERB, Environmental Responsible Behaviour; HVAC, Heating, Ventilation and Air Conditioning; SCT, Social Cognitive Theory; SPT, Social Practice Theory; TIB, Theory of Interpersonal behaviour; TPB, Theory of Planned Behaviour; TRA, Theory of Reasoned Action; VBNT, Value, Belief, Norms Theory.

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they are still applied on a small scale, they have been accepted as an effective way to improve the performance of buildings.

In contrast, building performance gaps due to occupants' behaviour are more difficult to predict and overcome, given that these factors have multiple causes and consequences on the building performance. With behaviour is meant here, the interactions of the occupants with a building and its systems such as HVAC systems (use of heating, cooling and ventilation systems) and opening and closing windows. We also consider as behaviour the occupants' actions that might have an indirect effect on energy consumption or indoor air quality (e.g. use of spaces, activities, clothing habits). The influence of occupants on building performance is emphasized in the residential sector, where a larger diversity of occupants and occupants' specific needs and preferences can be found. For example, buildings' occupants might have different preferences for indoor temperature. On the one hand, in office buildings, a standard setpoint deemed as comfortable for the most people according to the facilities manager is seen as acceptable, and its control is often out of the hands of the office workers. On the other hand, in residential buildings, the temperature setting is directly affected by the preferences of the occupants, since they will decide on the actual setting. Therefore, determining and understanding occupants' behaviour has increased in importance in building research in the last decade.

In the context of understanding the relationship between buildings and occupants' behaviour, building research often makes use of sociological and behavioural theories, specifically in the area of building performance. These theories have been used, to different extents, in three specific areas of building research: 1) the calculation of energy demand and indoor environmental quality, usually through building simulations; 2) during (energy) building performance evaluation (either to certify or improve it); and 3) for the design of user-centric buildings, interfaces, and smart (control) systems. These applications are further explained in the following paragraphs.

Occupancy profiles are used in building simulations to account for occupants' behaviour to generate more accurate energy results [11]. However, these profiles are based on assumptions or standardised situations, rather than measured observations. According to Balvedi [11], a common configuration in simulations is to assume deterministic occupants' behaviours (for example, by using static schedules). However, occupants' behaviour is stochastic, evolving over time without repetitive schedules. Consequently, the used behavioural patterns are often far from the reality of most households [12]. Standardised patterns can be used for sizing HVAC systems, or to determine the average energy demand of different types of systems configurations [13]. However, current simulation tools cannot fully reliably predict the performance of energy efficiency measures in a building [14], for example to define energy savings after renovations or to draw up energy contracts. Thus, there have been recent efforts to define more accurately the occupants' behaviour in buildings, specifically with the use of monitoring data. An overview of the use of data-driven methods to model occupants' behaviour can be found in Xu et al. [15]. So far, the main constraint in the development of occupancy models for simulations based on monitoring data is their lack of generalizability due to their direct relation with the data itself. Hidden information and unexplored parameters (occupant and systems characteristics, local climate, etc.) prevents the use of these models in different contexts [11]. Data science advances alone might not be able to solve this problem. Therefore, a more comprehensive framework is needed that allows for the use of monitoring data in a more structured and systematic manner, while at the same time considering contextual variables. In this context, a contextualised occupants' behaviour model could help practitioners to develop or select occupancy profiles for building simulations in a more efficient manner.

While building simulations are used to design buildings and thus, define the expected performance of buildings, monitoring performance is used to determine the actual performance of a building. Although energy meters and indoor environmental sensors are nowadays more often installed in buildings to measure energy consumption and indoor quality, building performance can only be truly understood when occupants' behaviours and their underlying drivers are investigated [16,17]. Past research has shown that monitoring projects where occupants' behaviour was investigated, are better at explaining the (under)performance of buildings [18]. To design user-centric buildings, systems, and interfaces, an interdisciplinary model could help to understand better how occupants behave and the reasons for their behaviour.

The impact of occupants' behaviour in energy performance might be larger in high-performance buildings. In these buildings, a variety of strategies to decrease energy use and to provide a comfortable and healthy environment are often implemented [19], but often unanticipated and unpredictable occupants' behaviours are seen [20]. In these same high-performance buildings, smart technologies and automated control systems are increasingly used to ensure or promote energy efficiency. This means that the relationship between people and buildings is changing [21]. In the design of user-centric interfaces and smart systems, information on occupants' behaviour and comfort can be a valuable resource in the control and fine-tuning of building systems. The systems could learn from the occupants' preferences and routings [11,19] and adapt systems' settings accordingly. The concept of human-in-the-loop transforms the occupants into active participants, controllers and even sensors within the system [11]. The incorporation of occupants' behaviour and comfort data into digital twins (real-time building models) for systems' control with support from a more comprehensive occupants' behaviour model could facilitate the transition into user-centric automated buildings.

In all these applications, the most commonly used theories borrow from the social and psychology sciences, namely behaviour change and consumer studies, although a few have been also developed within the energy and engineering fields. The main limitations of models from the social and psychological sciences are that 1) they lack the (technical) detail to decide how to measure and evaluate both, the behaviours and other constructs of the models, 2) they do not support the modelling of one or more important contextual aspects (such as buildings' and systems' characteristics), and 3) they often focus on behavioural change (thus assuming that a change is needed). One of the most recent efforts to model occupant's behaviour from a more engineering perspective has been focused on the modelling of behaviour in offices for building automation and control [22]. The DNAS model (Drivers, Needs, Actions, Systems) is characterised by its practical approach to the actual performance and variables of office buildings. Although containing several aspects that also apply to residential buildings, the model does not address the complexity and diversity of occupants. Modelling occupants' behaviour in residential buildings requires a more specific study.

Thus, an up-to-date occupants' behaviour model for residential buildings is needed to link measurable behaviour drivers directly to measurable (energy) outcomes [23], that takes into account the (building-related) contexts [24–30]; and that reflects the complexity of high-performance buildings. This model should allow researchers and practitioners to reveal underlying drivers of behaviour and consider the needs and preferences of the occupants without assuming that the behaviour is wrong [31]. A behavioural science perspective combined with engineering dimensions could be a good basis for such a model, as also suggested in Heydarian et al.'s [32] literature review about behaviour drivers in buildings.

In this paper we propose an interdisciplinary occupants' behaviour theoretical model for residential buildings. The aim of the model is to support the identification of the occupants' behaviour and its drivers, as well as the consequences for the design of user-centric and energy efficient buildings. Furthermore, the aim is to support better decision-making for building monitoring activities and simulations. The model could be used for different purposes: for the assessment and evaluation of building performance in monitored projects, for the extraction of data from monitoring projects to inform the design process (for both new and existing buildings), to inform building simulations for energy prediction, as a tool for design, and for energy contracting. This investigation focuses on the integration of engineering quantitative approaches (monitoring data analysis) and social sciences approaches (lessons learned from projects), with existing behavioural models and theories.

The objective of this research is to deepen our understanding of the drivers of occupants' behaviour in buildings to increase their efficiency while maintaining a health indoor environment. A second, operative objective of this research is to provide researchers and practitioners in the field of buildings performance, with better insight to make design and evaluation-related decisions. While on the one the one hand we aim to integrate different existing theories, on the other hand we focus on the analysis of case studies to understand and make visible the aspects of behaviour that are usually overlooked when studied from a top-down perspective.

The paper is organised as follows. Section 2 presents an overview of the existing theoretical models currently used to study occupants' behaviour. Section 3 introduces the research methods and case studies. Section 4 presents the results from the analysis. Section 5 presents the proposed model and its relation to existing models. Section 6 presents the discussion and Section 7 the conclusions of this study.

2. Existing theoretical models for occupants' behaviour

In this section we summarized the main types of models and theories that have been used to study occupants' energy-related behaviours. Table 1 summarises the theories and models.

2.1. Behavioural, psychological, and sociological models

Several behavioural and psychological theories have been used to address the relation between behaviour and energy in buildings [19,32,33]. These theories have been applied to explain either individual behaviours or the overall use of a building and its HVAC systems.

Heydarian et al. [32] provided an extensive review of how various psychological, sociological, and economic theories have been applied to explain occupants' behaviours. They identified the most common theories and methodologies applied within the existing research and reported general findings on how these theories have been used to explain energy efficient behaviours. For a full overview on the use of the theories, we refer to their paper. Their findings will be further considered in the results and discussion of this paper. According to their findings, the most used psychological theories are *Theory of Reasoned Action/Theory of Planned Behaviour, Norm Activation Model, Value Belief Norm (VBNT), and Theory of Interpersonal Behaviour* [32].

From a perspective related to behaviour change Kollmuss & Agyeman [33] described the two most influential and commonly used analytical frameworks to investigate pro-environmental behaviour: early US linear progression models (altruism, empathy, and prosocial behaviour models), and sociological models (see following section). They conclude that all the models discussed have some validity in specific circumstances. Important models identified are the *information 'deficit' models of public understanding and action* and *Attitude-behaviour measurement* theories. The former assumed that educating people about environmental issues would automatically result in more pro-

Table 1
Summary of relevant theories and models.

Model type	Model name/description	Authors/reference	Contributions
Behavioural and psychological models	Theory of Planned Behaviour (TPB) and Theory of Reasoned Action (TRA)	Ajzen,1985 [35], Fishbein and Ajzen, 1975 [36].	Three main components shape an individual's behavioural intentions: attitude, subjective norms (opinions of significant others), and perceived behavioural control.
	Norm Activation Model	Schwartz, 1977 [32]	Identifies the drivers influencing human intention towards altruistic and pro-environmental behaviours. Behaviours/intentions are a function of personal norms, which in turn, are regulated by awareness of consequence and ascription of responsibility.
	Value Belief Norm (VBNT)	Stern, 1999 [32]	Proposes that behaviour is driven by personal values and norms.
	Theory of Interpersonal Behaviour	Triandis, 1977 [32]	Behaviour is connected with three main factors: facilitating conditions, habits and behavioural intention.
	Responsible behaviour theory	Hines, Hungerford, and Tomera in 1987 [37]. Stern et al. [39]	Possessing an intention of acting is a major factor influencing ERB.
Sociological models	Social Practice Theory (SPT)	Bourdieu, 1977 [42], Shove & Walker [43]	Practices result from the integration of three dynamic elements: materials (objects, products, things), skills (know-how, competencies, rule-following abilities), and meanings (embedded symbols, images, ideas).
	Ecological Behaviour model	[33] [40]	Educating people about environmental issues would automatically result in more pro-environmental behaviour.
	Value–Action Gap model	[41] [33]	Model identifies three barriers to action that outweigh environmental concern.: individuality, responsibility (similar to locus of control), and practicality (social and institutional constraints).
Physical–technical–economic models	Technical models	[45]	Estimate energy flows though physical systems and calculate the energy requirements based on physical laws.
	Economical models	[45]	Consider the implications of energy prices, taxes, income, and expenditure on household energy use.
	Diffusion of Innovation model	[45]	Theory assumes a linear progression of knowledge, awareness, intention, and behaviour resulting in the adoption of technologies
Design oriented theories	Environment-Behaviour (E-B) theory	[19]	Illustrates the relationship between the design, the user, and the resulting outcomes.
	Integrated energy design (IED)	[19]	Highlights the need for an integrated approach between the architect, engineer, interior designer, facility manager or building operator, and the occupants themselves.
Integrated models	Raaij and Verhallen	Raaij and Verhallen [48]	Addresses energy-related behaviour and energy use in residential buildings.
	DNAS (Drivers–Needs–Actions–Systems) framework	DNAS [22] [25]	Integrates two social driven theories TPB and SCT to determine effects of behavioural interventions and control systems on comfort and energy use in office buildings.

environmental behaviour [34]. However, later research showed that in most cases, increases in knowledge and awareness does not lead to pro-environmental behaviour [33]. Like Heydarian et al., Kollmuss & Agyeman [33] also highlight the *Theory of Reasoned Action* and the *Theory of Planned Behaviour* as relevant within the *attitude-behaviour measurement* theories.

The *Theory of Planned Behaviour* (TPB) developed by Ajzen in 1985 [35], links beliefs to behaviour, and it was intended to expand the *Theory of Reasoned Action* (TRA) created by Fishbein and Ajzen in 1975 [36]. In TPB, three main components shape an individual's behavioural intentions: attitude, subjective norms, and perceived behavioural control. Knowing these would make it possible to predict behaviours. 'Perceived behaviour control' was TPB's addition to TRA. In TRA, if an individual's attitude towards a behaviour is positive, and if they believe significant others want the person to perform the behaviour (subjective norm), the intention to perform the behaviour will be greater and the individuals will be more likely to perform the behaviour. Attitudes and subjective norms influence behavioural intention, and behavioural intention in turn influences the actual behaviour. However, subsequent research showed that behavioural intention does not always lead to actual behaviour when individuals do not think they have control over it. Thus "perceived behavioural control" was added to the TPB theory. Perceived behavioural control refers to the perception of the individuals' own abilities to perform the behaviour. Another commonly used theory is the *Value, Belief, Norms Theory* (VBNT), which similarly proposes that behaviour (such as energy saving behaviour) is driven by personal values and norms, both of which are constructs within the theory [32].

Other theoretical concepts relevant to the domain come from the Environmental Responsible Behaviour (ERB) theory as defined by Hines, Hungerford, and Tomera in 1987 [37]. According to this theory, self-motivation and self-guidance, and not only compliance or rewards, affect behaviour. The major factors affecting responsible behaviour are: Knowledge, Locus of control (perception of whether somebody is able to bring about change through their own behaviour), Attitudes, Verbal commitment, and Individual sense of responsibility [38]. Stern et al. [39] expanded this model with the notion of altruism, differentiating between 'social', 'egoistic' and 'biospheric' orientation.

According to sociological and anthropological models, human behaviour is social and collective, and thus energy models should consider the social context of individual actions. Within Sociological Models investigating behaviour, Kollmuss & Agyeman [33] summarized Fietkau and Kessel's [40] *Ecological Behaviour* model and the *Value–Action Gap* model [41]. The Ecological Behaviour model comprises five variables that influence individual pro-environmental behaviour: Attitude and values, Possibilities to act ecologically, Behavioural incentives, Perceived feedback about ecological behaviour, and Knowledge (which can modify attitudes and values). The Value-Action Gap model identifies three barriers to action: individuality, responsibility (similar to locus of control), and practicality (social and institutional constraints). The model posits that these barriers outweigh environmental concern.

Another social theory used in the ambit of buildings is the Social Practice Theory (SPT). According to this theory, social practices result from the integration of three elements: materials (objects, products, things), skills (know-how, competencies, rule-following abilities), and meanings (embedded symbols, images, ideas) [42,43]. Social theory makes a clear link with a material context (e.g. the building and its interfaces), facilitating the analysis of interaction between the building and its occupants. For example, Morgan et al. [44] used the social practice theory to investigate the social, spatial, and symbolic elements of interactions relating to wellbeing in the building environment, focusing on the physical context of the users. Psychological and behavioural theories focus on the role that knowledge, attitudes, norms and (perceived) control have on behaviour. Sociological models, on the other hand, tend to give more importance to the external (social) factors influencing behaviour, such as feedback, incentives, and responsibilities.

2.2. Physical–technical–economic models

Moving into studies considering an economic and engineering dimension (physical–technical–economic models or PTEM models), *technical models* make estimations of energy flows though physical systems and calculate the energy requirements based on physical laws. *Economic models* go further in exploring human decisions regarding energy usage. They seek to understand the implications of energy prices, taxes, income, and expenditure on household energy use. In these models, individuals are rational actors with consistent preferences, yet a large body of research shows that people do not respond rationally to economic and technical opportunities [45].

Technology adoption theories are the result of sociologists' and psychologists' attempts to understand why people adopt new certain technologies. For example, Kowsari & Zerriffi's *Diffusion of Innovation model* describes a social communication process that influence individuals' decisions in adoption of new technologies [45]. The theory assumes a linear progression of knowledge, awareness, intention, and behaviour resulting in the adoption of technologies. From this, Kowsari & Zerriffi's created a three-dimensional framework based on energy demand, energy carrier and conversion technology fora more realistic assessment of household energy use. The framework integrates personal and contextual variables often neglected in studies on energy use, and they specifically apply it to rural areas.

2.3. Design-oriented theories

Day and O'Brien [19] applied the *Environment*-Behaviour theory and *Integrated Energy Design* (IED), which are design oriented theories, to analyse occupants' behaviour and energy studies to offer lessons learned for future research and design efforts. The (*E*-B) theory illustrates the relationship between the design, the user, and the resulting outcomes; and the IED model highlights the need for an integrated approach between the architect, engineer, interior designer, facility manager or building operator, and the occupants themselves. Both theories emphasize the importance of understanding the interactions among design objectives, interior environment, and resulting occupants' responses (building use patterns and occupants' needs), all of which can have an impact on overall energy use and occupants' satisfaction. Day and O'Brien [19] advocate for the use of qualitative methods, such as survey stories, in addition to physical data collection and other quantitative methods to gain a better understanding of building occupants and their energy-related behaviours.

On the one hand, the main limitation of social, psychological, and behavioural models when being applied to explain occupants' behaviour in buildings is that they tend to be abstract, for example focusing on people's intentions or the opportunities offered by perceived control. This makes behaviours difficult to measure since there is a lack of connection with tangible (and measurable) outcomes such as actual behaviours (actions) or actual control (the actual interaction between people and buildings that in turn affects performance). Furthermore, as these models have not been developed specifically to understand building or energy-related behaviours, they lack a connection with the physical aspects of the buildings, and thus with the influence that the physical context (such as the building itself) has on behaviour. Last, since many of these models come or are very related to behavioural studies, they tend to focus on behavioural change, therefore assuming that a change is possible and necessary, thus neglecting the fact that some 'inefficient' or 'undesirable' behaviours are sometimes necessary for the wellbeing of the buildings' occupants, or due to the constrains brought by the design of building. On the other hand, the limitation of Physical–technical–economic models is that their energy consumption and costs estimates do not match well with real world measurements because they fail to recognise humans as active energy users [45].

According to Lutzenhiser [46] and Shove [47], integrated approaches to household energy use analysis are required to provide a more realistic and comprehensive understanding of energy usage than isolated and disciplinary studies. Such an approach needs to simultaneously address the social and behavioural determinants of energy use as well as economic and technological aspects of energy use.

2.4. Integrated models

The models presented in the sections above focus on a specific area of research, resulting on a lack of a holistic approach needed to tackle the real-life applications in the field on energy efficiency and occupants' behaviour in the built environment. There have been some efforts to focus in a more multidisciplinary approach integrating behavioural theories or socio-psychological theories with building and engineering science [25,48–51]. Among these examples, the most relevant are the model of van Raaij and Verhallen [48] and the DNAS theoretical framework [22], which we introduce below.

The model of Raaij and Verhallen [48] is one of the oldest integrated models. It addresses energy-related behaviour and energy use in residential buildings. In this model, energy-related behaviours are categorised into use-related (frequency, duration, and intensity of use of appliances, systems, lighting, and more), maintenance-related (actions to maintain appliances and systems), and purchase-related (such as household appliances or building components). In this model, occupants' behaviours follow general intentions which are based on energy related attitudes and social norms but are also directly affected by the characteristics of the buildings and appliances, building usage culture, intentions, and the formation of habits. Importantly, these authors posit that habit formation can be influenced through feedback information (coming from energy and behaviour assessments) as well as energy prices and social reference. These external prompts also promote learning processes and internalization of energy related attitudes and social norms. Learning in turn affects the way occupants consider cost-benefit trade-offs, energy knowledge, acceptance of responsibility, and perceived effectiveness. Lastly in the chain of effects, learning about these four factors affects whether someone's general intentions, which are based on energy related attitudes and social norms, turn into specific intentions for behaviour. Energy related attitudes and social norms are, as in other behavioural models, influenced by personal variables, socio-demographics, values, and personality, as well as by general information and building usage culture. Fig. 1 shows Raaij and Verhallen model [48].

More recently, D'Oca et al. [22] proposed a new framework for office buildings that integrates two social driven theories, the TPB and the SCT, into their own physical-led theoretical framework DNAS [25]. Their goal was to be able to determine effects of behavioural interventions and control systems on comfort and energy use in office buildings. The DNAS framework explains the interaction between occupants and building/system as a consequence of occupants' needs (dependent of cognitive factors and biological factors) to perform their daily activities (or actions) in a way that results in their satisfaction. The needs are driven, firstly, by the physical environment (brought by the SCT theory), specifically by motivational drivers in it, group behaviour, ease and knowledge, and a desire for satisfaction and productivity. The TPB completes the DNAS framework, secondly, by adding social environment influence (attitudes, social norms, perceived behavioural control) to occupants' needs and social drivers. They validated their theoretical framework in diverse office settings through a purposely developed survey.

3. Research framework, data, and methods

3.1. Research framework

In the previous sections we have shown that theories and their constructs have already been applied to explain or predict behaviours (interactions of the occupants with the building and building systems). According to Heydarian et al. [32], theories formalise behaviour manifestations, and the constructs within a theory describe operationalizable variables that drive the behaviour manifestations. By formalizing behaviour and operationalising variables, both behaviour and its drivers can be more easily measured or observed.

In this paper, we do not intend to develop a new behavioural theory, but rather to integrate different existing and relevant theories into a single interdisciplinary residential occupants' behaviour theoretical model. This model can be practically applied in the design, implementation, testing, and validation of the effectiveness of (behavioural) interventions and building (systems) designs, including building controls and performance calculations.

We will do this by determining the relations between different constructs (and the different existing theories), and integrating them to more tangible elements, for example actual measurable behaviours. As Heydarian et al. [32] found in their review, while previous research refers both to theories and their constructs when describing user-

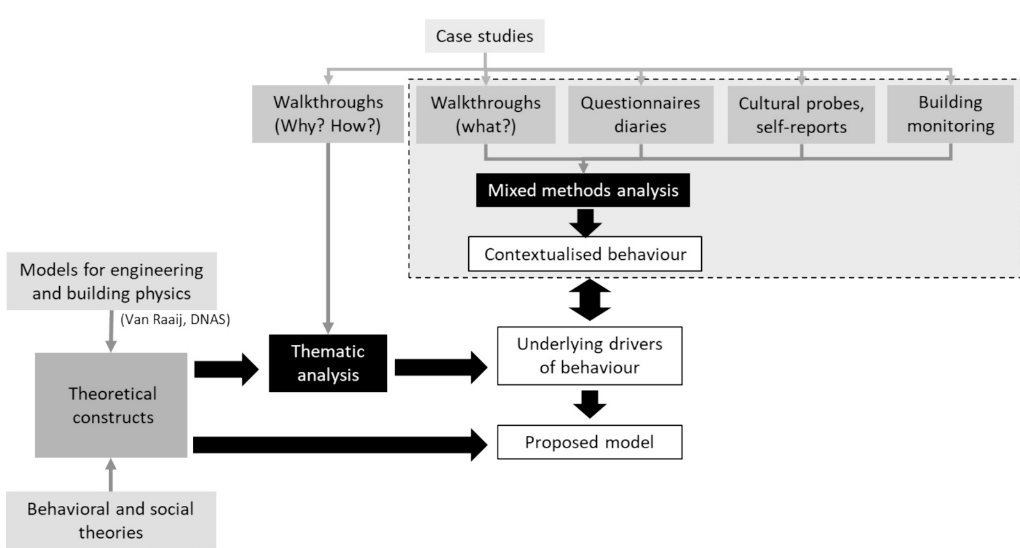

Fig. 1. Research framework in relation to the collected data.

building interactions, others only referred to the constructs. For us, this highlights 1) the need for a more standardised overview of the different constructs and how they relate to each other, and 2) the possibility to build an integrated occupancy behaviour model, using the constructs, which can be employed from the perspective of the different existing theories. Through the use of constructs as indicators for measurable variables, this integration would facilitate the use of these theories, not just the currently predominant research on behaviour (change), but also in building industry practice, such as building simulations, performance monitoring and evaluation, and the design and development of smart buildings and digital twins.

To carry out this research, we have employed building monitoring qualitative and quantitative data from a number of case studies. The proposed model is built up based on the results of the analysis of the monitoring data, which results are presented in Section 4, and the relevant theories seen in Section 2. The research framework showing the steps followed to analyse the data is visualised in Fig. 1. Each case study consisted of diverse data collection methods across different buildings: longitudinal building monitoring, user questionnaires and diaries, walkthrough interviews, cultural probes, and self-reports. As a first step, the data was analysed with a mix-methods approach to determine the contextualised building-related behaviours ('what?'). These resulting observed or measured behaviours (for example, how is the heating system used?, when are windows open?) were used as preparation for the walkthrough interviews, so that participants would talk about the reasons for their actual behaviour (why?). To define the model in Section 5, walkthrough interviews were analysed using thematic analysis to identify the drivers of the contextualised behaviour based on the existing theoretical models. In the following section we first introduce the case studies, and the data collected from them, and then proceed to explain the further steps of the methodology.

In the development of our model, we do not choose a specific existing theory or model, we also do not aim at creating a new theory or model. Our objective is to develop an integrated model that can be linked to all existing theories and that can be used in research and practice from different perspectives. The aim of the research is to find the links between the existing models and theories, expand them with current knowledge of occupants' behaviour in buildings, and to make the first steps towards the instrumentalization of the drivers of occupants' behaviour.

3.2. Case studies

The data used for this research consisted of the results of three different monitoring campaigns in the Netherlands. The monitoring campaigns were carried out between 2016 and 2023. Only monitoring projects in which the objective was to understand occupants' behaviour in residential building were considered. A wide variability of types of dwellings were included: multi and single-family housing, renovated and not renovated, and with different types of heating and ventilation systems. Although some of the most representative Dutch housing typologies are included (multi-family porch flats and row houses), some others are not represented, such as gallery flats. However, given that we focus on occupants' interaction with HVAC systems and windows, the lack of representation of more housing typologies should not undermine the conclusions of this research. The specifications of the monitoring campaigns can be found in Table 2, while the characteristics of the dwellings and households can be found in Table 3.

A small sample is used in this study. Monitoring data from a total of 11 individual dwellings are used for this analysis. However, given the richness the data in each case study, analysis of a much larger sample would be prohibitive, both because of the expenses associated with monitoring buildings, and time-consuming data analysis. Due to the qualitative nature of the interviews analysis, we aimed at finding data saturation. During the analysis, we concluded that data saturation was reached after the analysis of the 11 cases, since the last four cases did not bring many more new insights into the analysis. Recent research has found that about 9 to 17 interviews are usually necessary to reach data saturation in qualitative research [52].

Table 2
Monitoring campaigns.

	Case #1	Case #2	Case #3
Number of dwellings	3	4	4
Monitoring length	1 year	2 to 4 weeks	1 year
Monitoring period	2016	2020	2022–2023
Quantitative methods	Temperature, CO_2, RH, radiators surface temperature Thermal comfort self-reporting	Temperature, CO_2, RH, convectors surface temperature.	Temperature, CO_2, RH, ventilation, windows, and doors opening.
Qualitative methods	Interviews Questionnaire	Interviews Diaries Questionnaire	Interviews Diaries Questionnaire

The monitoring campaigns were all planned around the same two main research questions: 1) What are the behaviour of the occupants in their homes that are directly or indirectly related to energy use? and 2) What are the reasons behind the behaviour? The campaigns varied in the data collection methods due to differences in the characteristics of the dwellings and building systems (i.e. mechanical ventilation, heating system, user-building interfaces, etc.).

Data were collected through diaries, questionnaires, meters, and sensors. In addition to these commonly used methods, walkthrough interviews were designed to obtain data regarding the reasons behind the behaviours previously identified through quantitative data analysis. For the walkthrough in the participants' homes, a specific set of open questions was prepared per case study, since they had different characteristics, systems, interfaces, and household types. To avoid bias from the occupants when answering questions regarding the behaviours and reasons for it, the quantitative monitoring data was analysed before the interviews. Furthermore, the data gathered from the occupants was triangulated with monitoring data. The variety of data collection methods ensure the reliability of the data.

IIn each household, only the adults participated in the interviews, with exception of HH4, where only the mother participated. The participants signed a consent form and were explained their rights regarding their data. The studies complied with ethical procedures of the Universities affiliated to this study. Table 4 shows the data collection methods, the type of data collected, and the intention for the data analysis.

The dwellings in all cases were selected based on the willingness of the residents to participate in the study. Given the need for engagement of the residents in the intensive data gathering for the study, it was important to be welcomed into the residents' homes to carry out the study. The studies were carried out in different years, for different periods of time and in different seasons. However, this does not have consequences for the research, since the subject of the study was not to compare the behaviour of the households, or their energy consumption, which are highly dependent on the weather conditions. Rather, it was to identify underlying reasons, and for this it is advantageous that the data are diverse.

3.3. Methods

3.3.1. Contextualising behaviours through mixed methods analysis

A mixed methods analysis was used to determine the relationships between the occupants' behaviour, actual indoor environmental parameters, and the reason given by the occupants regarding their behaviour. The mixed method analysis aims at linking objective

Table 3
Dwellings and household characteristics.

	Case #1	Case #2	Case #3
Reference name	CF37, CF38, CF39	HH1, HH2, HH3, HH4	HHA, HHB, HHC, HHD
Household characteristics	2-parents' households/2-parents household/single-parent household (father)	Single woman/single man/2-parents household/ single woman	Couple and adult child/couple/couple and child/couple
Dwelling type	Single family dwellings	Multi-family dwellings	Single family dwellings
Dwelling typology	Row house[a], corner house	Porch flat	Row house[a], corner house
Dwelling characteristics	Non renovated	Renovated zero energy	Non renovated
Systems present	Gas boiler, high temperature heating, mechanical ventilation	Heat pump, low temperature heating, mechanical ventilation with heat recovery	Gas boiler, high temperature heating, mechanical ventilation
Interfaces	Manual and automatic thermostats, radiators.	Automatic thermostat, ventilation control panel, convectors with controls.	Manual and automatic thermostats, radiators.

[a] Also called terraced house (UK) or townhouse (US).

Table 4
Data collection methods.

Data collection method	Purpose
Sensor installed in all the rooms in the dwellings: main bedroom, second bedroom, kitchen and living room.	To determine the actual indoor parameters of the dwellings such as indoor temperature, RH, and CO_2. The data provides context to the self-reported data from the residents.
Diaries for the use of ventilation system, heating system and opening of windows and external doors.	To determine the behaviour of people/ households at home regarding the use of the ventilation system, heating system and opening of windows and external doors.
Self-reporting thermal comfort device[a]	To determine in-the-moment self-reported thermal comfort of individual people at home.
(Telephone[b]) questionnaire survey about overall behaviour, satisfaction with the indoor qualities of the renovated home, and attitudes towards the environment.	To determine further factors affecting individual/household behaviour.
Walkthrough interview regarding the use of different system and spaces around the home.	To determine the reasons for individual/household behaviour.

[a] The self-reporting thermal comfort device was only used in case #1.
[b] Telephone questionnaires were used to limit contact due to the Covid pandemic.

contextual measurements (e.g. temperature, CO_2, and RH), with other contextual information that cannot be measured but can be uncovered through the use of questionnaire, diaries, or sensor data (e.g. occupants' lifestyle, heating-related practices at home). This analysis helped to identify the behaviours of the occupants in a specific context (building, systems, season, indoor conditions, etc.). The results from this analysis are the measurable behaviours and outcomes within our proposed model (see Section 5). The following paragraph describes in general the setup of the investigation. For more information on the methods and results, we refer the reader to the specific case study publications [53,54].

For the analysis, the monitored data (temperature, RH, CO_2 concentration) were analysed to determine the actual performance of the building in terms of indoor environmental quality. For this, existing standards and models were used to assess the indoor conditions [55–57]. This step was important to assess objectively the indoor quality of the building, since it is known that thermal comfort can be subjective and influenced by several factors [58]. Furthermore, since the dwellings were monitored in different periods, and their thermal properties were different (i.e. renovated vs. not renovated), it was important to determine the actual indoor conditions per dwelling. A variety of methods were used to show graphically the indoor conditions of the dwelling (heat maps, graphs, etc.) with the objective to communicate the results among the researchers, and the chosen method depended on the preferences of the researchers. The subsequent step consisted of the analysis of monitored (measured) data that can indicate directly or indirectly the occupants' behaviour (i.e. energy-related activities at home), for example occupants' presence and use of spaces, natural ventilation behaviour, use of HVAC systems, showering, etc. For this, variables associated with behaviours were analysed through statistical analysis, machine learning, or graphical means to determine behaviours. Temperature, RH and CO_2 were analysed using boxplots, heatmaps and graphical means (plots). Opening on windows and doors, occupancy and interactions with the HVAC systems were analysed through graphical means to link these behaviours with indoor parameters. In case study 3, where switch sensors were installed in windows and doors, machine learning was employed as data analysis method. The behaviours were then triangulated with information provided by the occupants through diaries and initial questionnaires. During this step, information gaps were identified, for example when a sudden increase in the indoor temperature was seen, a specific question was prepared for the resident of the dwelling during the walkthrough interviews.

This preliminary research was necessary to determine the actual behaviour of the occupants in the building. Knowing the actual behaviour allowed the researchers to asked specific questions to the participants about the reasons behind their behaviour in a concrete way. By measuring actual behaviour, we minimise the risk of the participants to refer to attitudes or drivers that do not actually lead to a real behaviour, which has been a critique made about research focused on behavioural theories [32].

3.3.2. *Defining the drivers for behaviour through thematic analysis*

To develop the interdisciplinary occupants' behaviour model, it was necessary to understand the drivers for the occupants' behaviour in the buildings, and the interrelations between the drivers and other relevant aspects. Grounded theory was used to analyse the data from the walkthrough interviews in the eleven homes within the three monitoring projects. The interviews were transcribed and analysed with support of Atlas software. A second round of coding was carried out to unify all cases.

In the first thematic analysis phase, codes were generated based on previous studies related to occupants' behaviour and occupants modelling but were not limited to them. Any (recurring) theme that explained the interviewers' reasons for carrying out or not an activity/ behaviour were noted. This first coding was carried out by a researcher or research assistant. During the second phase, the codes were labelled into pre-existing groups based, as far as possible, on the constructs of existing behavioural models and theories. Again, extra labels were created based on codes that did not seem to belong to any of the theoretical constructs. This step was carried out always by the main researcher. Given that our model seeks to describe cause and effect relationships (i.e. behaviour is triggered by a cause e.g. a need, and will have a consequence e.g. energy use), the links and relationships between the different labels and themes were also specified, again based on existing behavioural theories (i.e. attitude leading to intention, intention leading to behaviour), but also on technology-based and building physics models (opening windows leading to air quality and indoor temperature).

4. Results

4.1. Quantitative results: observed and measured behaviours

A mixed method approach was used to determine the behaviours based on quantitative monitoring data obtained from sensors (CO_2, Temperature, RH, light, movement, opening of doors/windows), diaries (window opening, use of spaces, presence at home), and other self-reporting means (thermal comfort, satisfaction). Tables 5a, 5b and 5c show the main results of the analysis of each dwelling in the case studies, according to the measurable behaviours in our model (see Section 5). Detail results from these analyses have been reported in other publications [53,54].

These results show that although there are large differences in the building characteristics and building systems within the case studies, the indoor conditions are well within the preferences of the occupants in most cases (except in dwelling HH3). This is shown by comparing indoor temperatures and thermostat settings, and also through the responses given in the questionnaire, where all households reported to be satisfied with their homes and rated their thermal comfort as good or very good. This indicates that in most cases, the occupants' behaviours lead to comfortable and satisfactory conditions for the occupants. The main complaints came from the renovated apartments, where people struggle more to achieve desirable indoor temperatures.

4.2. Qualitative results: drivers of behaviour

Table 6 shows the codes related in the three monitoring projects (Code), the code groups created (Code Groups), the themes in which they were categorised outside Atlas ([Theme]), and how many times each code was applied in the three case studies (Grounded). The column to the right shows the existing theory or model supporting the categorisation focusing only on the most commonly used theories in energy consumption and occupants' behaviour. The themes and codes are defined below. It is important to note that while the number of times a code appear in the interviews (grounded) might be an indicator of how important is that aspect for the specific sample, it is not meant to show how important are some constructs in relation to others.

The results show that although many of the constructs present in the diverse behavioural models and theories can be found in the codes, some codes did not correspond to any theory, for examples specific health conditions, preferences, daily activities, and pets. More importantly, intentions related to care for oneself (health/comfort), and others (care for others) are also overlooked in existing theories, which focus more on economic and environmental aspects.

Furthermore, the results also make clear the need to integrate an engineering dimension to behavioural models, since existing behavioural models tend to focus only on drivers of behaviour, while integral engineering-oriented models (DNAS, van Raaij) also consider the needs, means and actual behaviours.

Sankey diagrams of co-occurrences are used to visualise the connections between the different constructs (i.e. codes). The lines indicate links between constructs, for example if something related to *habits* is mentioned in relation to *opening windows*, a link between these two is shown. Thicker lines in the Sankey diagrams indicate that the link was found in more cases (across all case studies) than those with thinner lines. However, this does not indicate the general importance of a connection and cannot be generalised to the theoretical model.

Fig. 2 shows the Sankey diagram produced in Atlas with the co-occurrence of codes in the analysed interviews. The main energy-related behaviours: opening doors and windows, thermostat adjustment, use of radiators/convectors, use of heating system and use of ventilation system were plotted against all the codes, which are shown grouped in different colours. The colours were applied by the researchers and related to the *themes/code groups* (see in Table 6).

- In orange are the attitudes and norms: attitudes, social and personal norms.
- In purple are background and conditions: demographics, health condition, preferences, and ownership/tenure.
- In yellow are lifestyle aspects: daily activities and schedules, cleaning, hobbies, presence of pets, and work situation.

Table 5a
Results occupants' behaviour case study 1.

Behaviour	HH1	HH2	HH3	HH4
Purchasing/ investment	Not investigated	Not investigated	Not investigated	Not investigated
Maintenance	Not investigated	Not investigated	Not investigated	Not investigated
Heating system: mean temperature in living room (winter)	20 °C	20 °C	22 °C	23 °C
Heating system: setpoint	20-21 °C	18-19 °C	24 °C	18-22 °C
Heating system: setback	None	None	None	None
Heating system: radiators/ convector status	No interaction with convectors.	No interaction with convectors.	No interaction with convectors.	No interaction with convectors.
Appliances use	Not investigated	Not investigated	Not investigated	Not investigated
Ventilation system: mean CO_2 living room (winter)	600 ppm	500 ppm	1300 ppm	550 ppm
Ventilation system: max CO_2 main bedroom at night (winter)	1500 ppm	1700 ppm	3300 ppm	2400 ppm
Ventilation system: setting day	1	1	2	1
Ventilation system: setting showering/ cooking	3	3	3	3
Opening doors and windows: bedroom (winter)	Open at night	Balcony window open	Closed	Windows open during the day
Opening doors and windows: living room (winter)	Closed	Windows constantly open	Closed	Windows constantly open
Opening vents	N/a	N/a	N/a	N/a
Blinds and curtains use for temperature or light control	No	No	No	No
Use of spaces	N/a	N/a	N/a	N/a
Clothing adjustment	Yes	No	Yes	Yes

Table 5b
Results occupants' behaviour case study 2.

Behaviour	HHA	HHB	HHC	HHD
Purchasing/ investment	Not investigated	Not investigated	Not investigated	Not investigated
Maintenance	Not investigated	Not investigated	Not investigated	Not investigated
Heating system: mean temperature in Living room (winter)	19.4 °C	19.5 °C	19.4 °C	18.7 °C
Heating system: setpoint	19–20 °C	20.5 °C	21 °C	19.5 °C
Heating system: setback	15 °C	18 °C	15.5-17 °C	15 °C
Heating system: radiators/ convector status	Off in bedrooms if window open, open in bathroom	Some off.	Off in bedroom if window open, rest half open.	All always open
Appliances use	Not investigated	Not investigated	Not investigated	Not investigated
Ventilation system: mean CO_2 living room (winter)	889 ppm	917 ppm	850 ppm	728 ppm
Ventilation system: mean CO_2 main bedroom at night (winter)	3474 ppm	3947 ppm	2914 ppm	3323 ppm
Ventilation system: setting day	1	3	1	1
Ventilation system: setting showering/ cooking	3	3	3	3
Opening doors and windows: bedroom (winter)	Always open	Open	Open	Always open
Opening doors and windows: living room (winter)	Open	Sometimes open	Open	Closed
Opening vents	Open	Open unless windy	Open	Some open
Blinds and curtains use for temperature or light control	Yes	Yes	No	Yes
Use of spaces	N/a	N/a	N/a	N/a
Clothing adjustment	Yes	Yes	Yes	Yes

- In pink are common knowledge or upbringing, habits, and previous living situation.
- In blue are the intentions: related to caring for others, economy, energy, the environment, (personal) health and comfort, pleasant living at home, and society.
- In red are means: understanding of consequences of behaviours or use of the systems, mental model, (perceived) control, group control, ease of use or convenience, user friendliness, and information or instructions.

Table 5c
Results occupants' behaviour case study 3.

Behaviour	CP17	CP18	CP19
Purchasing/ investment	Not investigated	Not investigated	Not investigated
Maintenance	Not investigated	Not investigated	Not investigated
Heating system: mean temperature in Living room (winter)	17.7 °C	21.6 °C	18 °C
Heating system: setpoint	20 °C	27 °C	20 °C
Heating system: setback	16 °C	19 °C	16 °C
Heating system: radiators/ convector status	Some radiators open, some closed	Some radiators open, some closed	Some radiators open, some half open.
Appliances use	Not investigated	Not investigated	Not investigated
Ventilation system: mean CO_2 living room (winter)	840 ppm	658 ppm	616 ppm
Ventilation system: max CO_2 main bedroom at night (winter)	2296 ppm	2845 ppm	2323 ppm
Ventilation system: setting day	N/a	N/a	1
Ventilation system: setting showering/ cooking	No	No	3
Opening doors and windows: bedroom (winter)	Open at night	Closed (vent open)	Closed (vent open)
Opening doors and windows: living room (winter)	Closed, open in the kitchen while cooking	Closed	Closed
Opening vents	Open	Open	Open
Blinds and curtains use for temperature or light control	No	No	No
Use of spaces	N/a	N/a	Used of spaces according to thermal comfort
Clothing adjustment	Yes	No	Yes

- In cyan are the occupants' needs: acoustic comfort, fresh air (air quality), humidity level, needed spaces, privacy, safety, thermal comfort, visual comfort, accessibility, access/contact with nature, tranquillity and trust.
- In green are the behaviours: maintenance, purchase/investing, daily behaviours directly affecting energy use (appliances usage, cooking, cooling, showering, use of HVAC systems), and daily behaviours indirectly affecting energy use (opening of doors and windows, use of spaces, clothing adjustment, and use of curtains and blinds).

The overall Sankey Figure shows the large influence of all driver types on the behaviour of opening windows and doors (middle of figure). Preferences, activities and schedules, habits, need for fresh air and need of thermal comfort are the drivers occurring the most in our case studies interviews (left of figure). The figure also shows how the opening of windows and doors also occurs along other behaviours (right of figure). For clarity, the same information but separated per driver type are shown in Figs. 3 to 6. Following subsections explain the relationship between occupants' behaviours and the diverse identified drivers.

4.2.1. *Attitudes and norms vs. occupants' behaviour*

Fig. 3 shows the co-occurrences between occupants' behaviours and attitudes and norms. Personal norms seem to influence the use of clothing adjustment and other non-energy related practices to achieve

Table 6
Codes and groups.

Code groups [theme]	Code	Grounded	Existing theory or model
Attitudes and norms [Attitudes and norms]	A Attitudes	64	TPB, Van Raaij and Verhallen, DNAS
	A Personal norms	13	TPB, DNAS (personal motivational drivers)
	A Social norms	7	TPB, Van Raaij and Verhallen, DNAS
Drivers [Background and conditions]	DA Demographics	3	Van Raaij and Verhallen
	DA Health condition	17	N/a
	DA Preference	39	N/a
	DA Ownership/ tenure	3	N/a
Drivers [Lifestyle/daily life activities]	DB Activity/ schedule	92	N/a
	DB Cleaning	30	N/a
	DB Hobbies	3	N/a
	DB Pets	19	N/a
	DB Work	9	N/a
Drivers [Habit]	DC Common knowledge/ upbringing	8	N/a
	DC Habit	77	TIB
	DC Previous situation	12	TIB
Behavioural intentions [Intentions]	I Care for others	34	N/a
	I Economy	26	Van Raaij and Verhallen
	I Energy	31	Van Raaij and Verhallen
	I Environment	26	DNAS (env. motivational drivers)
	I Health/ comfort	27	N/a
	I Satisfaction/ sense of home	41	DNAS (satisfaction)
	I Society	5	N/a
Means [Actual control through interfaces – building/systems' characteristics]	INT Appliances	24	Van Raaij and Verhallen (building characteristics), DNAS (physical environment, systems)
	INT Convector/ radiator	11	
	INT Doors and windows	10	
	INT Heating system	28	
	INT Hot water system	6	
	INT Thermostat	2	
	INT Ventilation system	45	
Means [Means]	M Understanding	43	TPB, Van Raaij and Verhallen (i.e. energy knowledge), SCT
	M Mental Model	49	Van Raaij and Verhallen (perceived effectiveness, acceptance of responsibility, cost-benefit trade-off), SCT
	M (Perceived) Control (Incl. autonomy and capacity)	32	TPB, DNAS, SCT
	M Group control	24	DNAS (group behaviour, intention to share control)
	M Ease of use (convenience)	20	DNAS (ease and knowledge)
	M User friendliness	1	N/a
	M Information/ instructions	48	Van Raaij and Verhallen (specific information, feedback)

Table 6 (*continued*)

Code groups [theme]	Code	Grounded	Existing theory or model
Needs [Needs]	N Acoustic comfort	12	DNAS (Needs)
	N Air quality/ fresh air	60	
	N Humidity	16	
	N Needed spaces	34	
	N Privacy	8	
	N Safety	5	
	N Thermal comfort	140	
	N Thermal comfort (draught)	14	
	N Visual comfort	5	
	N Accessibility	2	
	N Nature	5	
	N Tranquillity	3	
	N Trust	1	
Behaviour [Seasonal behaviour]	OB Maintenance	34	Van Raaij and Verhallen
Behaviour [Seasonal behaviour]	OB Purchasing/ investing	1	Van Raaij and Verhallen
Behaviour [Non-energy related]	OB Recycling	7	N/a
Behaviour [Energy related-direct]	OBD Appliances usage	32	Van Raaij and Verhallen (usage-related energy behaviours), DNAS
	OBD Use of ventilation system	38	
	OBD Cooling	11	
	OBD Use of heating system	27	
	OBD Thermostat adj.	46	
	OBD Use of convector/ radiator	16	Van Raaij and Verhallen (usage-related energy behaviours),
	OBD Shower	23	
	OBD Cooking	14	
Behaviour [Energy related-indirect]	OBD Opening doors and windows	151	DNAS
	OBD Opening vents	25	N/a
	OBI Clothing adjustment	25	N/a
	OBI Non-energy related solutions	21	N/a
	OBI Use of curtains blinds	16	DNAS
	OBI Use of spaces	28	N/a
External influences	EXT (Local) weather	16	N/a
	EXT Renovation process	12	N/a

thermal comfort, as well as showering behaviour, and to the (more or less intensive) use of the heating system. For example, in the interviews the respondents refer to the importance of upbringing and their attitudes towards the environment when choosing whether to put on a sweater instead of turning higher the heating system. According to R1 "*Why would you turn up the heating and use raw materials when you can also grab the sweater that is in the closet*"; while R2 mentions: "*It also has to do with your upbringing. You know that you can also put on a sweater*" (C37).

Attitudes related to care for others is associated to the use of doors and windows for ventilation, as well as to the use of the ventilation system and thermostat adjustments, although not only in relation to family members or guests but also to pets. For example the residents of

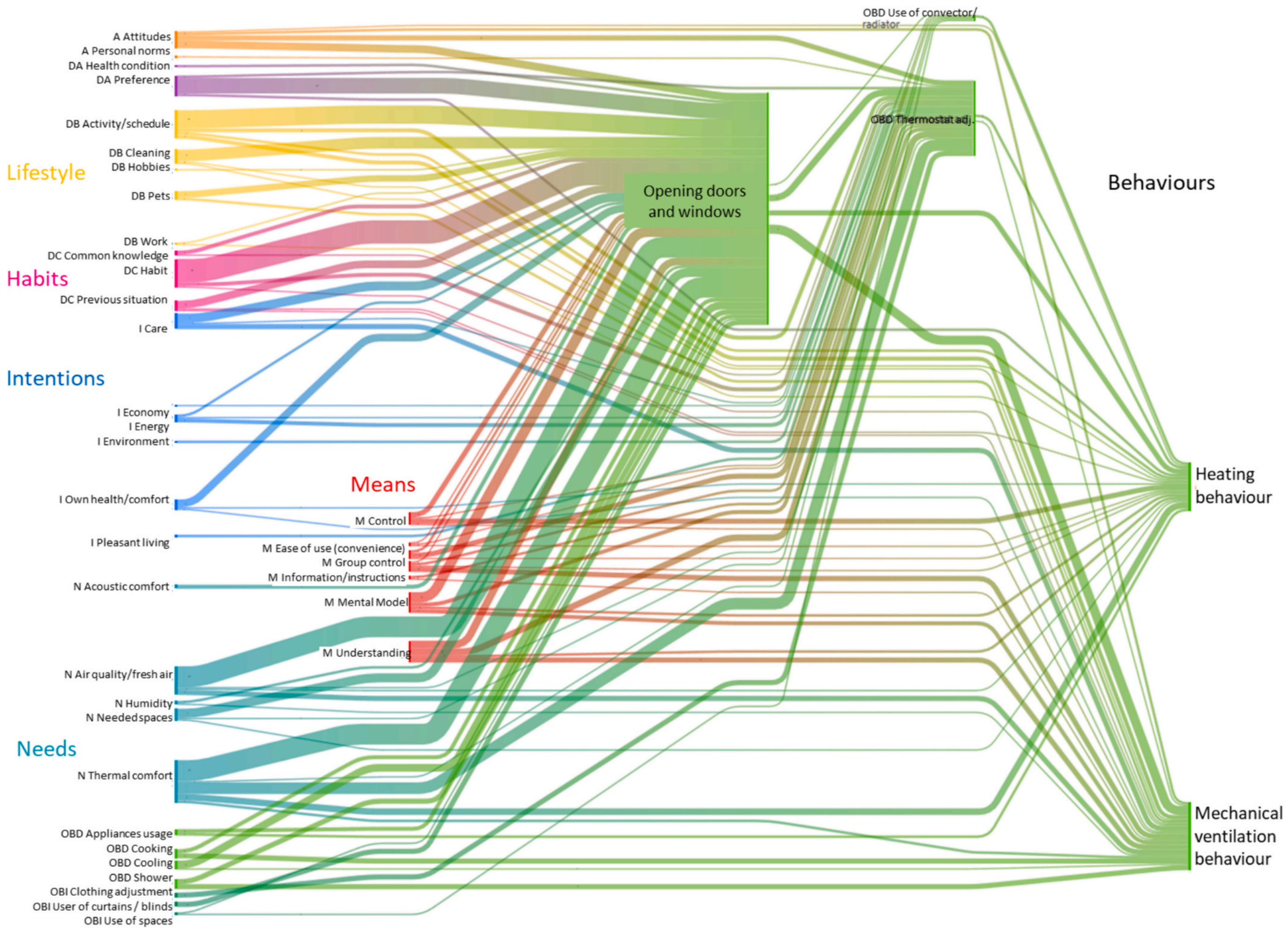

Fig. 2. Sankey diagram of co-occurrences between main energy related behaviours and all other factors.

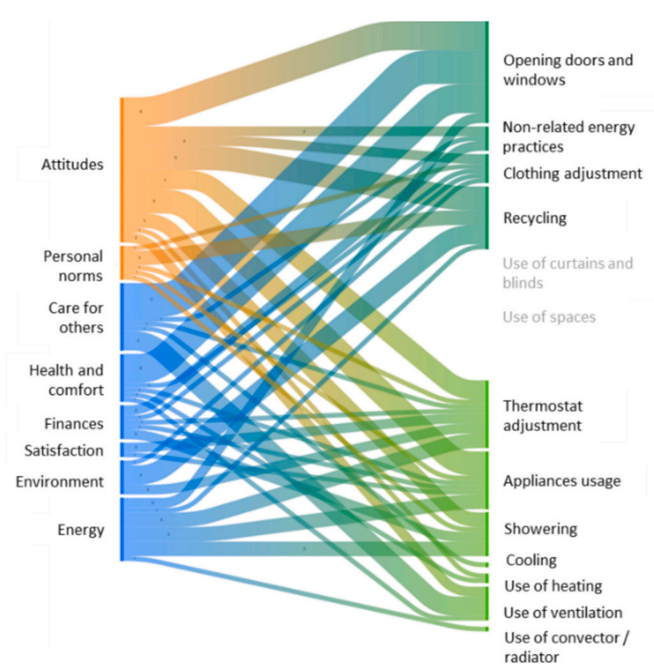

Fig. 3. Sankey diagram of co-occurrences between occupants' behaviours and attitudes and norms.

HH4 mentioned her cats as the reason to open the balcony door: "*For the cats, they can then sit on the balcony and also for fresh air*", while HH1 and HH4 mentioned visitors as the reason to set the heating higher: '*…and I had the heating on 21 for my grandchildren, but they are only here one day a week*' (HH1);"*… for example my mother-in-law, who is always cold. But she comes from a flat where it is always 23* (C37).

Attitudes related to health and comfort showed to be very often associated to opening doors and windows, and to a lesser degree to the use of the ventilation and heating systems. For example, indoor air is important for HH2: "*when I exercise myself, it gets very stuffy quickly, so then I have to open windows and balcony door and living room door too*"; while C38 values comfort more than energy consumption: "*I think comfort is the most important thing. I'm not going to sit in the house with extra sweaters…. There are people who turn the heating down 3 degrees and they sit on the couch with a sweater on. Well, if I hate something then it's cold, so yes, I would prefer to be on Curacao, in 30 degrees*!".

Both directly and indirectly energy-related behaviours were associated to household finances: users seem to see a direct relation to the costs for energy for their showering behaviour, appliances usage and for the adjustment of thermostat, and see that clothing adjustment and other non-energy related practices have a positive influence on costs. For example, in words of HH2: "*I assume that if you put it on 18, then you save energy. So. And if I don't need 19, why do I need to put it on 19 if that's just going to cost money?*" Cultural attitudes towards finances were mentioned by the respondents of C37 "*Well, just call it Dutch stinginess. Why would you turn up the heater when you can also just grab a blanket.*"

Attitudes towards the environment are seen mostly in relation to

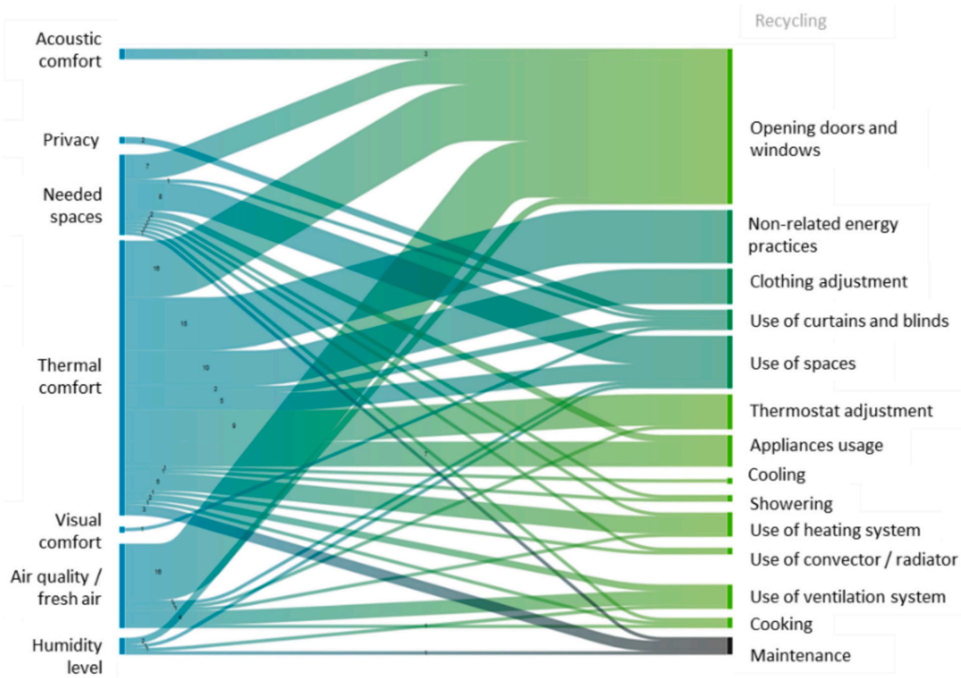

Fig. 4. Sankey diagram of co-occurrences between occupants' behaviours and needs.

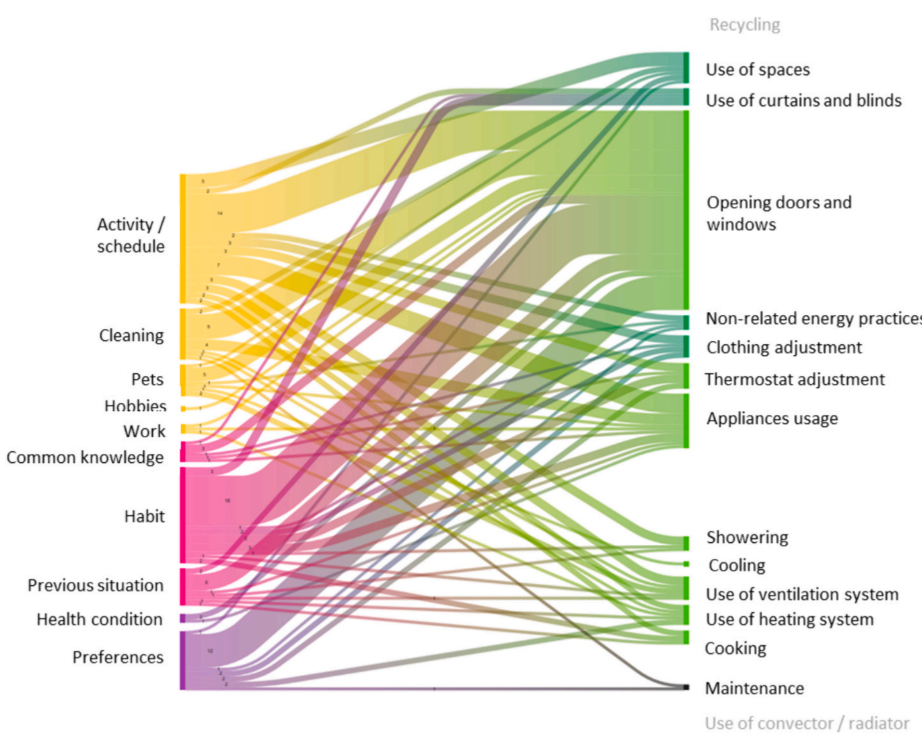

Fig. 5. Sankey diagram of co-occurrences between occupants' behaviour and lifestyle, habits, and background.

recycling behaviour and to a lesser extend to thermostat or clothing adjustment, while attitudes towards energy use (regardless of whether it is linked to the environment or to costs) is seen mostly in relation to showering, appliance usage, thermostat adjustment, and as a consequence of opening of doors and windows. Here is a quote from C37 regarding recycling attitudes: "*…the new kitchen has a very small garbage can, but I was happy with it because if a small garbage fills up so quickly, then you can also try to make it fill up less quickly. So that is an attempt to have less waste.*"

4.2.2. Occupants' needs vs. occupants' behaviour

Fig. 4 shows the co-occurrences between occupants' behaviours and identified needs. The most often co-occurrences are seen in relation to thermal comfort and to the need for fresh air (air quality). Need for fresh air is mostly associated with opening doors and windows, and to a much lesser degree to the use of the ventilation system, even though 4 out of 7 of the monitored houses had good heat-recovery ventilation system. For example, the need for fresh air in the winter is mentioned by HH2 in the case study with heat recovery ventilation: "*if I can't sleep, then I go to the*

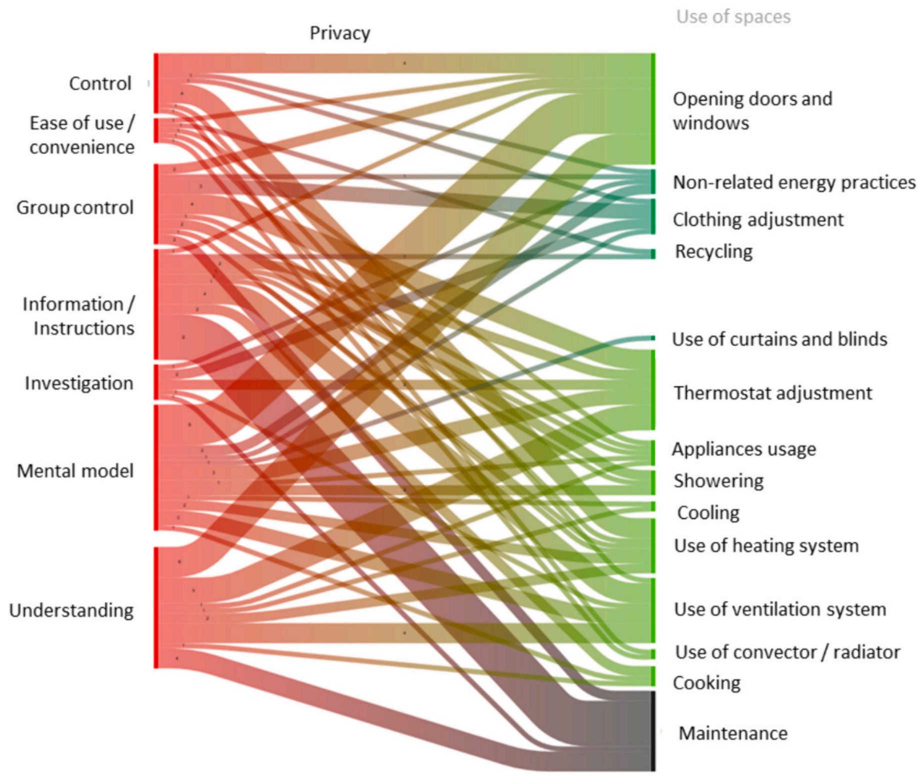

Fig. 6. Sankey diagram of co-occurrences between occupants' behaviour and means.

toilet and then I open the balcony door right away". However, opening windows and vents during the winter in the bedrooms of less airtight houses is also common, as mentioned by the respondents in C37: "*we always prefer to have it open a bit. Because if everything is closed, then we do not sleep well;*" and the respondent in C38: "*In winter, unless the wind is blowing, I always have the vents open. I find that nice and fresh in the bedroom.*" The respondents from HHD also make a direct reference to health: "*Here the windows are open day and night… and the vents are also opened for my asthma. When I have the window closed, I don't sleep. Then I don't get enough oxygen*".

Thermal comfort is more often associated to indirectly related energy behaviours, specially to opening doors and windows, clothing adjustments, use of spaces, and other non-energy related practices. For example, HH1 mentions opening the window in her bedroom to cool it down: "When I wake up, I often feel the need to open the window, but that's mainly because I feel hot". HH4 and C37 mention adjusting clothing level to achieve comfort. HH4 says: "in the winter I am more inclined to get a blanket instead of turning on the heating". Quoting C37: "We are more likely to put on a cardigan or a sweater... Because why should I walk here in my short sleeves with 20 degrees?"

Some directly related energy behaviours are associated with thermal comfort, for example thermostat adjustment, but these co-occurrences are seen more often in the non-renovated houses, indicating that thermal comfort is less of a worry in the renovated homes. For example, respondents in C37: "*Well I start with a blanket, and yes then I turn it up by 2 or 3 degrees at most*".

Appliance usage is also an important co-occurrence, and this is usually related to the use of extra heating appliances in the homes.

4.2.3. Drivers related to lifestyle, habits, and background vs. occupants' behaviour

Fig. 5 shows the co-occurrences between occupants' behaviours and drivers related to lifestyle, habits, and background and conditions. The most important relationships are seen between opening doors and windows and habits and occupants' activities/schedules (including cleaning), indicating that opening windows behaviour is not only a reaction to restore thermal comfort or to provide fresh air. For example, HHD refers to habits related to upbringing to open doors: "*I can't help it, my father always left all the doors open. Sorry, it's in the genes*"; while HHC refers to habits related to daily lifestyle: "*in the morning, as soon as the heating turns on, the window also opens… but I've always done that, like in my previous house*".

Furthermore, preferences are also often connected to opening doors and windows. On the other hand, use of heating systems is not often mentioned in relation to these drivers. Natural ventilation is therefore embedded in the daily routines of people, either based on activities or habitual preferences. For example, HH4 and C37 prefer colder bedrooms: "*in the winter I just open my window when I go to work. I just like that, a cool room*" (HH4). "*Actually, we open windows as much as possible ajar. And we try to open the vents as much as possible at night. Because I love to just sleep with fresh air*" (C37).

4.2.4. Means vs. occupants' behaviour

Fig. 6 shows the co-occurrences between occupants' behaviours and means available to the occupants. The most frequent co-occurrences are seen between opening windows and doors and control, mental models and understanding. These are usually related to the lack of control and understanding (and therefore trust) over the other building systems (ventilation or heating), and the mental model that users have.

Thermostat adjustment is associated often with group control, mental models, information and understanding, while the heating system as a whole is mentioned often in relation to (lack of) control, but also understanding and mental models. Although part of the heating system, the use of convectors and radiators was less mentioned by the participants in relation to means, mostly because they tend to interact little with these.

For example in the energy-neutral homes, residents mentioned the lack of control given by the heating system and their way to cope with it. For example HH1 mentioned that to control the temperature in the bedroom "The only thing you can do is open the window". The resident of this home especially felt the difference with the previous situation: "if I started cleaning, I could turn off the heating for a while. Then I feel more comfortable to clean. And when I finished, I just put it back on 20 or 21 and within an hour it will be that temperature again, but now it's just not like that any more… if it cools down then you just don't get warm any more". Resident of HH2 also compained about the lack of control with the heating system: "The convector doesn't work. "The control is not good. With one the lights go on, with the other not. Or they go on and off quickly."

The use of the ventilation system was a usual subject in the interviews in the renovated homes, and less often in the non-renovated homes. This was associated to understanding of the system, mental models and the feedback provided by the interface (information). For example, HHB justified their lack of knowledge on how the system works: "*it was already there when we came here, so we were only told how to view the control panel, but not how the rest of the operation is.*" On the other hand, HH4 explains how she knows that the ventilation system is working: "*I usually put it on the loudest. I don't really know why but I think it's the most effective*".

5. The proposed model

Fig. 7 shows the proposed model. The model was built upon the results from the case studies analysis presented in the previous section, and on existing theoretical models introduced in Section 2. The model is completed based on previous research on the factors associated with occupants' behaviour or energy consumption. In this section the model is explained from left to right.

5.1. Drivers

Background and other occupants' conditions **[A]** refer to the characteristics of the occupants. The factors previously identified as influencing behaviour and energy consumption are: demographics or non-economic household characteristics, such as household composition, gender, age, background or country or origin, and preferences associated to it (e.g. cooking) [45,59–62]; socio-economic factors or economic household characteristics, such as employment status, income, education and housing tenure [45,60–64]; health related habits or health condition (i.e. smoking, limited mobility); and preferences for comfort [31]. These aspects usually remain unchangeable for a long period of time and will directly influence the occupants' *attitudes and norms* **[B]**, their *lifestyle* **[C]**, and their *habits* **[D]**. For example, a highly educated expat from a warm country might care about the environment but might prefer (and be used to) higher indoor temperatures.

Attitude refers to the degree to which a person has a favourable or unfavourable evaluation or appraisal of the behaviour in question [65]. Norms refer to shared beliefs, as well as expectations and aspirations. Personal norms are the individual expectations that people hold for themselves [66]. Social norms (also called subjective) are individuals' beliefs about the extent to which others expect them to engage in a behaviour [32]. According to existing behavioural models (TPB, TRA), these *attitudes and norms* **[B]** define the occupants' (behaviour) *intentions* **[E]**. Occupants' *lifestyle* **[C]** or daily life activities, defined here as ways in which the occupants decide or have to live (daily activities, presence of pets, work situation, cleaning activities and hobbies) [45] may be temporary and can be influenced also by *attitudes and social norms* **[B]**. In the context of occupants' energy-related behaviour at home, *habits* **[D]** can have a defining and direct role on *behaviour* **[I]**. Habits can generate from common knowledge passed through family members (for example morning airing routines) or might come from previous behaviour. For example, occupants that still open a window in the kitchen of their newly renovated home when cooking, even though an efficient extraction hood has been installed. Habits are particularly important in renovated homes and in new (energy efficient) homes, due to the presence of new technologies, which functioning is usually unknown by the occupants. These habits might have to be modified when new controls, systems, information, and knowledge are present (Means **[G]**).

The occupants' *lifestyle* **[C]** directly defines the occupants' indoor

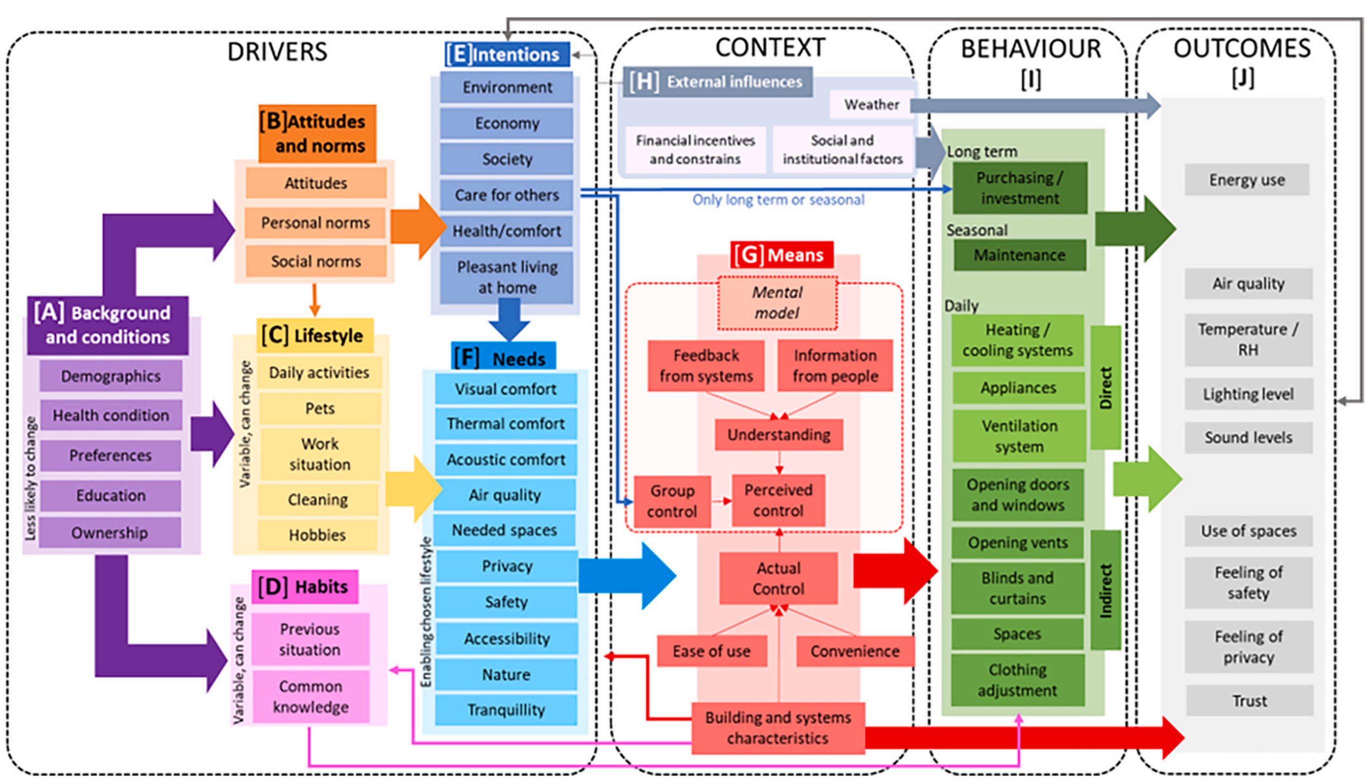

Fig. 7. Proposed occupants' behaviour model.

environment *needs* **[F]** at home. In the context of this research, occupants' needs are defined as indoor environment needs at home such as visual, thermal, and acoustic comfort, air quality, as well as the use of spaces and their sense of privacy (i.e. visual contact with neighbours and to the street), safety, accessibility, access to nature and tranquillity. These indoor environment needs would complement and support some of the basic needs defined in Maslow's hierarchy of needs pyramid as physiological needs and safety needs [67]. According to Locke and Kristof [68] in [69] a need is translated into an (instrumental) activity (i.e. behaviour) to fulfil the need. For example, a person working from home will need to heat the house all day long.

Behavioural intentions **[E]** are influenced by *attitudes and norms* **[B]**. According to Ajzen [70], behavioural intention is an individual's readiness to perform a given behaviour and it is assumed to be an immediate antecedent of behaviour. In previous research, behavioural intentions related to saving energy for economical or environmental reasons (including energy) have been mostly studied, because most of the studies focus either on energy efficiency in office buildings [22], or on changing behaviour for environmental reasons. Satisfaction as behavioural intention has been also identified [22], although in the context of residential buildings, we have renamed it as "pleasant living at home". In the proposed model, we also consider other factors such as the household's finances, care for society in general, care for others (guests, family members, pets), own wellbeing (health and comfort), and society (doing or not doing something in benefit of society), since these are recurring themes in the case studies.

Behavioural intentions have been assumed to be an immediate antecedent of behaviour. For example, a household concerned about the environment might prefer to use extra jumpers at home instead of turning on the heating higher in cold days. In another example, some occupants might decide to turn on the heating higher or lower when caring for pets or (visiting) family members. However, to achieve this behaviour the occupants have to interact with the building systems, which might enable or disable them to satisfy both their intentions and needs. Thus, in this study we add the layer of *context* between intentions and behaviour.

5.2. Context

With the incorporation of low carbon technologies in buildings, occupants are faced with complex systems that are difficult to operate, which can lead to an increase on energy consumption and a decrease in overall satisfaction [71–73]. Thus, the way in which the occupants interact and understand the building becomes an important factor on occupants' behaviour and building performance. Human-building interactions are highly context-dependent [24]. There is evidence that human-building interactions are driven by contextual factors such as building conditions and characteristics [25,26]. However, most studies fail to provide a systematic analysis of the contextual factors [28]. Thus, the technology available and other building characteristics will affect people behaviours. On the one hand, not all technology is available to all potential users, for example smart meters and digital displays. On the other hand, for some people, the use of these technologies might be challenging [74]. Several authors have stressed the importance of providing clear operation manuals and inductions to new homes [75,76], or better visualization of the energy use and systems. All these factors affect the perceived behavioural control of the user, which is defined as the individuals' beliefs about their ability to act a behaviour (capacity) and whether or not their actions are completely under their control (autonomy) [45].

As mentioned before, in current behavioural models, the occupants' intentions are usually interpreted as the actual behaviour, although the actual behaviour is never measured [32]. These models assumed that an intention to carry out a specific behaviour will translate into acting said behaviour. However, as seen in multiple research studies, this is often not the case [77,78]. Therefore, in our proposed model, in addition to *needs* **[F]**, we add a layer of *means* **[G]**, which are here defined as the conditions that allow the users to perform the behaviour that will satisfy their needs, according to their intentions. This is similar to material culture, which is defined as technology and infrastructure that influences the use of energy [45]. Some of these means had already been defined by Van Raaij and Verhalen [48] as 'intervening factors between attitudes and behaviour' such as: acceptance responsibility, perceived effectiveness, energy knowledge and cost-benefit trade off; and in the TPB as perceived behavioural control. However, in existing models, these factors influence the intention, while in our model, these influence the execution of the intention and the satisfaction of needs. Furthermore, the influence of the presence of technology and the interaction of occupants with it are often neglected. Our model follows the idea of the Social Cognitive Theory [79], acknowledging the fact that situational factors (the physical environment, including building characteristics and systems) and people's understanding of technologies (behavioural factors such as self-efficacy, skills and practice) influences behaviour. These factors can still affect the intentions to carry out a behaviour (as stated in existing models) but in the study of specific behaviours of people in relation to the use of systems, an extra layer is needed. For example, social norms can influence the attitude that individuals have towards environment care, and their knowledge on energy efficiency can increase their feeling of control to live an environmental friendly life, however, if the means to save energy are absent in their homeplace (e.g. a faulty thermostat, lack of feedback, etc.), they will not be able to enact their energy-saving behavioural intentions.

Therefore, in this model *means* are defined as: the *actual control* of the occupants on the building and building's systems, the occupants' *understanding of the building's systems* functioning and the consequences to their actions, and the occupants' *perceived control*, which is influenced by the other two. The actual control is defined by the building characteristics, systems, and interfaces available, as well as their user friendliness, *ease of use* and *convenience*, but also by organisational factors or *group control* within the building, for example household members might be forbidden to change the thermostat settings at home.

The occupants' understanding of the building's systems functioning and the consequence to their actions is more often seen in newly built or renovated buildings when innovative technologies are implemented. This understanding depends on the type of *information* given to the occupants during the delivery of their (new) building (e.g. manuals, guidelines, induction process), and on the type of *feedback* that the occupants receive during occupancy (e.g. thermostat display). In our model, the set of factors related to the users' understanding of the systems and their functioning, as well as their perceived control over them is defined as *mental model*.

Furthermore, we have *external aspects* **(H)** influencing, both the behaviour of people, and their original intentions. Among these are: local weather condition, energy prices, financial incentives, macro-level economic, social, energy, and policy factors [80–82], and in the case of renovated homes, the renovation process itself [14]. For example, weather conditions will not only affect energy consumption through the building systems (e.g. in cold days the building will require more energy), but also influences the behaviour of people when they open windows, close curtains, or spend more time indoors or outdoors.

5.3. Behaviour and outcomes

According to Balvedi et al. [11], occupants' behaviour is defined by human-building interactions related to energy use. However, many actions that impact energy consumption are not targeted at energy use itself but the services it provides [11] (e.g. comfort, cosiness), and occupants follow daily practices that can lead to higher or lower energy use (e.g. wearing extra layer of clothes). Thus, in the context of this research, occupants' behaviour comprises the activities that occupants carry out at home that are directly or indirectly related to energy consumption and indoor environmental quality. Occupants' behaviour can then be seasonal (maintenance activities, investment on low carbon technologies) [48] or daily. Daily behaviours are here categorised into directly energy-related (use of HVAC systems, showering, cooking), thus, the activities that require energy to be performed; and indirectly energy related (opening windows and doors, clothing adjustment, use of curtains and blinds, use of spaces, etc.), thus, the activities that do not required energy to be performed but that influence energy use. While direct behaviours have been considered widely in previous energy research, indirect behaviours have been only more recently incorporated [22].

Thus, in our model, *occupants' behaviours* **[I]** are distinguished according to their frequency: *daily*, *seasonal*, *and long term*. Daily behaviours are those carried out frequently and embedded in the daily life of people. Seasonal behaviour refers to the activities carried out according to the season or every few months or years, for example maintenance of a heating boiler or changing ventilation filters. Long term behaviours are those that require purchasing and a larger investment, such as renovation activities, improvements of the building, or repairing unexpected break downs. This can also include the purchase of appliances, solar panels etc. In our model, we also make a distinction between *direct and indirect energy usage behaviours*, which refer to behaviours that directly use energy, or to the behaviours (or practices) that influence energy use or indoor environment but that do not consume energy themselves. For example, turning the heating on is a direct behaviour, while opening a window is an indirect behaviour.

Another important difference between long term and seasonal behaviours, and daily behaviours is in relation to how much they are actually influenced by the occupants' intentions. As mentioned previously, current behaviour models directly link the intention to the behaviour and assume that an intention will eventually lead to the behaviour. However, our study suggests that the *means* available to the occupants will define the final execution of such intentions. Furthermore, when people explain their behaviour, they often do not link their behaviours to an explicit intention. Instead, a behaviour or action is presented more as a reaction to attain a specific purpose related to a need (for example restoring comfort).

On the other hand, although in our case studies we have not focused directly on purchasing or investing activities, we do have soon-to-be renovated homes. Purchasing and investing behaviours, such as home repairs and renovations, might be influenced by available means (for example, information), but it is likely that the intentions have a larger direct influence on them. In previous models, Van Raaij and Verhalen [48] had already differentiated between different types of energy-related behaviours in their model: purchase-related, usage-related and maintenance related. Thus, a direct link has been made in the model between intentions and long term/seasonal behaviours.

On the far right of the model, we can see the outcomes. *Outcomes* **[J]** are here defined as measurable consequences of the interaction between occupants' behaviour, building characteristics and external factors such as weather conditions. The outcomes are also related to the intentions since they can be seen as indicators to measure of whether the intentions are meet. For example, energy consumption can be measured to determine whether the intention to save energy for environmental or economic reasons is met, while indoor temperature and air quality can determine whether the intention to take care of oneself and others are satisfied.

5.4. Constraints of the model

A limitation in the model is in relation to the contextual factors influencing purchasing and maintenance behaviour since these longer-term behaviours were not studied in this investigation. In social housing, tenants are not always given choices regarding maintenance or renovation, and thus their preferences, intentions and needs might not be reflected in choices made by housing associations. In addition, this research did not investigate the factors driving the purchasing of energy-efficient electronics or appliances. Therefore, further research should be aimed at identifying the interaction between maintenance and renovation processes carried out by housing associations, the (lack of) participation of the tenants in the process, and how these decisions might affect seasonal or purchasing behaviours.

6. Discussion

The model proposed in this paper is meant to close the gap found in the literature presented in Section 1, which is the need for a more comprehensive, context-based, updated model for occupants' behaviour in residential buildings. The model is meant to complement existing models, since it builds up on them for specific application goals, for example to support user-centric design, to support the evaluation of building performance, and to support the incorporation of occupants' behaviour on building simulation models, building control and digital twins.

The limitations of exiting models have been defined as 1) the lack the (technical) detail to measure and evaluate behaviours and other constructs of the models, 2) difficulties to model contextual aspects, and 3) overfocus on behavioural change. The proposed model has been built both from a top-down approach by considering relevant models and theories, and from a bottom-up approach by studying the actual behaviour of people and the drivers for it. Thus, by utilizing monitoring and self-reporting data, the model shows that it is possible to make a direct connection between expected and actual outcomes to determine the influence of behaviour, and therefore of the drivers of behaviour, on the actual performance of buildings. Furthermore, explicit study on actual behaviours in real settings provides information on the contextual aspects, such as the building and systems characteristics, and highlights their importance. Last, by focusing on the actual needs and requirements of the occupants, as well as considering their background, lifestyle, and habits, it is possible to make a distinction between 'unexpected' behaviours that are inefficient, and those that are necessary to the specific occupants.

This research showed that there are two main sets of factors affecting behaviour and the intentions for behaviour: underlying drivers that are often overlooked (background, lifestyle, habits, and needs), and contextual factors (means and external factors).

Fig. 8 is an adaptation from the research by Heydarian et al. [32] and it shows the connection between our proposed model (presented simplified at the bottom of the figure but with the same colour scheme) and exiting models and theories. Different aspects of our model are shown linked and colour-coded to other models and theories. On the top left, are drivers on individual level. In orange, *attitudes and norms* in our model is expanded with the existing psychological and behavioural theories (introduced in Section 2). Blocks in orange form part of our model (since they directly affect intentions), while blocks in grey are complementary to our model.

On the top right are the contextual factors. These can be *social factors*, *external* economic, policy or market influences, and factors related to the physical environment (*means*). SCT (boxes in green) links directly the contextual drivers (*means* and *social factors* in our model), and the individual level drivers.

In the centre, *means* in our model (boxes in red area) are connected to *perceived behavioural control* that belongs to the TPB, *facilitating conditions* that are part of the TIB, and *skills*, *practice and self-efficacy that are* part of the SCT. This is the part of our model that differs the most from current models, since we considered that means have a prominent role, since instead of having an influence on intention, they directly affect the ability to perform a behaviour.

6.1. Underlying drivers of behaviour

Behavioural intentions have been previously identified in behavioural science models as predictors of behaviour. Although previous

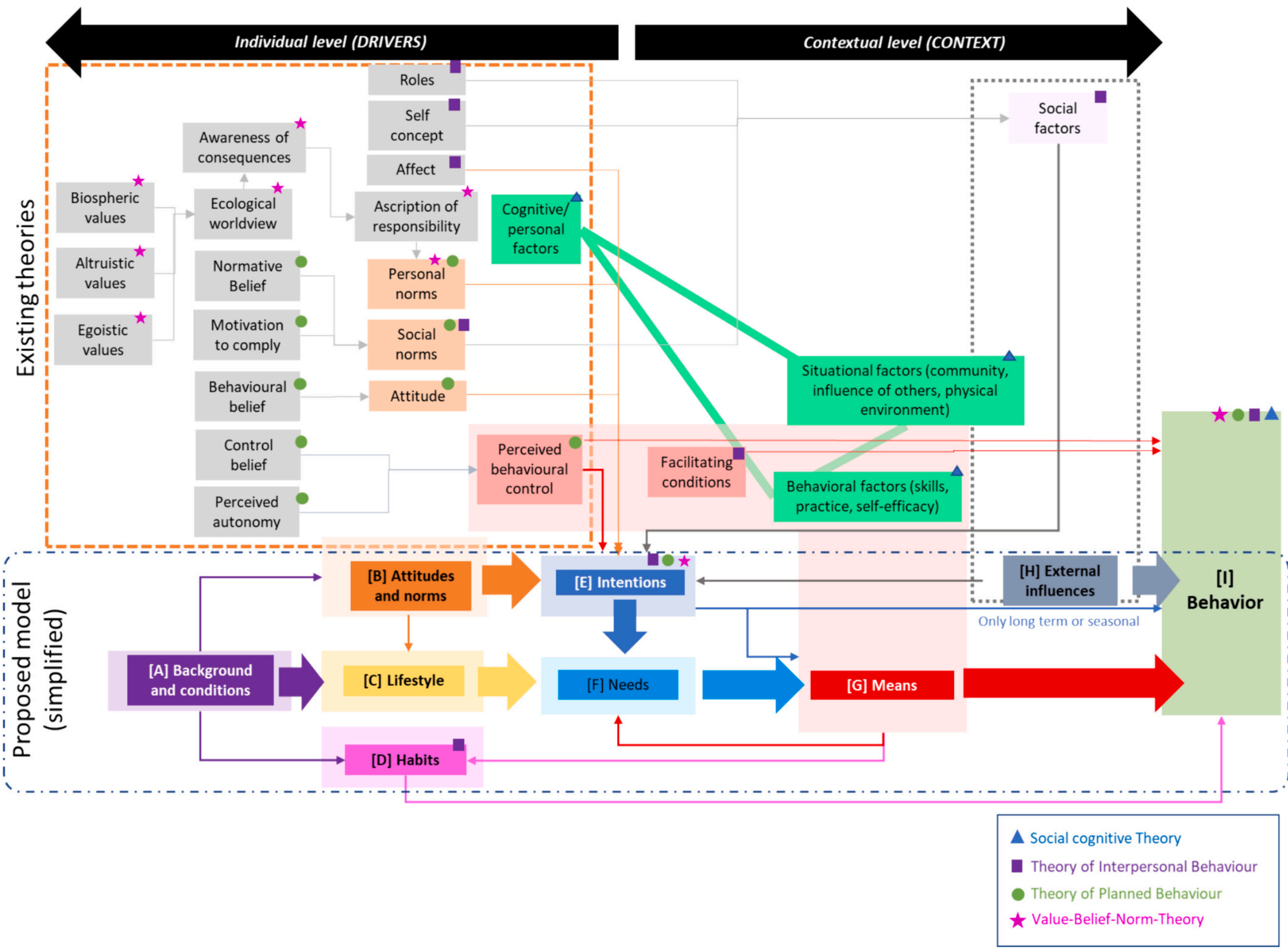

Fig. 8. Connection between proposed model and existing models.
(Adapted from Heydarian et al. [32]).

research focuses more on environmental or financial intentions, we identify other intentions that influence behaviour, such as care for others (including pets), own health and comfort, and pleasant living at home. In our research, these drivers do not directly lead to a behaviour since other drivers and contextual factors contribute to it. These factors are the needs of the users and material, and information means to enact the intended behaviour.

Other underlying drivers found in our model, and that had been previously found to be related to either occupants' behaviour or energy consumption, are lifestyle, habits, and occupants' background. These aspects are usually not part of behavioural or social theories but have been taken into account in several cases applied to energy-related behaviour in buildings, as Heydarian et al. [32] found in their literature review.

The underlying drives of behaviour (and their intentions) as classified as A) background and conditions, B) attitudes and norms, C) lifestyle, D) habits, and E) needs. Within attitudes and norms, drivers have been simplified in this model to focus on more tangible and measurable aspects of behaviour. However, as Fig. 9 (adapted from Heydarian et al. [32]) shows, most models from behavioural and social science can be 'connected' or expanded (see top left) to the 'attitudes and norms' in our model (bottom). Thus, research using current behavioural and social science models can employ our proposed model as an aid on the testing and evaluation of behaviour and its drivers.

6.2. Contextual factors: means and needs

The characteristics of the building and systems, as well as the building/system-user interfaces will influence the way people interact with the building, and thus the way they behave. Building-user interfaces (e.g. HVAC system controls) can influence greatly the occupants' behaviour since they can either enable or disable the users to perform the desired activity (behavioural intention). Furthermore, the understanding that the users have about the functioning of the systems, and the mental model of their home, have a big influence on behaviour, especially in building with more complex or unknown systems, while in non-renovated homes, people can make use of traditional mental models. In our case studies, we encountered the fact that mental models' elements are more often mentioned in renovated homes because a new mental model needs to be created, while in non-renovated homes, habits and common knowledge helps people to solve problems more easily (e.g. decrease energy use, restore comfort). Furthermore, in renovated energy efficient homes, we found that behaviour is less driven by attitudes towards the environment and norms, and more by the need to create a comfortable environment, indicating the struggle of people to control the systems to achieve comfort, and highlighting the importance of the 'Means' layer in our model.

The proposed model has borrowed some elements from the model by van Raaij and Verhallen [48], DNAS framework [22], and from the application of behavioural models mostly often used in energy research in social sciences (TRA, SCT, TPB). The model from Raaij and Verhallen is very complete in terms of taking into account also maintenance and purchasing, as well as the 'intervening factors between attitudes and behaviour (thus, realising that an intention does not immediately materialise in a behaviour), and the importance of feedback and knowledge. However, it needed to be updated to reflect the advances in the development of behaviour models, as well as the advances on building technology. In their review on studies focused on occupants' behaviour from the perspective of behavioural theories, Heydarian et al. [32] found studies in which behaviour related to the use of HVACs and windows operation were associated with feedback and information received, type of systems available, need for fresh air or thermal comfort, and to reduce noise.

Furthermore, in our interviews, residents rarely explained their behaviour in relation to behavioural intentions (i.e. care for others), but on specific needs (i.e. the need to heat the house because grandson is visiting), although the need originates on the intention. Needs are also influenced by the identified underlying drivers of behaviour (background, habits, and lifestyle) and by the buildings' characteristics. Thus, needs and intentions are closely related but describing needs makes more tangible such intentions, making them also easier to recognise, measure and evaluate. The identification of needs as influences of behaviour have been identified in frameworks and models applied in engineering sciences, such as D'Oca et al. [22] DNAS framework.

6.3. Limitations of the model

This model focused on understanding the behaviour of people in buildings, especially in residential settings. This model could be applied to non-residential buildings by explicitly incorporating some aspects from the DNAS model that are important in communal settings, such as in intention to share control (within 'care' in INTENTIONS), and group behaviour (within 'actual control'/'organisation characteristics' in MEANS). Satisfaction and productivity from the DNAS [22] model should also be included in the INTENTIONS part of the model, but from the perspective of all building users.

This study was conducted in social housing in the Netherlands in a relatively small sample of homes. Monitoring data and interviews were necessary to understand behaviour and thus, a small number of cases were analysed. Social housing in the Netherlands is provided to low-income households by private, non-profit organisations within strict and specific regulations. Although similarities in the drivers for behaviour might be similar to those of occupants of social housing in other countries, some specific drivers might differ in other countries. For example, some drivers might be influenced by how maintenance of the building is organised, how stable are the rents, or what are the specific household conditions required to have access to social housing. Further, comparative international research will be needed to answer these questions. However, although the findings from the interviews are therefore only conclusive for occupants of social housing, to build up the model, findings from previous research on the whole building stock were taken into account and incorporated as needed. Analysis of more interviews of monitoring projects could help validating the model.

Another limitation of the model is the relatively small role of social theories, represented mostly by the SCT. In the framework of this research, we consider that social influence might have a more prominent role in behavioural aspects of behaviour that are more socially visible, like those related to the mid- and long-term behaviours in our model (i.e. the installation of photovoltaic panels). Given that we are focusing on daily household behaviours, these social influences are considered less relevant. However, future research will be endeavoured to understand the relationship between daily and mid- and long-term energy related behaviours, for which social theories should be considered.

6.4. Advantages of the model

The main advantage of the proposed model is that it has been conceived from the point of view of its application in practice. We see a large variety of applications according to the field of study. For example, in behavioural studies, the model can help the researchers to determine what behaviours, building and household characteristics, and energy end uses to measure in order to test specific interventions being investigated. On the other hand, researchers from engineering fields, could use the model to investigate the reasons for underperforming buildings. For example, by looking at a higher-than-expected gas bill, a researcher could use the model to determine what type of data to gather to conduct a post-occupancy evaluation, investigating not only the behaviours leading to higher gas consumption, but also the drivers for using the heating system, or using natural ventilation while the heating is working.

7. Conclusions

The objective of this paper was to propose an updated occupants' behaviour model for residential buildings. The model can be used to determine occupants' behaviour, their underlying drivers, and consequences, to assess and evaluate more accurately the building performance in monitored projects, for the extraction of data from monitoring projects to inform the design process (for both new and existing buildings), and to inform building simulations for energy prediction and building control.

The model integrates relevant models and theories from behavioural and social sciences that have previously been applied to energy research, and multidisciplinary models used in engineering sciences, with actual, contextualised behaviours and drivers of behaviours observed and measured in monitoring projects in the Netherlands. Thus, with this study we test (and expand) theoretical frameworks with actual data. For this, thematic analysis was used to determine the underlying drivers for behaviour and their relationships, focusing on existing theoretical constructs. Theoretical constructs and their theories were used to further identify the relationship between the drivers, context, and behaviours. Furthermore, this theoretical occupants' behaviour model can be also applied in behavioural and social sciences research for the evaluation of interventions or other research outcomes. The proposed model helps identifying tangible aspects related to occupants and their behaviours (i.e. needs, means and underlying drivers) that can be more directly identified and measured. Thus, our model can be expanded with the Theory of Planned Behaviour (or other models or theories) for studies or interventions intended to modify behaviour or can help users of the TPB to predict more accurately occupants' behaviour by considering more explicitly the context of the behaviour (e.g. the building and its systems).

7.1. Recommendations for industry stakeholders and policy makers

This research has shown that diverse factors affect occupants' behaviour and therefore building performance. However, in practice, little attention is still given to these aspects during the design and the monitoring of buildings and systems. In regular practice, it might not be possible or cost-effective (yet) to include these diverse drivers for behaviour in building performance simulations or building control systems. Nevertheless, by considering their influence on behaviour, it might be possible to understand better the discrepancies on building performance, and to provide the right feedback to both, designers and occupants to improve it.

7.2. Directions for future research

Future research is aimed at the operationalisation of the intangible aspects of the model (the drivers) through existing methods to collect and analyse data. In particular attention will be paid to the link between outcomes and intentions, and on practical ways to apply the model to the usual problems faced by the building industry introduced in this paper: for building simulations to calculate of energy demand and indoor environmental quality; for (energy) building performance evaluation (either to certify or improve it); and 3) to aid in the design of user-centric buildings, interfaces, and smart (control) systems.

Furthermore, as mentioned before, given that the development of this model was based on data obtained through interviews carried out in monitoring campaigns, the number of case studies is limited. Further research will aim at validating this model with interviews data from more monitoring studies. Furthermore, the case studies were located in the Netherlands, thus further research should be aimed at the drivers for behaviour in other countries or regions. Since monitoring campaigns are resource consuming, further research will be also aimed at developing questionnaire surveys to further validating these findings, and as an alternative form of data collection when monitoring/interviewing is not feasible.

Last, future research should be directed to the instrumentalization of the recognition of the different drivers for behaviour, for their application in regular building practice involving building simulations, building monitoring, and building control.

CRediT authorship contribution statement

Olivia Guerra-Santin: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Luyi Xu:** Writing – review & editing, Investigation, Data curation. **Stella Boess:** Writing – review & editing, Methodology.

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

Data will be made available on request.

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