ePANACEA

Smart European Energy Performance Assessment & Certification

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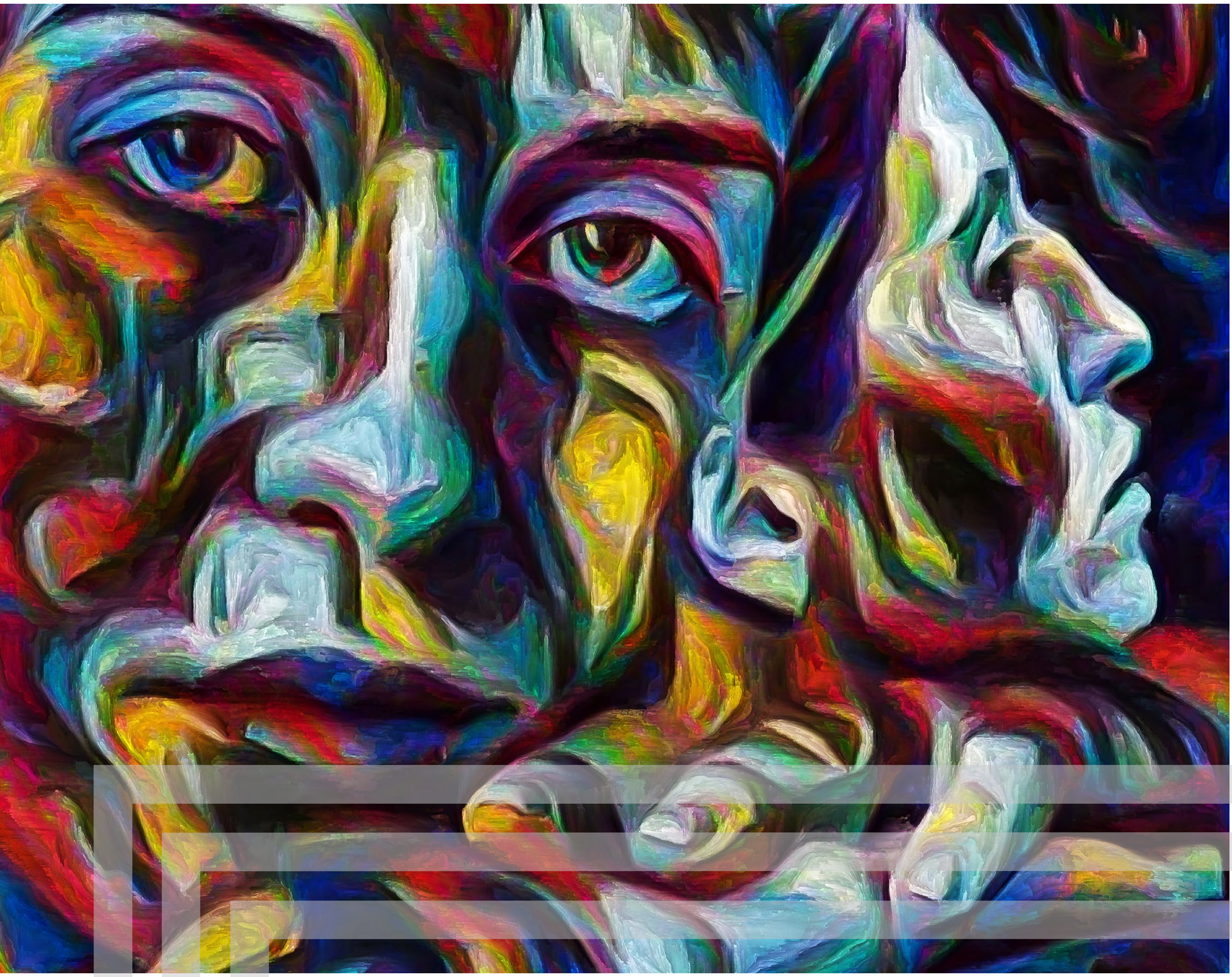

The human factor in energy use in buildings

Fact sheet on energy-related behaviour patterns in the context of buildings

Version 1, July 2021

IZES gGmbH – Institut für Zukunftsenergie und Stoffstromsysteme

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OVERVIEW OF THE EPANACEA PROJECT

After 10 years of track record, the current EPC schemes across the EU face several challenges which have led to a not full accomplishment of their initial objectives: lack of accuracy, a gap between theoretical and real consumption patterns, absence of proper protocols for inclusion of smart and novel technologies, little convergence across Europe, lack of trust in the market and very little user awareness related to energy efficiency.

The objective of the ePANACEA project is to develop a holistic methodology for energy performance assessment and certification of buildings that can overcome the above-mentioned challenges. The vision of ePANACEA is to become a relevant instrument in the European energy transition through the building sector.

ePANACEA comprises the creation of a prototype (the Smart Energy Performance Assessment Platform) making use of the most advanced techniques in dynamic and automated simulation modelling, big data analysis and machine learning, inverse modelling or the estimation of potential energy savings and economic viability check.

A relevant part of the project is to have a fluent dialogue with European policy makers, certification bodies, end-users and other stakeholders through two types of participatory actions: a feedback loop with policy makers, carried out through the so-called Regional Exploitation Boards (REBs) covering EU-27+UK+Norway on the one hand, and dialogue with end-users, established by means of specific thematic workshops, on the other.

Thanks to these participatory actions, the acceptance of the ePANACEA approach will be tested and validated in order to become aligned with and meet the needs of national public bodies, end-users and other stakeholders.

ePANACEA will demonstrate and validate reliability, accuracy, user-friendliness and cost-effectiveness of its methodology through 15 case studies in 5 European countries.

EXECUTIVE SUMMARY

The energy consumption in buildings is determined by diverse factors, one of which is energy-related occupant behaviour. Currently, occupant behaviour is not well understood which leads to its inadequate representation (standard occupancy profiles) in building energy modelling (BEM), facilitating the performance gap regarding the energy performance of buildings (EPB). Therefore, this fact sheet aims to increase our understanding about energy-related occupant behaviour. Also, this fact sheet seeks to provide us with information on the development of user profiles for a more accurate integration of the user dimension in the ePANACEA methodology.

For this, a desktop research was conducted, encompassing a review of different types of occupant behaviour, factors influencing it, existing occupant behaviour models and user profiles for the integration in building energy assessment. The literature review was framed by a focus on everyday energy behaviour, taking all building uses into account and considering building-related (e.g. space heating) as well as occupant-related (e.g. DHW; appliances) energy use. Regarding factors influencing energy behaviour, the focus is on occupant-related factors. A feedback session with part of the project partners (CENER & VITO), who are involved in the methodology development in ePANACEA, took place in order to ensure that the fact sheet will contain useful information for them. Despite the focus on everyday energy behaviour, the literature review also covers behavioural interventions that can motivate behavioural change, in order to acknowledge the fact that behaviour is subject to change and can contribute to increase the energy efficiency of buildings. This fact sheet presents the processed information from the literature review and derives the conclusions for the ePANACEA methodology from it. Furthermore, this fact sheet includes a draft user profile interface, representing the information that constitutes the user dimension regarding energy-related occupant behaviour in buildings.

GLOSSARY

The following abbreviations are used in this report.

BACS	Building automation and control system
BEM	Building energy modelling
BES	Building energy simulation
BPS	Building performance simulation
DHW	Domestic hot water
DNAs	Drivers needs actions systems
EEM	Energy efficiency measure
EPB	Energy performance of buildings
EPC	Energy performance certificate
GHG	Greenhouse gas
IBID.	Ibidem (i.e. in the same place), used to indicate that a reference is from the same source as mentioned before
IEQ	Indoor environmental quality
NAM	Norm activation model
NRB	Non-residential building
SCT	Social-cognitive theory
SRI	Smart readiness indicator
TPB	Theory of planned behaviour
XML	Extensible markup language

1. INTRODUCTION

This chapter explains the importance of understanding 'energy-related occupant behaviour' in terms of building energy simulation. In this sense, it points out the importance of energy consumption in buildings with regard to climate change mitigation, the factors influencing energy consumption in buildings, followed by the influence of occupant behaviour on energy consumption. After that, it presents the performance gap (i.e. the discrepancy between theoretical and real energy demand of buildings), which is partially caused by the insufficiently accurate consideration of energy-related occupant behaviour in building energy simulation (BES). Finally, this chapter outlines the objective, scope and limitations and the structure of this fact sheet.

1.1. Energy consumption in buildings

Buildings play a pivotal role regarding the global energy consumption and greenhouse gas (GHG) emissions: they make up 40% of the worldwide energy consumption and produce a third of the global GHG emissions (Ahmad *et al*. 2018). Therefore, one of the key strategies to reduce climate change impacts is to improve building energy efficiency. To pursue this strategy, one measure is to design new constructions as low-energy buildings (Simanic *et al.,* 2020). However, the total energy consumption in buildings keeps rising according to the international energy agency's (IEA) *energy efficiency 2017 report* (Wagner & O'Brien, 2018). On the one hand, energy efficiency (mainly driven by technology and policy) increases; on the other hand, efficiency gains are exceeded by the increasing average floor area per person (Wagner & O'Brien, 2018). This suggests that other factors than technology and policy instruments influence energy consumption, and that additional measures are needed in order to reduce energy consumption in buildings. Energy consumption has become an important social issue, not only for residential but also for workplaces (Schwartz *et al*., 2010). Organizations consume a large amount of electricity and cause 20% of the global emissions, emphasizing the necessity to contribute to reducing electricity demand (Russell *et al.,* 2016; Staddon *et al.,* 2016).

1.1.1. Factors influencing energy consumption in buildings

Factors from a variety of categories influence energy consumption in buildings. According to Yoshino & Chen (2016), **building energy consumption is in general mainly influenced by six factors:**

1) Climate
2) Building envelope characteristics
3) Building services and energy systems characteristics
4) Building operation and maintenance
5) Occupant activities and behaviour
6) Indoor environmental quality (IEQ)

related to human

The latter three factors are related to human behaviour and their influence is reported to be at least as high as of the first three factors (Yoshino & Chen, 2016). These six factors have also been identified as most influential in the *annex 53-total energy use in buildings* (Hong *et al*., 2016). Furthermore, Huebner *et al.* (2015) describe the extent of the influence on energy consumption by different variables as follows: "building variables explain 39% of the variability in energy consumption; socio-demographic variables explain 24%, heating behaviour 14% and attitude and other behaviours only 5%" (Huebner *et al.,* 2015, p.589). But, a "combined model encompassing all predictors explained only 44% of all variability indicating a significant extent of multicollinearity between predictors" (Ibid.). Hence, the results suggest that more than half of the variability in energy consumption cannot be explained. **Concluding, the uncertainty regarding factors influencing energy consumption is large.** Likewise, a study by Guerra Santin, Itard and Visscher (2009) showed that only 4.2% of the energy use was determined by occupant characteristics and behaviour, whereas building characteristics determined a large part of the energy use in a dwelling (42%). However, they remarked that the effect of occupant characteristics might be larger than expected, since occupants determine the type of dwelling or HVAC systems which in turn have an influence on occupant behaviour (strategic behaviour influences habitual energy behaviour). Also, Huebner *et al.* (2015) state that choices about the dwelling type itself can be considered as a type of behaviour. The focus of this fact sheet is on non-building aspects that affect energy consumption. Despite this focus we need to remember that geographical and building characteristics play a pivotal role in shaping the amount of energy consumption (Huebner, Cooper & Jones, 2013).

1.1.2. The influence of occupant behaviour on energy consumption

The variance in energy consumption on the household level due to residents' behaviour is an international phenomenon (Hong *et al*., 2017). **Hong *et al.* (2017) describe that the primary consumers of energy are occupants, not buildings, because they seek comfortable personal conditions and conduct tasks which require energy.** Different information on the theoretical extent of the influence of user behaviour on energy consumption can be found in literature: "Differences in individual behaviour can produce large variations (>300%) in energy consumption, even when controlling for differences in housing, appliances, HVAC systems, and family size" (Janda, 2011, n.p.). Clevenger and Haymaker in Yan *et al*. (2015) concluded that maximizing and minimizing occupant-related variables theoretically lead to a variance of 150% in energy consumption or more. Moreover, plug loads can account for more than 20% of the total building energy consumption (UBA, 2020; Yan *et al*., 2015) with associated "uncertainties between occupants or households as high as a factor of 400%" (Yan *et al*., 2015, p. 267). Hence, the extent of the influence is quantified differently; however, the reported impact is large either way. Nevertheless, these numbers are surprising in view of the small influence of occupant behaviour on total energy consumption quoted above. One reason for this could be that the values quoted here relate more to user-related energy behaviour (use of plug loads), than to building-related energy consumption (such as heating) referred to above.

Regarding the impact of occupant behaviour in the workplace (open-plan office) Hong *et al.* (2017) point out that occupants with a wasteful work style use up to twice as much energy as the non-wasteful employee. According to Delezendeh *et al.* (2017) a study on the energy consumption of six commercial buildings in South Africa showed that 56% of the total energy consumption occurred during non-working hours. This is because occupants fail to turn off the HVAC system and lights prior to leaving the buildings. This indicates again the impact occupant behaviour can have on building energy consumption. Hong *et al.* (2017) report similar findings.

The behaviour of residents has far-reaching consequences insofar as it does not only influence the energy performance of buildings (EPB), but also the costs for the consumed energy and the impacts on the environment (Tam, Almeida & Le, 2008). Despite the focus of this fact sheet, we need to bear in mind that regarding heating and cooling of a building other aspects such as building physical characteristics, location and the quality of the technical building systems have a greater influence on energy consumption than person-related variables (Csoknyai *et al.,* 2019).

1.1.3. The performance gap: discrepancy between theoretical and real energy consumption

The 'performance gap' defines the difference between the theoretical and real energy consumption in buildings (Guerra-Santin *et al*., 2018). The performance gap exists for any type of building, including non-domestic ones (Menezes *et al*., 2012). The causes of the performance gap are manifold: according to Guerra-Santin *et al*. (2018) it is caused by the 'pre-bound effect' (i.e. real energy consumption is smaller than assumed) and 'rebound effect' (i.e. real energy consumption is higher than assumed). In contrast to this, de Wilde (2014) groups the causes into three main categories:

1) Causes rising in the design stage
2) Causes rooted in the construction phase (including handover) and
3) Causes that relate to the operational stage.

Causes rooted in category two are e.g. installation faults, malfunctioning of the engineering plant systems and poor performance of the building (Hong *et al.,* 2017). Causes related to the operational stage e.g. refer to an insufficient integration of user-related characteristics and occupant behaviour in building simulation tools (Guerra-Santin & Silvester, 2016). The reasons for the performance gap are individual for each building and in many cases there will be a combination of several causes (de Wilde, 2014). **Consequently, all of the causes need to be addressed in order to minimize the performance gap (Simanic *et al.,* 2020). However, the aim of this factsheet is to better understand energy-related occupant behaviour in order to take it into account more precisely in the energy assessment and thus to make a contribution to reducing the performance gap.**

1.1.4. Occupant behaviour as contributing factor to the performance gap

There are multiple references in the literature stating that inadequately presented energy behaviour in building energy models (BEM) are main contributors to the performance gap (cf. Hong *et al.,* 2017; Tam, Almeida & Le, 2018; Laarroussi *et al*., 2019). For instance, Yan *et al.* (2015) report that occupants' behaviour significantly affected energy consumption predictions, though weather conditions, the building envelope and the equipment had been well defined. Next, Gram-Hanssen & Georg (2017) state that here is a significant difference between the predicted and actual EPB as soon *as the use phase begins*. For low-energy buildings, relying on passive design features (e.g. natural ventilation, or use of daylight) or proactive interaction between occupants and building systems, the prediction error for energy is even larger (Hong *et al.,* 2017). This indicates an increased importance of occupant behaviour to reach energy performance, which can result in a larger performance gap if it stays absent.

Also, with regard to the intention that electricity consumption should be included in energy performance certificates (EPCs), while the user dimension is currently insufficiently taken into account, we understand that the performance gap would become even larger (since electricity consumption is more dependent on user-related variable than e.g. gas consumption).

From this, we perceive that building users may play a critical role; which however is yet "poorly understood and often overlooked (…) in the built environment." (Janda, 2011, n.p.). Our limited understanding of occupant behaviour leads to overly simplified assumptions, resulting in "inaccurate expectations about EPB and large discrepancies in building design optimization, energy diagnosis, and building energy simulations" (Yan & Hong, 2014, p.3). Accordingly Delzendeh *et al.* (2017) state that the performance gap is caused by deterministic methods and the use of unrealistic schedules (of occupancy) in building simulation tools. The employment of an 'average household' and 'average building occupancy' leads to – in some cases – lower real energy consumption than expected (cf. pre-bound effect). This may be due to large differences between the standardized occupancy patterns and the real occupancy patterns, resulting from a large diversity in household characteristics, preferences and lifestyles (Guerra-Santin *et al.,* 2016).

The pre-bound effect refers to the situation when energy savings are lower than assumed because the energy consumption was overestimated before the renovation (Guerra-Santin *et al.,* 2018). Thus, the pre-bound effect has consequences for the economic viability of energy retrofit programs because cost savings might be smaller than expected. This means that the payback period for low-carbon technologies would be longer in reality than calculated (Guerra-Santin & Silvester, 2016). Another consequence of overestimating energy use for domestic hot water (DHW) in the design phase may be that more thermal insulation is required in order for the building to theoretically meet the national building energy requirements, which means higher capital investment costs (Simanic *et al*., 2020). Furthermore, because the demand for more energy efficient buildings is increasing, the building company is challenged to guarantee that the predicted EPB at the design stage is complied with, once a building is occupied and used (Menezes *et al*., 2012).

Concluding, in order to achieve high-performance and low-energy use in commercial and residential buildings, it is –among others - pivotal to understand occupant behaviour (Hong *et al.,* 2017). Furthermore, a better comprehension is necessary for a more accurate integration of occupant behaviour in BES. For this, we need to understand both the existing behavioural patterns and the factors causing those (Guerra-Santin & Silvester, 2016).

1.1. Objectives

The ePANACEA project aims at addressing the current challenges of the EPC which includes - among others – reducing the gap between calculated and measured energy performance of buildings. One measure to address this issue is to use more accurate and additional input data for the energy assessment, e.g. (for this fact sheet most important) making better assumptions of the occupant behaviour. Therefore, this document seeks to provide information in the form of a fact sheet to better understand energy behaviour. Thereby, it presents the state-of-the-art of the (in)actions that constitute energy behaviour, the factors that influence it, different methods to model occupant behaviour and interventions strategies to change behaviour. Furthermore, this fact sheet provides information for the methodology development of the next generation of EPC in the ePANACEA project. More precisely, it provides first conclusions for the choice of user profiles for the integration into the ePANACEA methodology.

1.2. Scope and limitations

With regard to energy use in buildings, we identified three dimensions that predetermine energy use in buildings: the temporal dimension, the use/function of the building and the type of energy service (e.g. space heating or use of electrical appliances which are associated with the use of different assets such as gas or electricity).

On a 'temporal level' we can distinguish energy behaviour which is strategic (i.e. one-off/one-shot actions) or habitual (Verbong, Beemsterboer & Sengers, 2013). Habitual energy behaviour comprises everyday practices such as heating behaviour (Huebner *et al.,* 2015), clothing, use of electricity and plug loads, use of fans and air conditioning and hot water, window opening behaviour (Delzendeh *et al.,* 2017). These actions are referred to in chapter 3.3. One-off/ one-shot behaviours require monetary investments and reduce energy consumption. They can be distinguished into energy efficient retrofit investments and adoption of energy efficient appliances (Trotta, 2018). We can assume that strategic and everyday energy behaviour is each influenced by different factors. According to Huebner *et al.* (2015) the impact of strategic behaviour on energy consumption is larger than curtailments linked to everyday practices. **However, for this fact sheet we focus on habitual energy behaviour because it is primarily important for the integration in BES.** An exception to our focus is behavioural change (such as saving energy), which can be viewed as strategic energy behaviour. Behavioural change is considered in this fact sheet for the sake of completeness because everyday energy behaviour is not static but dynamic. Nevertheless, we are aware that other strategic behaviour such as the choice of a dwelling or the initiation of energy efficiency measures (EEMs) also impacts everyday energy use. Behavioural change is also interesting as a way of increasing energy efficiency.

Moreover, the use of a building (e.g. residential, educational, commercial or public) predominantly determines the occupancy of a building and therefore also the energy use (Delzendeh *et al.,* 2017). In this sense, the use of a building determines when and for what actions energy is predominantly used (cf. occupancy). Moreover, the building use predefines what degree of control occupants have over building systems and components and therefore shapes the kind of interactions occupants can take. Moreover, the use of the building is linked to 'the relation between the occupant and the building' (i.e. in a workplace a person might be an employee and therefore 'only' occupying the building, whereas in a residential building the person might be owner or tenant which presents a different starting point in terms of energy behaviour). In order to obtain a comprehensive understanding of energy behaviour (in different building types) we considered literature on energy behaviour in all building types that are eligible for the EPC. However, the vast majority of existing studies concern energy behaviour in residential buildings, while a few exist about offices, schools and commercial buildings. **Therefore, the availability of studies and literature inevitably determines the focus of this fact sheet.**

Other than that, associated with a specific type of energy service (i.e. space heating or use of electrical appliances), energy behaviour can be differentiated into user-related and building-related energy behaviour (Guerra-Santin *et al.,* 2018). Building-related energy consumption is associated with energy use for services which are related to the building itself, like space heating and cooling, ventilation and lighting. Therefore, the design can directly influence these energy services in new and existing buildings. By contrast, user-related energy consumption comprises cooking, domestic hot water, and the use of electric equipment and appliances. User-related energy consumption can mostly be influenced by the building occupant and is therefore more dependent on users' habits (Guerra-Santin *et al.*, 2018). Likewise, Brounen, Kok & Quigley (2012) describe that residential gas consumption in the Netherlands is predominantly influenced by structural characteristics like construction year, building type and characteristics. By contrast, electricity consumption is more dependent on household composition (i.e. income and family composition; Brounen, Kok & Quigley, 2012; Trotta, 2018). Hence, different energy behaviours are influenced by different sets of factors.

The fact that electricity consumption is rather independent of building characteristics may be one reason why electricity use is not (yet) contemplated in most EPCs (e.g. in the German), as the EPC was predominantly developed to compare the energy performance of buildings with each other (neglecting or normalizing user-related energy behaviour). **For this fact sheet we take both, building-related energy behaviour and user-related behaviour into account since e.g. electricity consumption in buildings will become more important in the future. We can assume that electricity use becomes more important in future, in view of the increasing electrification (including on-site electricity generation, the use of electrical heat pumps and EVs), the introduction of building automation and control systems (BACS) and the smart readiness indicator (SRI) concept. Finally, there is the contemplation within the ePANACEA project to take electricity use into account for the energy assessment of buildings**; **in regard to the uptake of electricity use in future EPCs, the importance of user-profiles increases.**

It remains to be said that with the term "occupant behaviour" we always refer to occupant behaviour which is energy-related. The term "energy behaviour" is used interchangeably with occupant behaviour in this fact sheet.

Concluding, the aspects mentioned here (temporal dimension of energy use, use of the building and the type of energy service) predetermine energy behaviour. There are more factors that influence energy-related occupant behaviour which will be presented in chapter 4 of this fact sheet. **However, this fact sheet excludes the quantification of the impact of different influencing factors on energy consumption.**

1.3. Structure

From here on, this fact sheet is structured as follows: first, the fact sheet briefly presents the methodology which was used to understand occupant behaviour and what factors are causing it (chapter 2). After that, in chapter 3 the fact sheet provides a definition of energy-related occupant behaviour, explains the motive behind it and differentiates between different types of energy-related occupant behaviour. Next, the different factors influencing energy behaviour are presented (chapter 4). Chapter 4 also describes the DNAs (drivers, needs, actions and systems) framework and the development of user profiles, representative for the Netherlands. Chapter 5 is about different methods used for occupant behaviour modelling and integrating these in existing BES. In this sense, Chapter 5 also describes what data need to be collected and how they can be collected for occupant behaviour modelling. While chapters 3-5 concentrate on everyday energy behaviour, chapter 6 addresses behavioural change, focusing on possible interventions to change energy behaviour, rather than on other factors causing behavioural change or modelling behavioural change. Chapter 7 presents the synthesis of the fact sheet with the aim to provide indications for the development and integration of user profiles in the ePANACEA methodology. This encompasses considerations regarding the implementation of user profiles within the context of EPC and a summary of the information that could constitute a user profile, which is visualized in a draft user profile interface. This chapter also points out remaining concerns and questions that are related to the implementation of user profiles. Chapter 8 presents the conclusion of this fact sheet, summarizing the information and findings previously presented. Text passages marked in bold indicate particularly important information.

2. METHODOLOGY

A desktop research (consisting of literature reviews) was conducted in order to understand energy behaviour, including its facets and the factors influencing it. Conclusions from *Annex 53, 55 and 73* (IEA) were taken into account, assuming that they contain valuable information for the integration of user profiles in the ePANACEA methodology (in particular for the implementation of advanced occupancy models and advancing occupant modelling for dynamic energy assessments and certification schemes).

Different fields of literature were reviewed such as types of energy behaviour, factors influencing energy behaviour, user profiles for BES, occupant behaviour modelling and behavioural intervention strategies. Key terms were used to find literature on Google Scholar, Research Gate and Springer Link. The following collection of search terms indicates with which focus literature research was pursued: “user-related variables determining energy consumption in buildings”, “estimation of energy consumption according to user profile”, “integration of user profiles in energy assessment of buildings”, “factors influencing energy behaviour in buildings”, “parameters determining user profiles” (…). The snow-ball effect was used to find new research terms and sources. A total of 55 sources are cited throughout the document. The information of different literature sources was compared and brought into a logical context and order, which is reflected in the structure of this fact sheet.

In June 2021, a feedback session with part of the project partners (CENER & VITO), who are responsible for the methodology development in ePANACEA, took place. During the meeting the interim state of the fact sheet was presented and discussed in order to ensure that the fact sheet meets expectations (i.e. the content is considered as useful input to the development and integration of user profiles in the ePANACEA methodology).

3. EXPLORING ENERGY-RELATED OCCUPANT BEHAVIOUR

This chapter seeks to provide the reader with a good general understanding of energy-related occupant behaviour. Therefore, it presents definitions of energy-related occupant behaviour, describes the main motive behind it and divides energy-related occupant behaviour into different types.

3.1. Definitions of occupant behaviour

Three definitions of energy-related occupant behaviour are listed here:

- Behaviour is simplified by Shuqin Chen *et al*. (2015, in Laaroussi *et al*., 2019) "as visible **action/reaction to adapt** to the **ambient environmental conditions**".
- Zeiler *et al*. (2014 in Tam, Almeida & Le, 2018, p.12) define occupant behaviour as the "the presence of occupants in workplace location and the **action** occupants take (or not take) to **influence their indoor environment**".
- Delzendeh *et al*. (2017, p.1065) define occupant behaviour as referring to "**the interaction with building systems** in order to **control the indoor environment** for health, and to obtain thermal, visual and acoustic comfort inside buildings".

These definitions have in common to speak of 'actions to achieve comfortable indoor conditions' when defining energy-related occupant behaviour. In this sense, we can comprehend that "buildings don't use energy: people do" (Janda, 2011) - through their interactions with the building systems to attain comfort. **The second definition considers that next to actions, the presence of occupants (i.e. occupancy) constitutes energy behaviour which is acknowledged in the course of this subchapter as well (referred to as non-adaptive action).** Also, we address occupancy profiles in chapter 3 as factors influencing occupancy and therefore also the use of energy in buildings.

3.2. The goals of energy-related occupant behaviour

Linked to the definitions of energy-related occupant behaviour above, Humphrey's principle explains what occupants' main intention behind energy-related occupant behaviour is: "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Hong *et al*., 2017, p. 519). Matching to this, Delzendeh *et al.* (2017) explain that mankind's desire is to control environmental factors of both the outside environment and living spaces. Occupants determine comfort criteria (i.e. regarding thermal, visual and acoustic conditions) and interact with building systems to maintain comfort levels (Hong & Lin, 2013; Delzendeh *et al.,* 2017). **Hence, environmental discomfort triggers the operation of the building and thus influences energy use (Hong & Lin, 2013; Yan and Hong, 2014).**

The finding that comfort (mostly thermal) plays a big role regarding energy behaviour was already reported in *Insights on user perceptions and needs regarding the Energy Performance Certificate (EPC);* DOI: https://zenodo.org/record/4569465#.YKJqp6FCQ2w). This report describes among others that end users in Belgium would rather pay for EEMs or more fuels than that they wanted to reduce their thermal comfort. Hence, end users are not willing to reduce their comfort in order to save energy. In turn, an expected increase of energy comfort is considered as a motive to initiate EEMs. This matches to the suggestion from end users in Spain and Belgium to add additional indicators about indoor air quality and thermal comfort to the EPC, which emphasizes once again that comfort is of primary interest for occupants.

Concluding, the will to maintain or improve environmental comfort is the main motivation for humans to 'behave' referring to energy-related occupant behaviour in residential and non-residential buildings (NRBs). However, the will to maintain or improve environmental comfort cannot be the motive for energy-related occupant behaviour considering occupancy or the operation of electrical appliances such as kitchen devices or entertainment technology. In this case the motive may be to achieve comfort on a different level; comfort which is not directly related to IEQ. **Hence, to our understanding the explanation that occupants use energy in order to maintain or to improve comfort is only applicable to adaptive actions (cf. chapter 3.3.1).**

Moreover, energy consumption should be understood as *indirect* since energy is rather used as means to fulfil certain needs, **such as maintaining thermal comfort and air quality.** Hence, end users' perspective on energy consumption is rather comfort management than a consideration of energy as such *(*Aune, Berker & Bye*).* This goes hand in hand with the fact that residents are often unaware of their energy consumption. Therefore, it is an increasingly popular approach to focus on *everyday social practices* when researching energy-related occupant behaviours; not referring to *energy use* but rather to *practices that use energy* like cooking, showering or using the air conditioning (Staddon *et al.,* 2016).

3.3. Types of energy-related occupant behaviour

This subchapter presents the range of identified behaviours with which occupants influence the energy consumption of buildings. Because there are many different types of behaviours related to energy use this chapter first presents a categorization of them. After that, it describes the differentiated types in a more detailed way.

3.3.1. Adaptive and non-adaptive behaviours related to energy-use

Hong *et al.* (2017) distinguish between adaptive actions and non-adaptive actions with regard to occupant behaviours that influence the EPB. Adaptive behaviours, in turn, can be divided in:

a) Actions in which occupants adapt the indoor environment to their needs or preferences (e.g. opening/closing windows, adjusting blinds and thermostats, turning lighting on/off, and

b) Actions in which occupants adapt themselves to their environment (e.g. adjusting clothing and moving through the building).

In addition to this, Paone & Bacher (2018) state that adaptive behaviour can either be conscious or unconscious. **Occupants' presence (i.e. occupancy) and operation of plug-ins and electrical appliances (e.g. in homes, schools and offices) are comprehended as non-adaptive actions (Hong *et al.*, 2017)**, i.e. that they are not carried out in order to maintain or improve IEQ (despite the fact that people may leave a building as response towards uncomfortable IEQ). However, looking at the operation of electrical heaters, fans and systems for space heating/cooling, one can also attribute the usage of plug-ins to adaptive actions. This kind of plug-in usage directly depends on the occupants' comfort needs (and/or preferences).

Besides action, occupants can also choose to be inactive as a conscious choice (e.g. accepting more uncomfortable indoor environmental conditions) or because of a lack of access to suitable systems to adapt indoor environmental conditions (Ibid.; chapter 4.3.1). The distinction between adaptive and non-adaptive behaviours is presented in Figure 1.

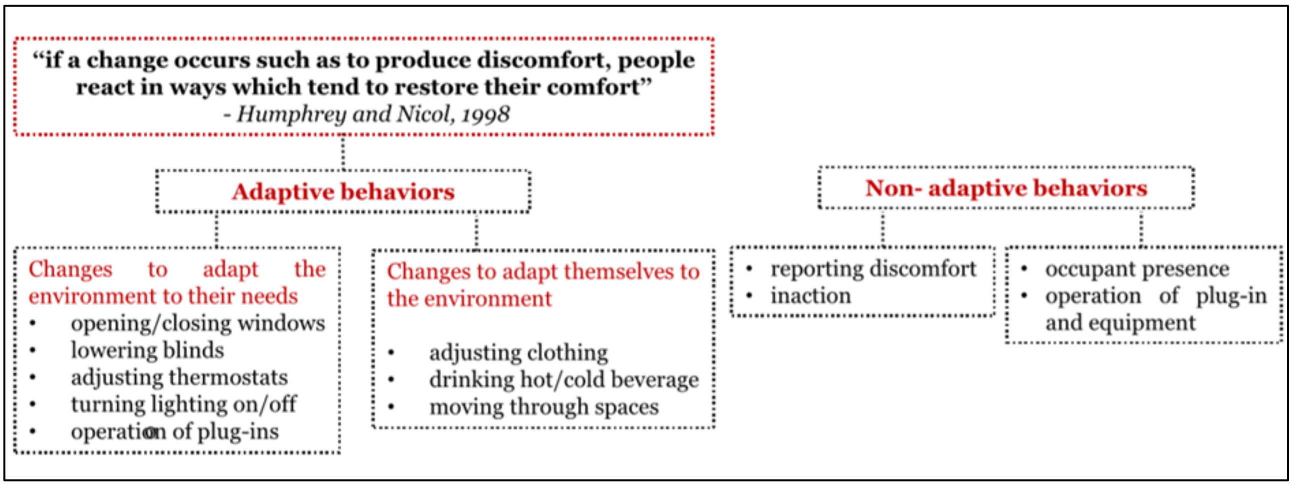

Figure 1: Occupant behaviour influencing building energy consumption and comfort (Hong et al., 2017)

Likewise, Hong *et al.* (2015, cited in Delzendeh *et al*., 2017) differentiate between actions (e.g. adjusting the level of clothing, opening a window and turning down the thermostat temperature) and inactions (such as moving to a different location and tolerating some discomfort). They are different strategies to response to the same thermal discomfort. That gives us a first clue as to why it is so difficult to predict energy behaviour.

3.3.2. Non-adaptive behaviour: occupancy

Building occupants can be in different 'states': arriving, present, departing, and absent. During their presence they produce metabolic heat, which is a passive form of energy behaviour**. In addition to this**, **being present is the basis for active energy behaviour (cf. de Simone *et al.,* 2018; Yan *et al*., 2015).** Between absence and presence there are the phases of arrival and departure during which the occupant conducts the most adjustments to the building systems and appliances, where occupants tend to adjust more at arrival compared to departure (Delzendeh *et al.,* 2017). In this sense, arrival, departure and duration of absence affect occupants' interaction with a building (Yan *et al*., 2015). More precisely, Guerra-Santin *et al.* (2018) explain that occupancy mainly determines how long something is used. **Hence, a realistic representation of occupancy is important in order to take the user dimension in BES into account (Yan *et al*., 2015).** The impact of the occupant status on energy behaviour, which in turn impacts the EPB, is visualized in Figure 2.

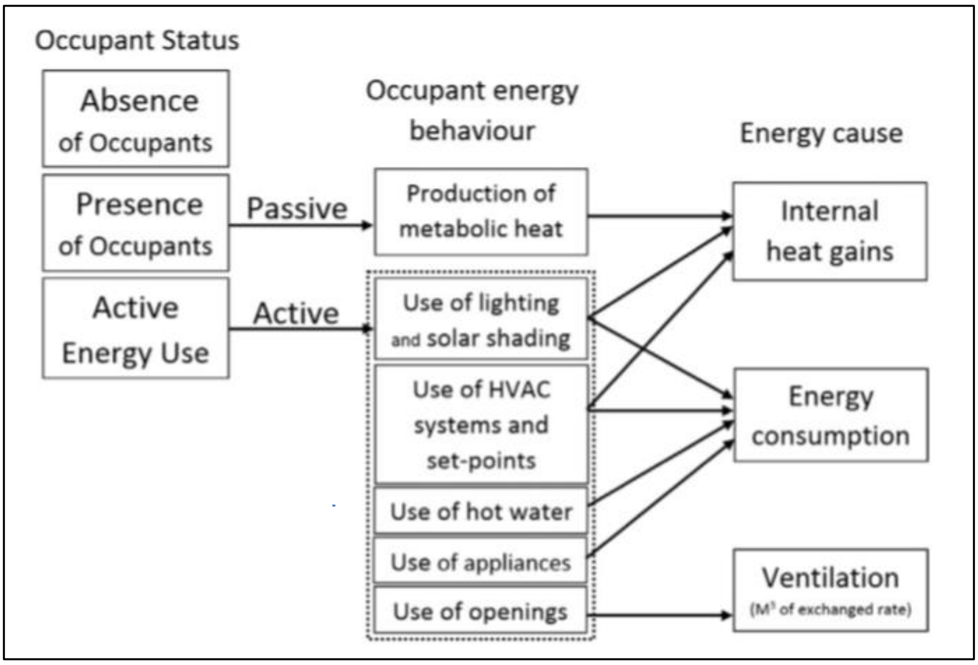

Figure 2: Occupants' types of activities affecting building energy consumption (Delzendeh et al., 2017)

3.3.3. Changes to adapt the environment to occupants' needs

As introduced above, occupants interact with building systems to reach their personally desired level of comfort (Delzendeh *et al.,* 2017). In literature about occupant behaviour there are various interactions with building systems mentioned: Yan *et al.* (2005) consider "light-switching, window-blind adjustment, window-opening, thermostat-adjusting, fan use and door use" as major behaviour of interest. Fans are particularly used for moving air in buildings which are warm and which are not equipped with air conditioning. Hong and Lin (2013) complement this list by turning on/off office equipment, ventilation, and air-conditioning (HVAC) systems. Furthermore, we can add the use of DHW (Delzendeh *et al.,* 2017).

Furthermore, with different functions of buildings, there are different types of users. Regarding NRBs, ordinary occupants are typically less empowered to adapt the environment to their individual needs. The interactions with building systems are often automated or taken over by building operators. Building operators' actions comprise turning on/off cooling units, pumps, fans, etc. and determining set points of building equipment (Yan & Hong, 2014). With regard to NRBs, it is interesting that a "mutual blindness" divides technologies and users (Aune, Berker & Bye, 2008, p. 46); the connection between them is missing. A "user-technician" or "super-user", who would, on the one hand, be able to consider the users (i.e. their behaviours and needs), and on the other hand, the capabilities of technologies, would be beneficial. In addition, this user-technician or super-user should be capable to track and induce changes on both parts (building occupants and building systems). Building operators would be suitable candidates, bringing technology and users together. They can be seen as mediation between the technology's capabilities and users' behaviours and needs (Aune, Berker & Bye, 2008). Hence, building operators may play a key role in meeting occupants' comfort preferences and increasing energy efficiency. They take over the majority of interactions with building systems for building occupants.

3.3.4. Changes to adapt themselves (occupants) to the environment

According to a study conducted by Huebner, Cooper & Jones (2013) warmth was most often associated with comfort by participants. Actions to create comfort were found to be to a large extent temperature-related actions that require low energy use such as putting on clothes, using a blanket, drinking a hot beverage, using a hot water bottle. Similarly, Yan *et al.* (2015) explain that the clothing level does not directly influence energy use but affects occupant comfort, i.e. it influences occupants' other adaptive behaviours. **If comfort is created through such low-energy actions, Huebner, Cooper and Jones (2013) also suggest that the total energy consumption is potentially not much influenced through comfort actions.** This is in contrast to the statement that occupants significantly influence the energy consumption of a building through their interactions and therefore contribute to causing the performance gap as described in detail above.

Concluding, energy-related occupant behaviour consists of many different forms. Often, as mentioned above, there are multiple behaviours which lead to the same goal: e.g. taking off a piece of clothing or turning on a fan both help the occupant to cool down. Although achieving the same goal, different behaviours require different levels of effectiveness, effort and energy intensiveness. Moreover, sometimes two actions are needed to adapt to a situation (e.g. opening the door and window to ventilate the room). But, two actions can also interfere with each other (e.g. closed blind reduces the air flow through an open window). This shows once more the complexity of energy-related occupant behaviour (Yan *et al.*, 2015).

3.4. Summary of exploring energy-related occupant behaviour

By conclusion, energy-related occupant behaviour is multifaceted. We learned that it can be distinguished into adaptive and non-adaptive behaviour. Adaptive behaviour is motivated by the desire to maintain/improve comfort. If the occupant adapts to indoor environmental conditions, this is less energy-intensive than if the occupant adapts the environment to his/her needs (e.g. turning up the heating). The presence in a space (occupancy) is understood as non-adaptive behaviour, constituting the basis for further energy-related behaviour (e.g. interactions with building systems). Other than that, different behaviours can interfere with each other or lead to the same goal (in terms of reaching comfort needs), which emphasizes the complexness of occupant behaviour. The next chapter describes the factors which influence (different) energy behaviours in more depth.

4. FACTORS INFLUENCING ENERGY-RELATED OCCUPANT BEHAVIOUR

Different types of energy-related occupant behaviour and the main motive behind adaptive energy behaviour were described above. This chapter presents the factors that influence non-adaptive actions (i.e. occupancy) and adaptive actions (for which the presence of occupants is the basis). As it was introduced in the scope of the fact sheet, factors influencing energy behaviour vary with the use of the building (and therefore occupancy) and the type of energy service. In addition to this, there are other influential factors presented in this chapter. Thereby, the focus is on the factors which play a role in residential buildings; simply because most studies and literature exist on it. Still, available information on factors influencing energy behaviour in NRBs is included in this chapter, represented on the basis of studies on energy behaviour in offices. The chapter ends with a summary of the presented information.

4.1. Overview of factors influencing energy behaviour in buildings

There are internal and external factors influencing energy behaviour (Tam, Almeida and Le, 2008). Factors resulting from external sources are e.g. linked to the location of the building including physical environment, building properties and time, whereas factors resulting from internal sources are occupant-related and are e.g. linked to biological, psychological and social aspects. The overview is shown in Table 1.

Table 1: Energy-related occupant behaviour, according to the International Energy Agency (IEA) (Tam, Almeida & Le, 2018)

	Internal Driving Forces	
Occupant related	Psychological	Expectations and needs of comfort lifestyle and habits environmental awareness, . . .
	Social	Interaction with other individuals family composition
	Biological	Clothing age, gender and health activity, . . .
	External Driving Forces	
Location related	Physical environment	Light and solar radiation temperature and humidity air rates and wind speed, . . .
	Building	Type of control availability and accessibility
	Time	Duration temperature and humidity air rates, . . .

Correspondingly, Hong *et al.* (2015, p. 7) describe that: "drivers represent the environmental factors from the outside world that stimulate occupants in their inside world to fulfil a physical, physiological or psychological need". Hence, factors from the outside world and factors determining the inside world of individuals influence adaptive behaviour. Other external features that influence energy behaviour and which are not included in the table are politics, economics, and culture (Tam, Almeida & Le, 2018). These are also included in Figure 3 which depicts the factors and sub factors influencing energy behaviour according to Delzendeh *et al.* (2017). The factors which are occupant-related according to our understanding are marked in blue in Figure 3. However, these factors cannot all be described as "internal" (e.g. income, state of occupant).

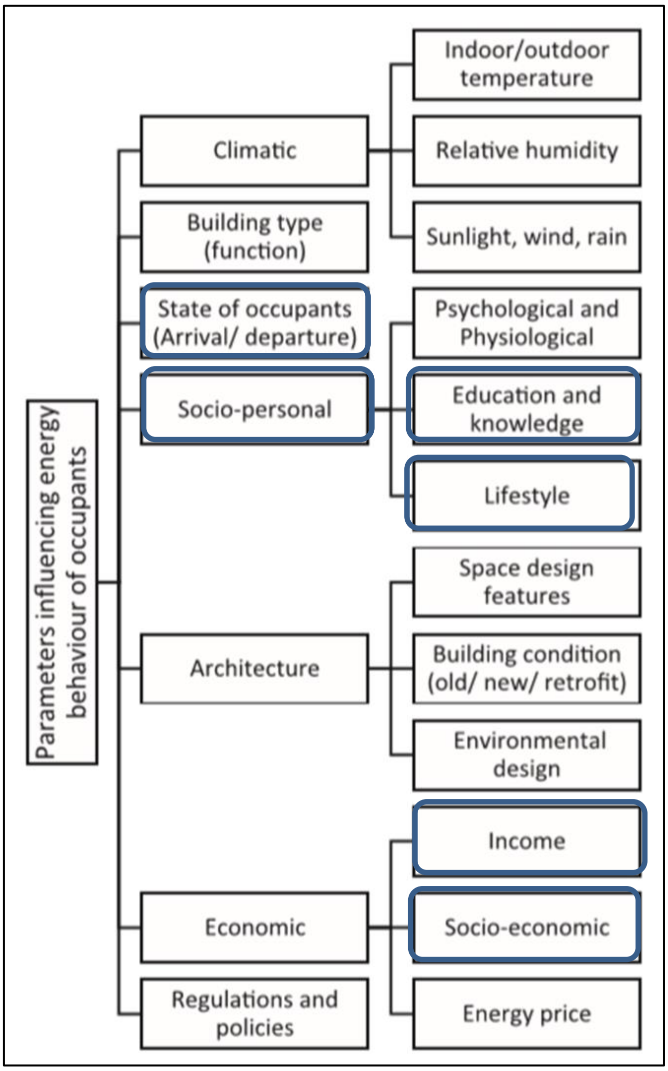

Figure 3: Factors and sub-factors influencing energy behaviour of occupants (Delzendeh et al., 2017)

Concluding, Delzendeh *et al.* (2017) identified similar factors influencing adaptive energy behaviour as presented by Tam, Almeida and Le (2018). The mentioned building aspects in Table 1 are extended by architecture – space design features; building condition and environmental design. Economic and political aspects are covered by income, socio-economic aspects and energy price. In addition, the function (i.e. use) of the building and the state of occupants is listed as influential factors on adaptive behaviour which were not included in Table 1. Other than that, it also plays a role whether we consider a dwelling or a building and, with regard to the former, where in the building the dwelling is located. Because in dwellings the influence of the neighbours' heating habits can be very high (Csoknyai *et al.*, 2019). Especially in so-called transition periods, characterized by moderate temperatures, the impact of e.g. neighbours' heating habits increases (Ibid.).

As indicated in the beginning of this fact sheet, building energy consumption is influenced by occupant behaviour. From the preceding table (Table 1) and figure (Figure 3) we can derive that occupant behaviour is also influenced by building characteristics. Hence, **there is a mutual relation between a building's performance and user actions (i.e. building variables influence occupant behaviour and occupant behaviour influences EPB; Aune, Berker & Bye, 2008).** Similarly, Yan and Hong (2014) state that occupant behaviour and building performance are strongly linked with multiple feedback loops (cf. selection of dwelling can be considered as energy behaviour). Likewise, Fabi *et al*. (2011) mention that the energy consumption along with the environmental quality in a building becomes a driver of energy behaviour.

For both figures the distinction between factors influencing adaptive or non-adaptive behaviour was not made. However, we can suppose that the factors mentioned here may refer to adaptive energy behaviour because regarding non-adaptive behaviour, such as the use of electrical appliances, location and building-related variables may play a negligible role. Moreover, as introduced in the scope of the fact sheet, electricity use (e.g. TV watching/ computer use) is rather dependent on occupant-related factors, while gas consumption (e.g. used for space heating) is rather dependent on the location/building. However, there are national/regional differences, since in many countries gas is also used for cooking.

In the further course of this chapter we will take a closer look at occupant-related factors influencing energy behaviour because they are most important for the development of user profiles in ePANACEA. Nevertheless, this chapter includes two selected external factors influencing energy behaviour: the EPC and the empowerment of occupants to interact with building systems (i.e. material possibilities to engage with energy).

4.2. Occupant-related factors influencing energy behaviour in buildings

To our understanding occupant-related factors influencing energy behaviour in buildings do not only comprise internal (i.e. psychological) factors but also socio-demographic factors. These are described in more depth in this subchapter, whereby the influence of psychological factors is explained by describing existing psychological models, explaining energy behaviour.

4.2.1. Occupancy profiles

The use of a building determines the occupancy of a building which in turn influences energy use of a building (introduced above). **Occupancy profiles can be very diverse and their determination is essential as they are pivotal inputs to energy building simulation (de Simone *et al.,* 2018). Diverse driving factors determine occupancy profiles; these include e.g. household characteristics, cultural traditions, social and economic parameters** (de Simone *et al.,* 2018). Hence, most factors influencing occupancy profiles are occupant-related. They are discussed in more detail in this subchapter.

It is in general possible to signify two types of variables: on the one hand, variables that determine occupancy profiles (variables Type_1) which this section is about; on the other hand, variables that are influenced by occupancy profiles (variables type_2: presence variables, de Simone *et al*., 2018) which were already covered above (cf. actions influencing EPB; chapter 3.3).

Socio-demographic variables determine the occupancy of residential buildings, i.e. are determinants of *when* people are at home. For instance, 'household composition' and 'employment' are classified as socio-demographic variables. The 'household composition' affects the energy consumption in the sense that "one-person households consume on average (…) 55 % more electricity (per person) than four-person-households" (Trotta, 2018, p.537). Being married by itself is associated with fostering energy savings and living with a partner increases the probability to buy energy efficient appliances by 12% (Trotta, 2018). However, we cannot necessarily associate the latter with everyday energy use.

Regarding 'employment', work status (working full time, part-time, retired) and the industry in which one works (working schedules) shape occupant's schedules throughout the week (Ibid.). However, due to the current COVID-19 pandemic, people increasingly work from home. This seems to be an increasing trend which will not come back to a pre-pandemic state. Hence, they will show a different occupancy pattern compared to non-pandemic times which has consequences for the total energy use, since working from home significantly increases the gas and electricity usage (Huebner *et al*., 2015).

As we already know – next to the influence of occupancy profiles - energy consumption is significantly influenced by the way the building is used and the type of activities that are carried out. This constitutes the 'presence variables' (cf. chapter 3; de Simone *et al*., 2018). Figure 4 visualizes the distinction between 'variables type_1', determining occupancy profiles, which in turn result in 'variable type_2' that influence EPB. This emphasizes that first of all the presence plays a role and then the types of interactions between building and occupant (Tam, Almeida & Le, 2018).

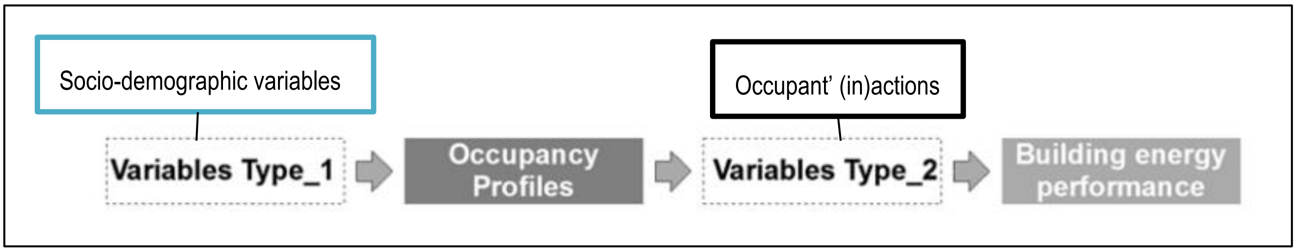

Figure 4: Variables categorization and reciprocal influences (de Simone et al., 2018)

But, we need to notice that next to occupancy, other factors such as occupants' preferences and attitudes exert influence on the use of equipment and building systems which are covered by the sections hereafter.

4.2.2. Other socio-demographic factors

There are household characteristics which do not (directly) influence occupancy but which influence energy-related behaviour nevertheless (i.e. adaptive and/or non-adaptive behaviour such as the use of TV). They are listed hereafter:

The **'household size'** means the number of household members, which is positively related to energy consumption (Huebner *et al*., 2015). The number of household members could easily be considered in energy assessment. More than 50% of the energy consumption could be saved in terms of demand control ventilation if the number of occupants was known and considered (Ahmad *et al*., 2008).

Besides, energy consumption increases with higher **'income'** (Huebner *et al*., 2015). More specifically, Gram-Hanssen & Georg (2017) report that the size and income of households affect electricity use (families and higher-income households consume more electricity than single-occupant households; Trotta, 2018). Low income households have a more elastic energy behaviour in the sense that they are more likely to react to fuel prices by e.g. saving energy through daily practices (Trotta, 2018).

With regard to the **ownership status**, it can be stated that occupants who are directly responsible for paying bills for energy fuels and service (e.g. owners and tenants) tend to be more motivated to save energy than e.g. employees or occupants who are only 'visitors' in buildings (Delzendeh *et al*., 2017).
There are several socio-demographic variables of which the effect on energy consumption is less clear such as **occupant age** (Huebner *et al.,* 2015), **gender** and **education level**. No clear statement about their correlation with energy consumption can be found among literature sources (Trotta, 2018).

4.2.3. Habits

Habits (i.e. being used to behave in a certain way) are a major behavioural factor in energy consumption, considering everyday energy behaviour (Tetlow *et al*., 2015). They affect our everyday actions that require energy (e.g. showering, cooking, TV watching). "Habits are often defined as learned sequences of acts that have become automatic responses to specific cues and are functional in obtaining certain goals or end states" (Verplanken & Aarts, 1999, in Huebner, Cooper & Jones, 2013, p.627). They are useful because they are automatic and provide resources for other activities that can take place at the same time (Tetlow *et al*., 2015). Also, habits do not involve conscious reflection of the behaviour and present the most important barrier to changing behaviour (Huebner, Cooper & Jones, 2013).

4.2.4. Individual comfort preferences

We already learned that maintaining or improving comfort is the main aim of energy-related occupant behaviour. This section shows that comfort preferences are different among individuals and countries which in turn has an influence on occupants' adaptive behaviour.

Thermal comfort is subjective; the American Society of Heating and Air-Conditioning Engineers describes it as "condition of [the] mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (Delzendeh *et al*., 2017, p.1065). People who are less able to endure uncomfortable conditions are more likely to take actions the longer they are exposed to these. Compared to that, people who are more tolerant to uncomfortable conditions tend to accept these (Yan *et al.,* 2015). **Yan *et al*. (2015) confirms that occupants have different preferences which lead to different responses to the same environmental conditions**, e.g. the preference regarding illuminance ranged from 230 to 1000 lux and the preferred thermostat set point varied from below 19° to above 25°. Moreover, it is not only the temperature which influences the opening/closing of blinds, but factors related to overall comfort such as noise, privacy and view (Yan *et al.*, 2015). Delzendeh *et al*. (2017, p.1065) explain that occupants do not perceive and respond in the same way to restore comfort, because there are physical, physiological and psychological differences between people. More precisely, individual characteristics related to the body fat and muscle tissue distribution, have a clear impact on thermal sensation. Especially gender and fitness seem to influence tissue distribution- and ultimately influence thermal sensation (Tuomaala *et al.,* 2013). **Besides individual preferences, preferences seem to differ between countries, too**. Estimates of the living room temperature during winter allowed to compare tolerable living room conditions between countries. For instance, the median temperature in both the Netherlands and England was 20°C, while in Denmark, Germany and Finland this was one or two degrees higher (Adjei, Hamilton and Roys, n.d.). **Therefore, comfort preferences (which are reflected in adaptive behaviours) should not be a standardized input to the energy assessment of buildings.**

We may consider comfort preference as an internal driver of energy behaviour (i.e. adaptive behaviour). Comfort preferences present only one out of several possible reasons to explain different interactions to the same conditions (Yan *et al.,* 2015.). Many other external drivers such as economic and regulatory issues lead to different behaviours. Moreover, we need to remember that comfort preferences shape adaptive behaviour but play a negligible role in terms of non-adaptive behaviour (occupancy and the use of electrical devices such as TV). Hereafter, psychological models to explain energy behaviour are described, thereby more occupant-related and interval driving forces influencing energy behaviour are mentioned and explained.

4.2.5. Psychological factors (used in psychological models)

Psychological models contribute to structure identified influencing factors or mechanisms regarding behaviour and to bring them into context. There exist several psychological models that were developed in order to explain pro-environmental behaviour. "Domestic energy consumption and energy savings can be seen as a subset of general pro-environmental behaviour and hence the variables that affect pro-environmental behaviour could potentially influence energy consumption in the home" (Huebner, Cooper & Jones, 2013, p. 626). That is why the developed psychological models to explain pro-environmental behaviour may also be applied to explain domestic energy behaviour.

For instance, the theory of planned behaviour (Ajzen, 1991) and the norm activation model (Schwartz, 1977) are often used to examine pro-environmental behaviour (Abrahamse & Steg, 2009). Another substantial psychological model in predicting pro-environmental behaviour is Stern's value-belief-norm (VBN) model which contends that values relate to an individual's beliefs which in turn form intentions to act through norms (Staddon *et al.,* 2016). The first two are described in more detail hereafter, pointing out the influence of specific internal (i.e. psychological) variables on energy behaviour.

4.2.5.1. Theory of planned behaviour

The 'attitude-behaviour gap' or 'value-action gap' means that people do not act in agreement with their values or attitudes. This gap has been referred to e.g. temporal discrepancies (i.e. that people's attitudes change over time). In order to find explanations for this gap, **Ajzen's (1991) theory of planned behaviour (TPB) was especially influential, proposing that behaviour is determined by intentions which in turn are influenced by a combination of attitudes, subjective norms, and perceived behavioural control**. The TPB is exemplary for a rational choice theory. Therefore, it assumes that "behaviour is a result of a reasoned process of weighing costs and benefits of the relevant behaviour (in terms of time, money, effort, social approval)" (Abrahamse & Steg, 2009, p.712). However, we also know that people have a bounded rationality and that therefore decision making may be heuristic; although they may be provided with complete information (Paone & Bacher, 2018).

Hong *et al.* (2017) report that there is evidence indicating that the three elements of the TPB (i.e. attitudes, subjective norms and perceived behavioural control) remarkably influence occupants' energy behaviour in the workplace. The three elements of TPB are shortly described hereafter:

- **Attitudes –** "refer to the degree to which a person has a favourable or an unfavourable evaluation of a behaviour, and depends on the weighing of various costs and benefits such as financial costs, effort or time" (Abrahamse & Steg, 2009, p.712).
- **Perceived behavioural control** – "is the perceived ease or difficulty of engaging in a behaviour" (Ibid.).
- **Subjective norm -** "refers to the perceived social pressure to perform or to refrain from a behaviour" (ibid.).

4.2.5.2. Norm activation model

The norm activation model (NAM) regards pro-environmental behaviour as a type of altruistic behaviour, in the sense that individuals need to forgo personal benefits in the interest of collective benefits (i.e. the environment). **The NAM variables comprise personal norms, awareness of consequences and ascription of responsibility (Abrahamse & Steg, 2009).** Common belief is that altruistic behaviour is determined by (activated) personal norms, which are experienced as a feeling of moral obligation. Behaviour which is in agreement with personal norms may cause a sense of pride, whereas behaviour not in agreement with personal norms may cause a sense of guilt.

So far the NAM has been successfully applied to diverse pro-environmental behaviours, also to energy conservation. In several studies, the TPB has been extended with NAM variables, especially the personal norm concept. Personal norms were found to considerably contribute to the explanation of the TPB for multiple environmentally-relevant behaviour. However, the explanatory power of the TPB model (complemented by NAM concepts) may differ under the consideration of multiple behaviours (Ibid.). **With the application of the extended TPB model, Abrahamse and Steg (2009) found that energy use is predominantly shaped by socio-demographic variables.** For instance, households with a higher income and more members tend to consume more energy. From this we can conclude that constraints and opportunities considerably shape the energy consumption patterns by households. **Interestingly, psychological variables were <u>not</u> found to be influential in explaining energy use (Abrahamse & Steg, 2009). This suggests that these variables do not necessarily have to be taken into account in user profiles.**

4.2.6. Factors influencing energy behaviour in non-residential buildings (offices)

This subsection presents the particularities of occupant-related factors influencing energy behaviour in NRBs, represented on the basis of studies on energy behaviour in offices. In line with the remark that the use of a building predetermines energy behaviour, this section shows what other (mostly occupant-related and psychological) factors come into play considering offices compared to residential buildings.

The behaviour of building users in workplaces differs from that of residents for various reasons: office buildings are more complex and there are more agents influencing energy use, such as owners, design professionals, operation staff, and the occupants (Tam, Almeida & Le, 2018). Furthermore, building operators or automated processes instead of occupants themselves might take over the majority of interactions with building systems in NRBs (cf. 3.3.3; 4.3.1). Looking at occupant behaviour in commercial buildings, Hong *et al.* (2017) found that next to individual-level factors, organizational or structural factors played an important influential role. For instance, top management support and organizational culture are key factors in explaining workplace pro-environmental behaviour. Managers are referred to as the 'gatekeepers to environmental performance'. They play a similarly important role for employees as landlords do for tenants (Staddon *et al.,* 2016).

Besides, in an office occupants can engage with energy through individual actions and actions for which all share responsibility (like regulating the lighting and heaters; Russell *et al.*, 2016). The fact that appliances and facilities are shared among co-workers may "inhibit a sense of individual responsibility for conservation" (Hong *et al.,* 2017, p. 525), which may lead to nobody feeling responsible. This phenomenon is also called 'social loafing' (Russell *et al.,* 2016). The fact that other occupants are present in shared offices influences occupants' behaviour in complex psychological and social ways (Yan *et al.,* 2015). Regarding shared offices the interaction between individual occupants is a key element (Yan & Hong, 2014). So far, understanding and modelling collective behaviours in NRB has only received limited attention (2017).

Besides, the fact that users of NRBs are not personally responsible for the amount of energy consumed, Aune, Berker and Bye (2008) mention that building technologies are often difficult to manage for laypersons (Aune, Berker & Bye, 2008). But, in the new paradigm, occupants are given responsibility for managing certain aspects of the building at the workplace (Tam, Almeida & Le, 2018). **The personal irresponsibility includes that employees are not responsible for paying energy costs.** Therefore, individual employees are not motivated to save energy in order to achieve monetary savings (Russell *et al.,* 2016; Hong *et al.,* 2017). Concluding, the use of a building does not only determine occupancy (and therefore has an effect on energy use) but also other energy-related behaviours such as the interaction with building systems.

4.3. External driving forces influencing energy behaviour in buildings

As introduced above, next to internal driving forces, there are external driving forces influencing the energy behaviour in buildings. Although this fact sheet does not focus on external influencing factors, two are selected and presented here, as they are closely related to the context of the ePANACEA project. Opportunities to control IEQ and the EPC as potential influential factors on energy behaviour are shortly described hereafter.

4.3.1. Opportunities to control indoor environmental quality

This section is linked to actions to adapt the environment to occupants' needs. **Material possibilities to interact with the building systems in order to control IEQ shape occupants interactions.** They are also linked to the type/use of the building, in the sense that occupants of residential buildings are usually more empowered to adapt the IEQ than occupants of NRBs.

As mentioned before, occupants like to have control over the IEQ; they feel discomfort if control is not provided or if it is ineffective. For instance, they appreciate the ability to decide about window opening, thermostats and blind positioning (Paone & Bacher, 2018; Tam, Almeida & Le, 2008). However, increased control and satisfaction does not necessarily imply a reduction in energy consumption. During the literature search, contradictory statements were found regarding the impact of control on energy efficiency. Tam, Almeida and Le (2008) found that energy consumption rose when occupants had increased control over energy use. On the other hand, Yan and Hong (2014) mention that increased occupant control over building equipment has a positive impact on energy efficiency. A comparison between a controllable and non-controllable ventilation system showed that the non-controllable system which had a higher standard rated coefficient of performance, consumed significantly more energy (Yan & Hong, 2014).

Referring to Wagner and O'Brien (2018) automation technologies were introduced to buildings in order to reduce energy consumption and the uncertainty which is associated with the influence of occupant behaviour on energy consumption.

However, automated building operations may not only be beneficial but may also lead to dissatisfaction of occupants (if e.g. comfort needs are not met by automated systems). Dissatisfied occupants could intervene in the automation, which can include energy-intensive actions like leaving a window open in winter, covering motion sensors installed to control lighting. Hence, finding the balance between automation and control/empowerment for individuals is crucial in order to maximize energy efficiency, users' satisfactions and comfort (cf. Wagner & O'Brien, 2018). **Finally, BACS can contribute to reducing the uncertainty related to occupant behaviour considering energy assessment because adaptive actions to maintain/improve environmental comfort become more predictable if they are (partially) taken over by BACS (Sürmeli-Anac & Hermelink, 2018).** However, in order for this to be successful, BACS need to "know" occupants preferences related to environmental comfort.

4.3.2. (Negligible) influence of EPC schemes on energy behaviour

In order to put the factors influencing energy behaviour into context with the EPC, the EPC as a policy tool with its impact on energy behaviour is described here. One external driver (more or less) influencing energy behaviour may be the EPC. We may consider the EPC as a source of information which could influence occupants' energy behaviour. Referring to Schuitema, Aravena and Denny (2019) buyers and renters of buildings often recognize the EPC but do not use it. The provided information may change end users' knowledge and awareness but does not necessarily impact their behaviour. Accordingly, Schuitema, Aravena and Denny (2019) mention that the EPC is often not considered in the decision process of renting or purchasing a building because the information of the EPC is too complex and other attributes such as price and location of the building are more important factors. However, Tigchelaar, Backhaus & de Best-Waldhober (n.d.) report that owners of buildings which have been labelled/certified carry out energy saving measures more often than owners of buildings which are not certified. Likewise, householders who are aware of EPC recommendations are found to be twice more likely to initiate EEMs, compared to households that are not aware. This means that either the awareness of EPC recommendations triggers the uptake of EEMs or that people who are interested in EE topics are more aware of EPC recommendations (Ibid.). However, this information refers to the impact of the EPC on *strategic* energy behaviour. The impact of the EPC on everyday energy behaviour is not discussed by the state-of-the-art and is presumably small to non-existent. Hence, there is room for improvement regarding the next generation of EPC.

4.4. A systematic representation of energy-related occupant behaviour in buildings: The DNAs Framework

The DNAs framework is presented here because it sets aspects that we presented so far (factors, comfort needs, types of energy behaviour and possibilities to interact with building systems) in relation to each other and prepares us for the next chapter which is about modelling occupant behaviour. Besides, it can also supplement our understanding that we have gained so far.

An ontology to represent energy-related occupant behaviour has been outlined in a DNAs framework, providing a systematic representation of energy-related occupant behaviour in buildings by Hong *et al*. (2015). The DNAs framework was developed following the IEA Annex 66 project and due to the notion that a reliable energy behavioural model did not exist (Tam, Almeida & Le, 2018). Furthermore, Hong *et al.* (2015) developed a XML (extensible Markup Language) schema, with the goal to normalize energy consumption in buildings for energy-related occupant behaviour (Tam, Almeida & Le, 2018).

The DNAs framework is depicted in Table 2.

Table 2: DNAs framework (Tam, Almeida & Le, 2018)

Drivers	Needs	Actions	Systems
Occupant Building Environment Time Systems	Physical Non Physical Comfort Biological	Movement Activating or deactivating Systems Inaction Discomfort	HVAC Light Equipment Shades and blinds Windows ...

In other words, the DNAs framework is based on four main components:

i) the **drivers** of behaviour
ii) the **needs** of the occupants
iii) the **actions** carried out by the occupants, and
iv) the building **systems** acted upon by the occupants.

In this list we can recognize preceding sub-chapters of this fact sheet: drivers – which we considered as factors, needs – considered as motive (comfort preference), actions – referred to as adaptive and non-adaptive behaviours, and systems - covered by possibilities to interact with the building systems.

Regarding drivers, five main categories were determined by Hong *et al.* (2016): building, occupant, environment, system and time. Hence the differentiation here is more detailed than the one suggested by Tam, Almeida & Le (2018; internal & external driving forces). The identified drivers are further distinguished by Hong *et al.* (2016) as presented in Figure 5. Occupant-related drivers/factors are marked again in blue.

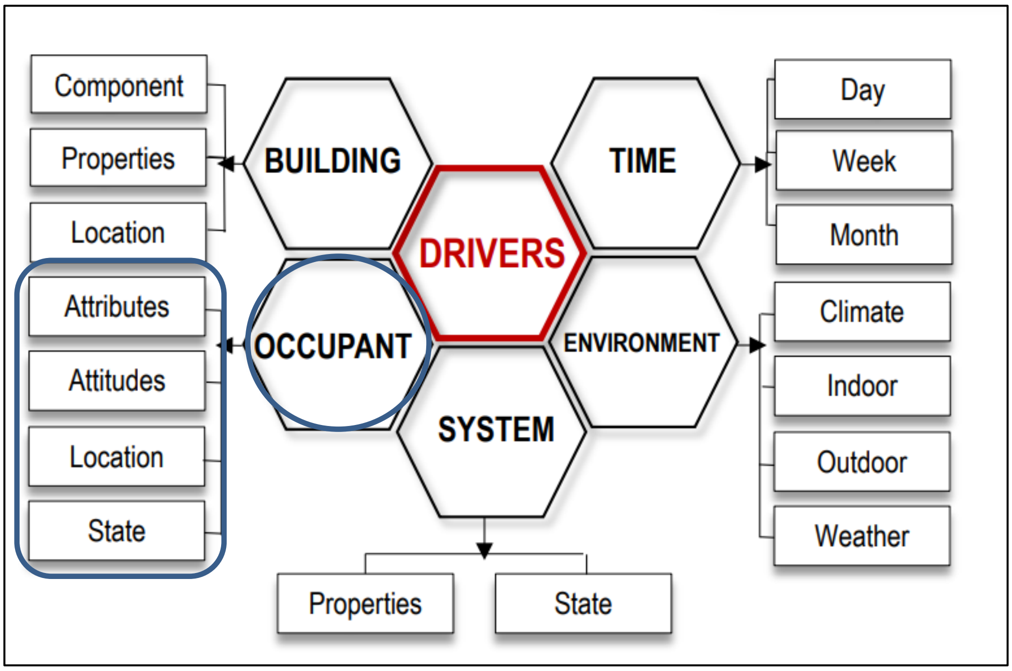

Figure 5: Drivers behind energy-related occupant behaviour (Hong et al., 2016)

As this fact sheet focuses on occupant-related drivers, these are mentioned in more detail here. Hong *et al*. (2016) consider occupant's age, gender and physical mobility as occupant-attributes influencing energy behaviour. Moreover, they consider the 'attitude' towards energy of the occupant (as introduced by the TPB) as important. Energy attitudes can range from 'energy frugal' to 'energy indifferent' up to 'energy profligate'. The exposure of an occupant to environmental drivers is determined by the location of the occupant. Furthermore, as we are already aware, the state of the occupant (i.e. occupancy of the building) can be related to the metabolic rate. The metabolic rate is acknowledged as an important input for thermal comfort models and has a significant impact on occupant behaviour.

The DNAs framework shall facilitate the quantification of the impact of occupant behaviour on building energy efficiency. The framework provides a more robust description of occupants' motives driving occupant behaviour. It can be applied to building energy modelling and simulation, building design, energy benchmarking and performance rating, development of codes and standards, and policy decisions.

The DNAs framework was integrated by d'Oca *et al.* (2017) with the TPB and the social-cognitive theory (SCT) within the aim of the IEA Annex 66 to develop a data-driven research framework that integrates multiple theories and interdisciplinary aspects relevant to occupant behaviour research. The integrated framework is presented in Figure 6.

Compared to the individual theories the integrated framework has several strengths. For instance, TPB ignores occupants' need to adapt IEQs, which is considered in the DNAs framework. However, data obtained through this linear approach are still based to the greatest extent on physical components and only insufficiently consider the degree to which social norms, group dynamics or individual motivations play a role. In turn, TPB extends and improves DNAs by considering how social dynamics influence the need to perform a certain behaviour (e.g. how the intention to share control is influenced by personal beliefs, habits or the perceived power over the control systems). The SCT presents the exterior layer of the integrated framework, arranging the dynamic interplay of environmental, personal, and behavioural factors (motivational drivers) of energy-use behaviour. The new framework suggests that people adopt certain behaviours to fulfil basic biological needs. This hypothesis is reinforced by the influences of personal cognitive factors from the social environment (i.e., attitudes, social norms, perceived behavioural control that is further explained using elements of TBP) or the physical environment (i.e., the actual access to the control systems as described in the specific element of the DNAs framework).

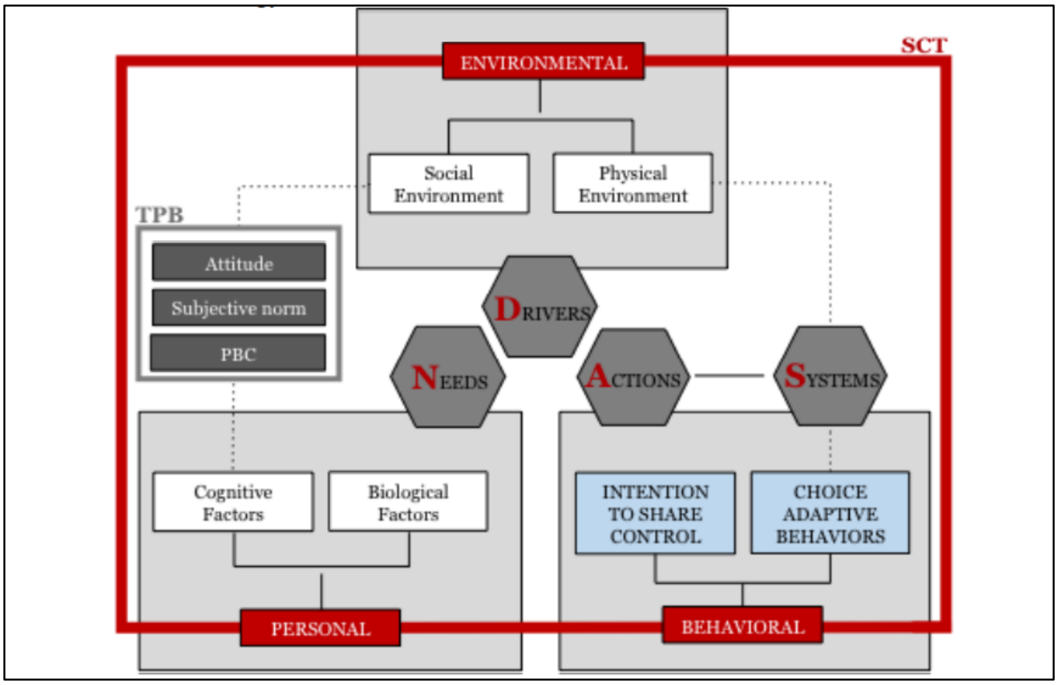

Figure 6: Interdisciplinary research framework integrating the SCT, DNAs, and TPB (Yan & Hong, 2018)

4.5. Development of user profiles, representative for the Netherlands

This subchapter sets the presented socio-demographic, characterizing households and energy use, and the range of comfort actions (actions to adapt the environment to one's needs) into relation by presenting the development of user profiles. More precisely, this section presents the development of user profiles, representative for the Netherlands, by Guerra-Santin & Silvester (2017). **The work in this study matches the objective of ePANACEA to develop user profiles for the integration in BES.** The application of occupant profiling could allow more accurate assumptions in the energy simulation of buildings (Delzendeh *et al*., 2017).

In the said study by Guerra-Santin & Silvester (2017), household types and corresponding occupancy patterns (presence & building operation) were defined. Based on these, user profiles were developed. The nationwide data set *Woononderzoek Nederland* (WoON) from 2012 (cf. www. rijksoverheid.nl) was used to determine the most common types of households in the Netherlands and to develop country representative occupancy and heating patterns. The WoON dataset includes information regarding household composition, housing needs, energy consumption and building operation.

Household types were determined, related to the household size, composition, occupants' age and the absence/presence of children and seniors. Guerra-Santin and Silvester (2017) identified eleven types of households, related to their sizes, composition, age and the absence/presence of children. Four other groups were too small in the sample and therefore were not further considered. The following household typologies resulted from the study: single senior, single adult, seniors couple, adults couple, three adults, single parent household and nuclear family.

In order to investigate the relation of these types of households **with electricity, gas and water consumption** (as an indicator for DHW) ANOVA tests (analysis of variance, used to compare the mean of more than two groups) were conducted. Electricity, water and gas consumption were found to be statistically significantly different regarding the seven household types. For electricity use the most influential factors are household size and presence of children. For water consumption the main determining factor is household size.

Occupancy patterns were defined as the use of the heating system, window opening behaviour, preferences for temperature settings and presence at home. Occupancy patterns were defined with exploratory factor analysis. Data for these variables refers to self-reported heating behaviour, stored in the WoON database.

The household profiles consist of the occupancy profiles (presence at home) and heating use patterns (use of thermostat and radiators) per household type. To determine the household profiles, analysis of variance (ANOVA) tests were performed between the factor scores (occupancy patterns) and the household types. For the development of the user profiles Guerra-Santin and Silvester (2016) used an approach which is deterministic and descriptive in nature. The process of developing Dutch household profiles is presented in Figure 7.

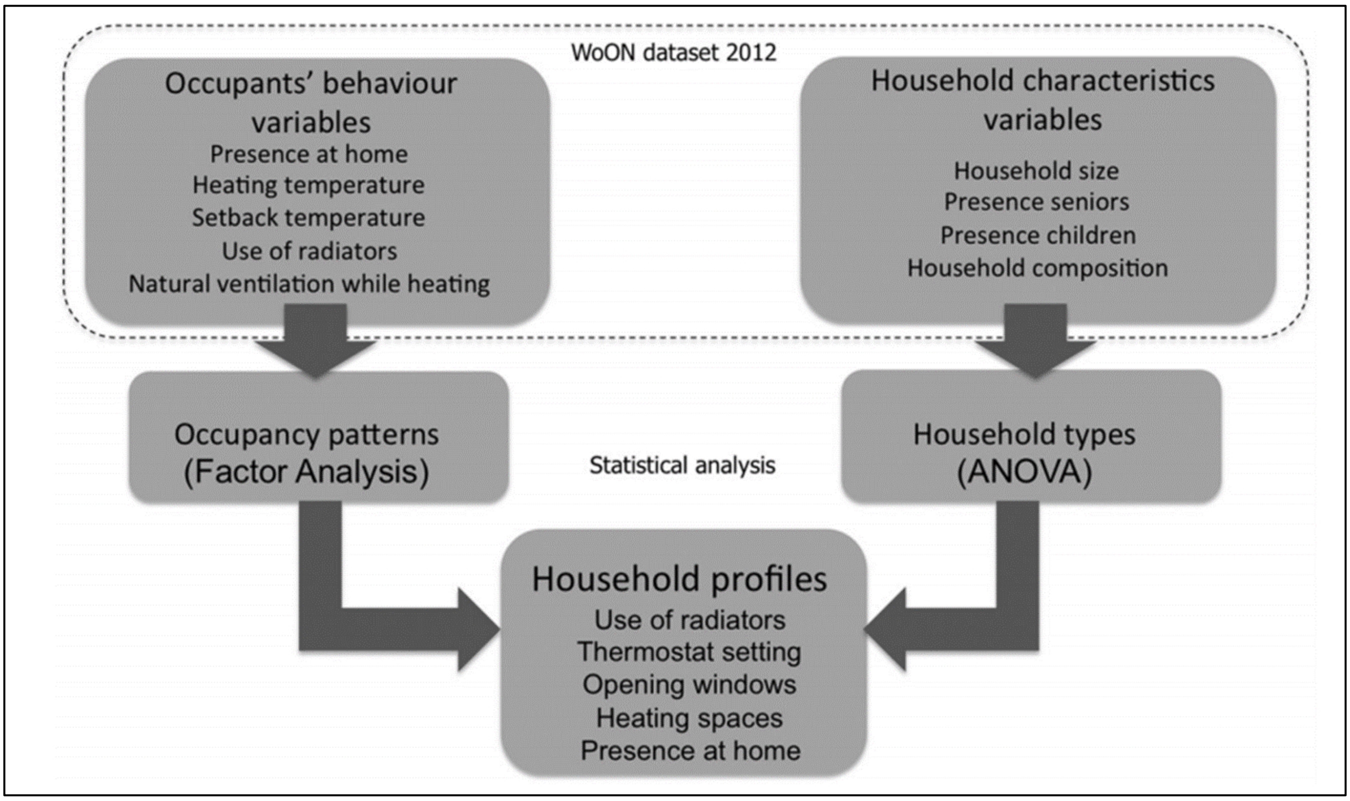

Figure 7: Process to define household types and occupancy patterns (Guerra-Santin & Silvester, 2017)

The developed household profiles reflect the lifestyle and preferences of the seven representative household types in the Netherlands. Results show that all behavioural factors were significantly different between household types except for the factor 'ventilation while heating'. Differences in heating behavioural patterns seem to be caused by **different lifestyles** among households (hours present at home), **comfort preferences** (e.g. senior households keep higher indoor temperatures) and **household composition** (e.g. presence of children; Guerra-Santin & Silvester, 2018).

Table 3 shows the resulting household profiles, consisting of a relative measure for intensity of behaviour (e.g. seniors use higher set-points than singles).

Table 3: Household profiles: intensity of heating behaviours and presence (Guerra-Santin & Silvester, 2017)

	Presence	Temperature	Setback	Radiators in the bedroom	Ventilation while heating	Radiators, others
1 senior	More	Warm	Wasteful	Semi-open	Higher rate	Semi-open
2 seniors	More	Warm	Setback	Semi-open	Average rate	Open
1 adult	Less	Cool	Setback	Semi-open	Higher rate	Closed
2 adults	Less	Average	Setback	Semi-open	Average rate	Semi-open
3 adults	Average	Average	Wasteful	Closed	Average rate	Open
Single parent	Average	Average	Setback	Open	Lower rate	Closed
Nuclear family	More	Average	Wasteful	Open	Higher rate	Semi-open

Figure 6 visualizes the household typologies and their intensity of behaviour and according to household size (smaller vs. larger household; Guerra-Santin *et al.*, 2018). Because simulation tools only focus on building-related energy demand, developed household profiles only relate to space heating and ventilation. Occupancy, lighting and the use of appliances was only taken into account to calculate internal heat gains (Guerra-Santin & Silvester, 2017).

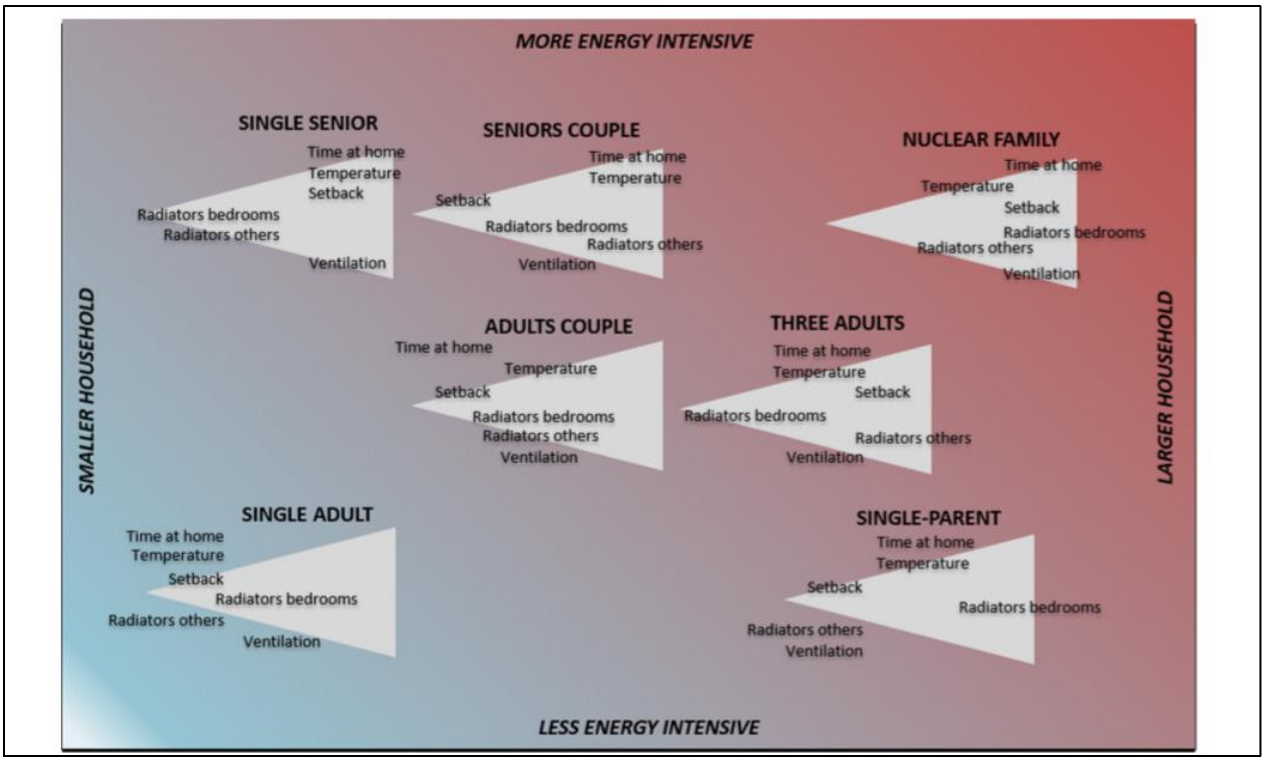

Figure 8: Household typologies and related energy behaviour (Guerra-Santin et al., 2018)

With respect to the relation between household typology and occupant behaviour Guerra-Santin *et al*. (2018) found that regarding the use of the thermostat, seniors tend to set the thermostat to a higher temperature than other households. Single adults tend to set the thermostat to lower temperature in comparison to other households. Besides, single seniors, nuclear families and households with three adults appear to choose a higher temperature for the setback of their thermostat. With reference to the use of radiators, households with children appear to heat the bedrooms more often than other households. In comparison, households consisting of three adults heat the bedrooms less often. Generally, households with one adult and single parent are associated with the least energy intensive behaviours, households with seniors and nuclear families are associated with the most energy-intensive behaviours (Guerra-Santin & Silvester, 2017).

We need to bear in mind that the development of occupancy and heating profiles aim at determining household-specific profiles; they do not predict occupancy patterns or energy consumption (as stochastic models do). **Accordingly, the relative difference in the intensity of behaviours between household types is more important than the absolute energy consumption to Guerra-Santin and Silvester (2017).**

The approach followed is deterministic and descriptive in nature, and thus the use of statistical data allows generalizations to be made to the population of study (the Netherlands). Seven household profiles were developed based on statistical analysis with the aim of providing nationwide occupancy input data for building simulation. The use of national statistical data allows the results to be generalized (Guerra-Santin & Silvester, 2016). The occupancy profiles and occupant behaviour do not only depend on the household type, but also on the region. Therefore, regional data can contribute to achieve more accurate predictions. Moreover, the profiles could moderately change if a specific sector of a population such as social rental properties (i.e. households with lower incomes), was considered (Guerra-Santin & Silvester, 2016). But, taking into consideration that the user profiles were developed based on a large dataset and with random sampling in the population, we can consider them as an improved alternative to 'standard' occupancy profiles originating from rules of thumb (Guerra-Santin & Silvester, 2016). **However, beyond the generalization for the Netherlands, we need to consider that some factors which influence energy behaviour greatly depend on the country of study. Also, different energy behaviours than heating might be**

more common in countries with e.g. a different climate: cooling is probably of as much interest as heating in Spain and Greece. This is relevant to consider for the development of an EU-wide methodology like in ePANACEA.

Yet, Guerra-Santin & Silvester (2017) offer that the presented approach could be applied in other countries for which datasets holding information about household demographics, building characteristics and occupant behaviour are at hand. The approach is even meant to be implemented (with some adaptations) in other countries than the Netherlands for which datasets like the one used in this analysis are not available. In this case, building monitoring campaigns could be used to validate statistical patterns or to determine household types in a country without statistical information. **The question is whether suitable databases on household characteristics and occupancy patterns regarding heating (& ideally cooling) exist for other EU MS.** Moreover, looking at the uptake of electricity use in the energy assessment within the scope of EPCs, electricity use may not only be considered to calculate internal heat gains.

Furthermore, the presented user profiles were used by Guerra-Santin *et al.* (2018) to take the influence of occupants' behaviour into account for zero energy renovation. More precisely, the heating demand was calculated taking into account statistically defined occupancy patterns by Guerra-Santin & Silvester (2017). For the calculation, the comfort temperature per room was determined per household type, based on the household types developed by Guerra-Santin & Silvester (2017). The DHW demand was calculated based on the requirements per person based on Dutch regulations. For the calculation of electricity demand the statistical occupancy profiles and hours of use of appliances per household type provided by Guerra-Santin & Silvester (2017) were used. Therefore, this study quantifies the effect of the user profile on energy use (heating and DHW). Therefore, this approach can be considered as a step towards integrating the user dimension into building energy assessment, which the following chapter deals with in more detail.

4.6. Summary of factors influencing energy-related occupant behaviour

Based on the chapter we can summarize that the factors influencing energy-related occupant behaviour can be roughly divided into external and internal factors. To our understanding, occupant-related factors, which we focus on, comprise internal and socio-demographic factors. A dominant factor which is related to the main motive behind adaptive behaviour and can be considered as an internal factor is the individual comfort need regarding IEQ (e.g. comprising thermal conditions, noise, privacy and view). Because comfort is perceived individually this is a factor that effects different reactions to the same indoor environmental conditions. Therefore comfort preferences (reflected in adaptive behaviours) should not be reduced to a standard input to the energy assessment of buildings. Interestingly, psychological variables (attitudes, perceived behavioural control, personal norm, awareness of consequences and ascription of responsibility), were not found to be influential in explaining energy use; socio-demographic factors (income, household size, age and gender) seem to be more influential. Regarding energy use in NRBs (represented on the basis of studies on energy behaviour in offices) different factors play a role in comparison to residential buildings. These include the presence of various agents influencing energy use, building automation or building operators who take over the interaction with the building systems for occupants and the space for actions for which all share responsibility. The reduced individual responsibility also applies to the responsibility for paying energy costs. Mentioned external factors that influence energy behaviour include possibilities provided by material to engage with energy (i.e. building systems to change IEQ) and the EPC as information tool, which however currently plays a negligible role regarding strategic energy behaviour and probably no role regarding everyday energy behaviour.

The types of energy-related occupant behaviour and factors influencing them are also described in the DNAs framework, relating drivers, needs, actions and systems. The DNAs framework provides a systematic representation of energy-related occupant behaviour in buildings and shall facilitate the quantification of the impact of occupant behaviour on building energy efficiency.

Finally, this chapter included a description of the development of user profiles, representative for the Netherlands. In the presented study the user profiles were developed based on household types with corresponding occupancy patterns. Data for the determination of common household types in the Netherlands and occupancy patterns was obtained from the WoON database. For the ePANACEA methodology the same approach could be chosen in order to develop user profiles. Ideally, country-specific databases should be available for this. If there is no country-specific statistical information available, building monitoring campaigns could be used to validate statistical patterns or to determine household types.

Preferences regarding indoor temperature are individual and preferences seem to differ between countries, too. Estimating the living room temperature during winter makes it possible to compare tolerable living room conditions between countries. For instance, the median temperature in both the Netherlands and England was 20°C, while in Denmark, Germany and Finland this was one or two degrees higher (Adjei, Hamilton and Roys, n.d.).

5. OCCUPANT BEHAVIOUR MODELLING

After the presentation of the facets of energy-related occupant behaviour, the factors influencing it and an approach to develop user profiles for the integration in BES, this chapter explores the approaches for modelling energy-related occupant behaviour and integrating it into BES. By modelling occupant behaviour, researchers relate various influential factors such as socio-demographics and psychological variables to the probability for occupants to carry out certain interactions in order to contribute to making more accurate predictions about the energy use in buildings. This requires a quantification of the effect of energy behaviour (i.e. comfort actions) on energy consumption.

This chapter first introduced the paradigm shift of occupant behaviour modelling and the related challenges. Then, it informs about parameters that can be used to describe occupants' energy-related actions and the methods that can be used to collect data on these parameters. Next, this chapter presents a categorization of occupant behaviour modelling and the current limitations before ending with a summary.

5.1. Paradigm shift of occupant behaviour modelling and its challenges

As mentioned above, occupant behaviour is acknowledged as a main source of the performance gap regarding energy efficiency. Therefore, researchers work on modelling occupants' presence and adaptive actions more accurately (Gaetani, Hoes & Hensen, 2016). **Accordingly, there is a paradigm shift regarding occupant behaviour modelling (Wagner & O'Brien, 2018): the conventional occupant modelling understands occupants as passive sources of heat, moisture and emissions, whereas the next generation of occupant modelling should understand occupants as active decision-making agents**, **who are responding to IEQ through adaptive actions to meet their comfort needs.** The approaches of conventional and the next generation of occupant modelling are depicted in Figure 9.

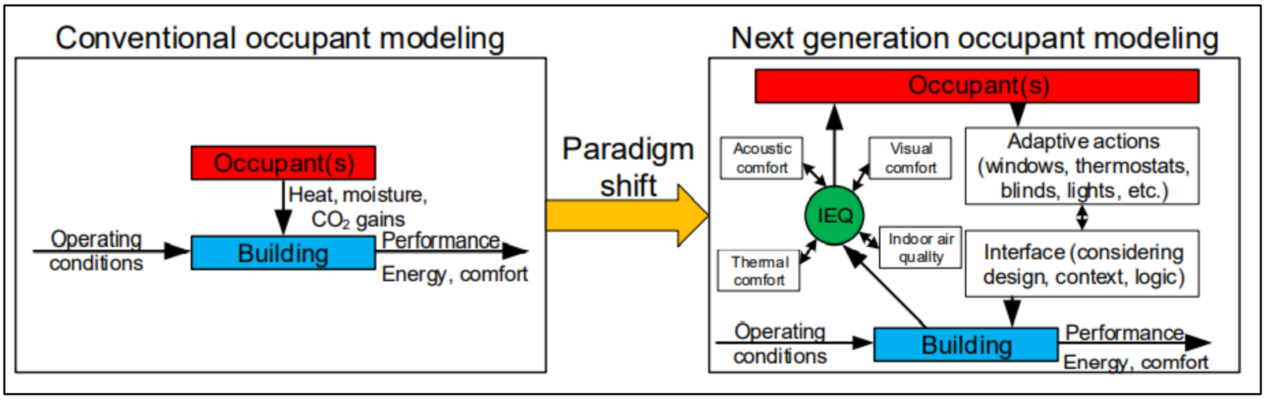

Figure 9: Paradigm shift of occupant behaviour modelling (Wagner & O'Brien, 2018)

Hence, the new paradigm of occupant modelling requires at least data on occupants' adaptive actions (interactions with building systems). To date and as introduced above, occupant behaviour is not well understood and is often over-simplified in the building life cycle because it is stochastic, diverse, complex, and interdisciplinary in nature (Hong *et al*., 2017). Moreover, the fact that multiple contextual factors influence occupant behaviour, makes occupant behaviour a complicated mechanism (Yan *et al.,* 2015). Also, multicollinearity between predictors and the finding that different interactions are influenced by different factors complicates accurate modelling. Furthermore, Laaroussi *et al.* (2019) explain that on the one hand, occupant behaviour has a stochastic nature which is contrast to having a deterministic nature, and therefore "needs an estimation of different probability simulations and distributions". On the other hand, the behaviour is determined by several factors/drivers which constitutes a deterministic component. The major problem thereby, as referred to by Laaroussi *et al*. (2019), is to integrate human behaviour, which is considered to have a stochastic and a deterministic nature, into BES "next to various axes concerning the building: (meteorological conditions, envelope and materials of the building, equipment of the building, systems energetics) and other aspects related to humans (physiological, psychological and social)" (Laaroussi *et al*. 2019, p.1).

Moreover, building simulation models should be able to depict a dynamic interaction between buildings and occupants (Yan *et al.,* 2015). But, often design teams are not able to predict the future building use since operational requirements and conditions might change significantly with time (de Wilde, 2014). Furthermore, Paone and Bacher (2018) explain that energy behaviour itself is dynamic because it changes with the experiences occupants make, and is often inconsistent. The use of NRBs is especially likely to change with new users during the buildings' lifetime (Ibid.). User-related parameters can also easily become outdated due to the implementation of new energy-efficient technologies, i.e. when they are applied to modern low-energy buildings they become inaccurate (Simanic *et al*., 2020). **These are several reasons supporting the goal to make the energy rating, taking into account the user dimension, more dynamic.**

Concluding, the fact that occupant behaviour is influenced by multiple factors, stochastic and deterministic in nature and dynamic makes it challenging to adequately model energy-related occupant behaviour, l*et al*one its integration into BES.

5.2. Data collection for occupant behaviour modelling

This subchapter aims to inform on what data needs to be collected for occupant behaviour modelling and how this data can be collected. The impact of occupant behaviour on EPB can be quantified through two different approaches: either through the comparison of the actual energy performance between similar buildings with different operations or the simulation of the building performance using building performance simulation (BPS) programs with varying occupant behaviour inputs (approach pursued in the ePANACEA project). The procedures for both, the direct assessment of behavioural influences and the simulated behavioural models build on advanced data-driven quantification methodologies (Hong *et al.,* 2017).

According to Yan *et al*. (2015) occupant monitoring approaches can be divided into three categories: 1) observational studies 2) surveys and interviews 3) laboratory studies. There are many observational studies in order to develop occupant behaviour models. For this, a large amount of data is required. Table A,5 (in appendix) maps the data that is needed to complete basic occupant behaviour. However, these models based on observational studies fail to map the various building typologies, cultures, climates etc. (Yan *et al.,* 2015). A further distinction is made among the observation methods in a) occupancy and equipment use monitoring and b) adaptive behaviour modelling. Occupancy and equipment use monitoring are grouped together because they are seen as independent of the building. On the other hand, environmental variables should be monitored when monitoring adaptive-behaviours, as they are possible predictors of adaptive behaviour (Yan *et al*., 2015). Monitoring occupant behaviour in buildings becomes facilitated through the advances in smart meter technology. Regarding residential buildings, the smart metering of electricity consumption is the most common approach to identify daily profiles. Unlike electricity consumption, heating and cooling consumption patterns are more difficult to measure, unless they are based on electricity (Csoknyai *et al*., 2019). Data for occupant behaviour modelling are typically collected in the working or living environment instead of in the laboratory (Yan & Hong, 2018). Figure 10 presents the distinction between objective and subjective measurements to collect data about energy-related occupant behaviour in buildings.

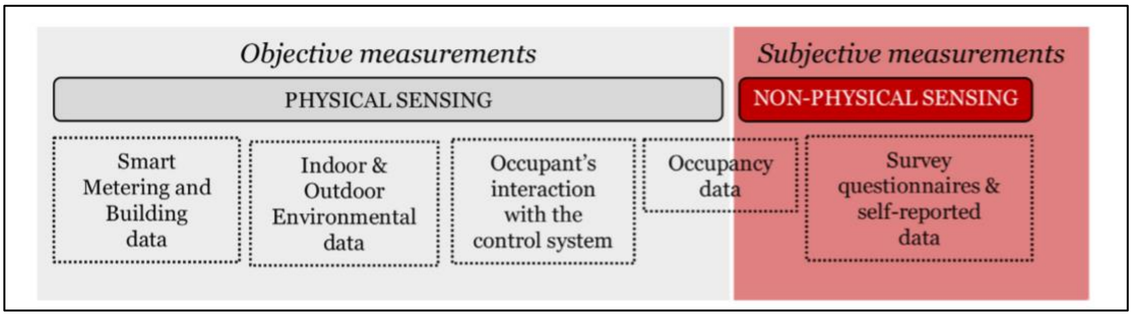

Figure 10: Scheme of methods for data collection about energy-related occupant behaviour in buildings (Hong et al., 2017).

For a comprehensive data collection on occupant behaviour e.g. consumption data, indoor and outdoor environmental data, occupants' interaction with control systems and self-reported data by occupants can be taken into account. However, considering surveys and interviews there are fundamental concerns: participants may (un)knowingly misrepresent their behaviour and participants might not remember their behaviours and extent of personal discomfort. Finally, participants are likely to respond the way they think they are expected to (Yan *et al.,* 2015).

Figure 11 presents a selection of parameters, related to occupancy and differentiated for building related and user-related energy use.

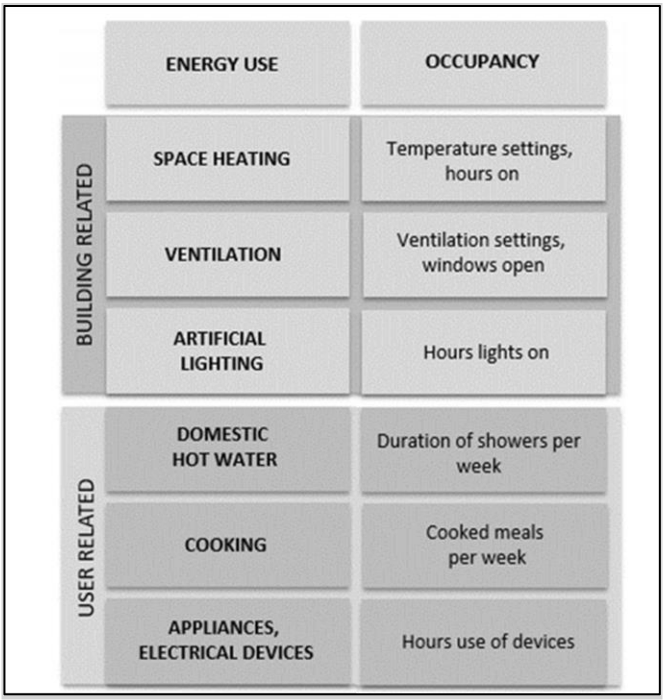

Figure 11: Building-related and user-related energy end-uses (Guerra-Santin et al., 2018)

Derived from this figure, occupants' interactions with control systems and user-related energy use can e.g. be measured by collecting data on temperature settings and duration of heating, ventilation settings and window-opening behaviour, duration of lights being turned on, duration of showers per week, cooked meals and duration of using electrical devices. Data on these parameters could e.g. be taken into account in occupant behaviour modelling/user profiles.

We need to consider that different energy uses (and therefore also actions to control them) have different degrees of influence on the total energy consumption of a building**. For occupant behaviour modelling it is crucial to identify the user-related**

parameters that are most influential on energy consumption (Simanic et al., 2020). Simanic *et al.* (2020) investigated how user-related parameters influence energy consumption in three recently built low energy schools (NRBs) in Sweden. The studied user-related parameters in this study were: indoor air temperature (during the heating season), occupancy rate, energy use for DHW, energy use for tenant electricity, ventilation rates and ventilation running times. The considered user-related parameters are therefore slightly different to the ones listed above; probably due to the consideration of a NRB instead of a residential. The results indicate that the set points for indoor air temperatures during the heating season and the energy required to run a demand-controlled ventilation system have an extensive influence, while tenant electricity use has a slightly lower influence on building energy use. These first two parameters are therefore most important to take into consideration, both during the design and operational phases of a building. Variations in occupancy rates and energy for hot water usage appeared to have the smallest influences on building energy use. These findings may be not transferable to any other type of building (e.g. residential). Also, the degree of influence of different energy uses (and the actions related to them) is likely to vary among countries.

Moreover, Csoknyai *et al.* (2019) concluded that a simpler, more cost effective and reliable way to analyse behavioural change regarding the use of heating systems is to monitor indoor temperature than monitoring energy consumption. The indoor temperature (in winter) may be used (in addition to other indicators) to draw conclusions on the heating behaviour of occupants. In addition, Cskoknyai *et al.* (2019) found out that regarding investigated homes in Spain and France, annual consumption figures can be easily estimated from the monthly consumption values of October, November, April or May for DHW and that of November or March for other electricity.

5.3. Categorization of occupant behaviour models

There exists a range of different modelling approaches for energy-related occupant behaviour. The most common categorizations of occupant models are based on the model's complexity, the object of investigation (e.g. occupancy or type of behaviour) and the used research approach (Gaetani, Hoes & Hensen, 2016).

Melfi *et al.* in Yan *et al.* (2015) distinguish models mapping presence of occupants in buildings according to their resolution (i.e. complexity) in three major dimensions: 1) temporal 2) spatial and 3) occupancy. Occupancy resolution means the specification of people; it can range from the indication whether an occupant is present (or not) to the determination of a specific action an occupant takes. Figure 12 visualizes different levels of resolution for the three mentioned dimensions.

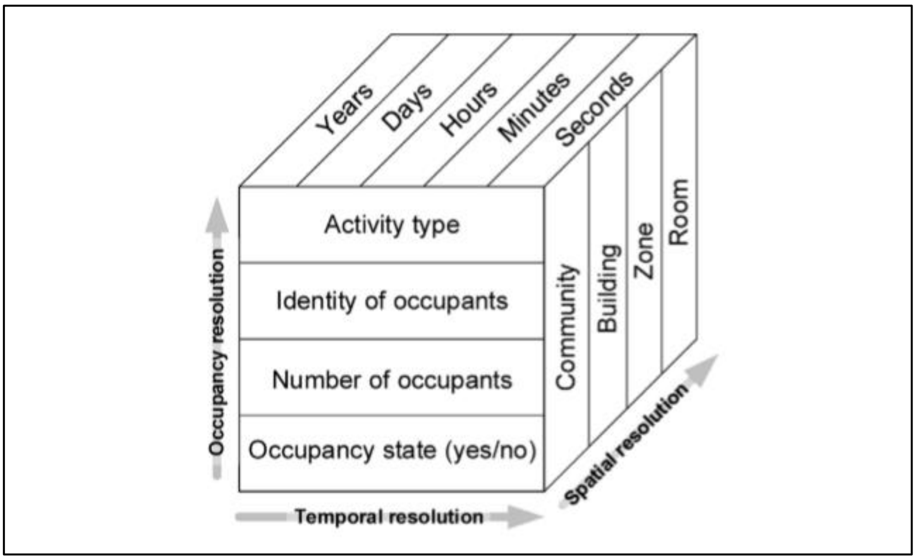

Figure 12: Illustration of different temporal, spatial, and state resolutions for occupancy modelling (Yan et al., 2015)

Accordingly, Gaetani, Hoes and Hensen (2016) suggest to apply fit-for-purpose modelling, i.e. that the most adequate model is chosen for a specific case with the lowest complexity, while at the same time preserving its validity (cf. decision matrix in ePANACEA). Thus, the complexity of the model should be chosen according to the case study (Ibid.). Likewise, Yan & Hong (2018) recommend choosing the occupant behaviour model according to the building context.

Furthermore, Gaetani, Hoes & Hensen (2016) identified three levels of occupant behaviour modelling, according to the size, resolution and complexity:

- **Level “0”:** non-probabilistic models, which mainly consider various factors from data-mining
- **Level “1”:** probabilistic or stochastic models, relying on Logit analysis, Probit analysis, Markov chain processes, Poisson processes, and survival analysis
- **Level “2”:** agent-based and object-oriented models, which are also called object-based models.

Gaetani, Hoes and Hensen (2016) neglected priori schedules and simple deterministic rules in their review. Table 4 provides an overview of the most common occupant behaviour modelling approaches, considering size, resolution and complexity.

Table 4: Overview of the most common occupant behaviour modelling approaches according to size, resolution and complexity (Gaetani, Hoes & Hensen, 2016)

Simulation framework	Type of model	Size	Resolution	Complexity
Conventional	Schedules	•	•	•
	Deterministic	•	↑	↑
	Non-probabilistic	•	↑	↑
	Probabilistic/stochastic	•	↑↑↑	↑↑↑
Agent-based	Agent-based stochastic	↑↑↑	↑↑↑	↑↑↑↑↑↑↑↑↑

According to Yan *et al.* (2015) most of the BPS programs enable users to define and input temporal schedules of thermostat settings (cooling and heating temperature set points), occupants lighting use, plug-loads and HVAC system operations. **User**

defined profiles work with specified deterministic rules describing the operation of building components and systems. An exemplary deterministic assumption is that windows are shaded if a space has too much solar heat gain. Likewise, a similar deterministic assumption is that "electrical lighting will be dimmed or completely turned off if a space has some or adequate daylight to meet occupant visual comfort needs" (Yan *et al.,* 2015, p.274). **On the one hand, this approach is easy to use; however, it lacks flexibility because users cannot create new categories of profiles or categories of rules. Another drawback is the fact that deterministic and simplified rules disregard the stochastic nature and complexity of occupant behaviour in buildings (Yan *et al.*, 2015).** Deterministic systems do not involve randomness in the development of future scenarios. Hence, starting from a given condition/initial state, a deterministic model will always deliver the same output.

The ASHRAE Standard 90.1-2004 (ASHRAE, n.d.) makes homogenous occupancy schedules related to different building types available. These can be used when actual occupancy and operational schedules are not defined (cf. Figure 13).However, this modelling approach shows a weak point in capturing the diversity of energy behaviour. Despite simulation assumptions, there is neither guarantee that occupants will be present in a space at fixed time intervals, nor that they will behave in a certain manner when triggered by the same environmental factors (Hong *et al*., 2017). This randomness of occupant behaviour contributes to a substantial discrepancy between simulated and actual building energy performance. **That is why rather stochastic than deterministic behavioural inputs are applied in BPS programs.** Figure 13 shows a comparison of a typical Monday-Friday schedule and stochastic occupancy schedules. We can see that the stochastic approach is more accurate.

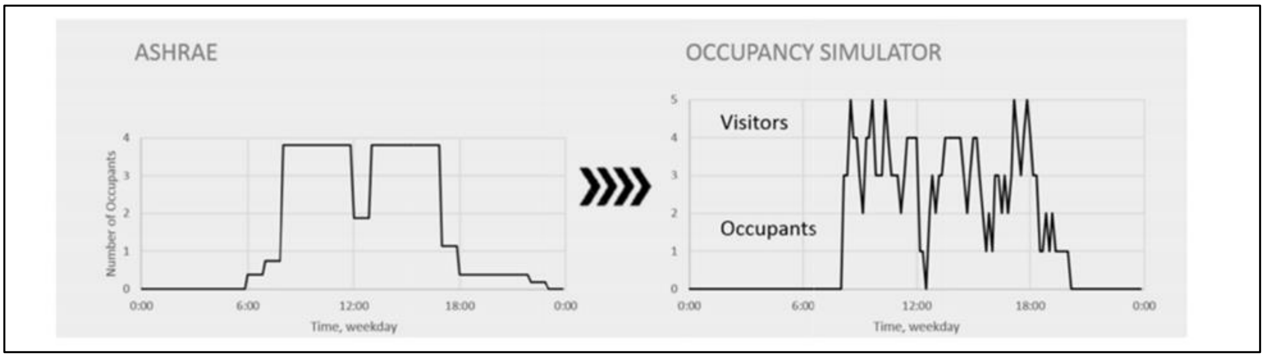

Figure 13: Typical Monday-Friday schedule compared to stochastic occupancy schedules (Hong et al., 2017)

Stochastic models are more capable of reflecting the variability in human behaviour (Ibid., Yoshino & Chen, 2016) because they possess some inherent randomness (Gaetani, Hoes & Hensen, 2016). In this sense, the same set of parameter values and initial states will result in an overall impression of various outputs. In stochastic models, actions are modelled based on a probability function with different drivers as input variables (Ibid.). Accordingly, Yan *et al.* (2015) explain that occupants' behaviour can be modelled stochastically because occupants' presence and behavioural patterns tend to develop over time. According to Laaroussi *et al.* (2019) there exist some studies which found that a suitable occupant behaviour model should be deterministic with the best selection of scenario application. Despite the mentioned advantages, Yan & Hong (2018, p. 127) remark "that stochastic models, to capture spatial, temporal and individual diversity do not necessarily always perform better than simplified deterministic models". Hence, whether deterministic or stochastic modelling approaches are more suitable may depend on the specific case (cf. fit-for-purpose modelling).

Agent-based models are based on a more complex simulation framework. **They are mapping group-level behaviour instead of individual-level behaviour.** They predict the influence of occupant behaviour through the modelling of individuals, mutual actions between individuals and their interactions with the building. This kind of modelling requires a huge amount of information (e.g., role of agents, relationship between agents, etc.), which may not always be accessible. Consequently, agent-based models significantly increase the size of the model. The outputs are still based on stochastic modelling, and that is why the resulting complexity is very high (Gaetani, Hoes & Hensen, 2016).

Finally, occupant behaviour models need to be integrated in the state-of-the-art BEM programs so that the influence of occupant behaviour on the EPB can be simulated (Yan & Hong, 2014; Hong *et al*., 2016).

5.4. Current limitations of occupant behaviour modelling

Gaetani, Hoes and Hensen (2016) reviewed available occupant models according to their level of complexity; simulation or modelling framework; type of behaviour; modelling approach, validation, implementation in BES and model's name; building typology; location; pros and cons. Based on this, they drew the conclusion that there exist many models; models are rarely developed as a simulation framework and the implementation in BES happens on a project-based level, often without guidelines for future use. **Other than that, models are specifically developed for a selected type of behaviour; however, the models which take the whole spectrum of occupant behaviour into account have increased recently (Ibid.).** When modelling multiple behaviour, an additional model layer needs to address the combination of different behaviours (Yan *et al*., 2015). Another challenge related to modelling multiple behaviour is to establish hierarchies of behavioural actions. When sequences of behaviour are modelled, obviously the complexity of the model increases. **In this context Kollmuss & Agyeman (2002) explain that a model which tries to consider all factors determining behaviour might neither be feasible nor useful. However, it could emphasize how complex the mechanism behind occupant behaviour is.** One aspect that advocates modelling multiple energy behaviours is that in reality energy behaviours are often inter-linked: e.g. the lighting to cooling/heating ratio indicating an interdependence between variables (Delzendeh *et al.,* 2017). Also, Huebner *et al.* (2015) found that independent predictors of energy consumption correlate with other variables. Concluding, studies on the inter-relationship between various energy behaviours of occupants are useful but currently limited and further analysis is much needed (Delzendeh *et al.,* 2017).

Currently, households and offices are the most studied types of buildings (Gaetani, Hoes & Hensen, 2016) which is also reflected in this fact sheet. Single occupancy offices present the largest share of studied offices. The development of models for a specific location limits their generalizability to other locations (Ibid.). **Also due to the given stochastic nature of human behaviour, one of the key research challenges is the issue of generalization of behavioural findings across multidisciplinary research areas (Hong *et al*., 2017).** Because occupants are not homogeneous and have diverse backgrounds and characteristics it is crucial for researchers to consider a more representative sample in order to generalize the results at the population level (Hong *et al*., 2017).

Advantages of models vary, while common limitations among the reviewed models were reported: complexity, case-specificity, lack of validation, calibration, generalizability, strong dependency on (outdated) time use surveys (Gaetani, Hoes & Hensen, 2016). However, because of the models' case-specificity and the lack of standardized methods to report results it is difficult to compare models (Ibid).

As mentioned above, occupant behaviour may change with time (even in the short term) and therefore also user profiles are dynamic in reality. Ideally, this phenomenon should be considered in occupant modelling (Csoknyai *et al*., 2019; cf. ePANACEA: dynamic energy assessment). Yet, this involves a higher level of model complexity with probably higher uncertainties (Roldán-Blay, Serrano-Guerrero**,** Escrivá-Escrivá, 2018). The identification and quantification of changes in energy consumption patterns have not been evaluated in depth. Roldán-Blay, Serrano-**Guerrero,** Escrivá-Escrivá (2018) proposed an index of change to assess the consumption changes with respect to the calculated pattern.

5.5. Summary of methods for occupant behaviour modelling

Concluding, there is a paradigm shift of occupant behaviour modelling; moving away from considering occupants as passive sources of heat, moisture and emissions, to understanding occupants as active decision-making agents, who are responding to IEQ through adaptive actions to meet their comfort needs. However, the new approach faces various challenges, related to the nature of occupant behaviour, which is considered to be stochastic, diverse, complex, and interdisciplinary. In addition, occupant behaviour is changing over time, placing the demand on occupant modelling to be dynamic. Large amounts of data are needed for occupant behaviour modelling. Occupant monitoring approaches can be divided into observational studies, surveys and interviews and laboratory studies. Other than that, for a comprehensive data collection on occupant behaviour, there are objective and subjective measurements, taking into account e.g. consumption data, indoor and outdoor environmental data, occupants' interaction with control systems and self-reported data by occupants. Next, occupant behaviour models can be categorized according to the model's complexity (resolution), the object of investigation and the used research approach. The resolution is determined by three major dimensions: 1) temporal 2) spatial and 3) occupancy. Based on the resolution, complexity and size of the models three levels of occupant behaviour modelling can be identified: level 0: non-probabilistic models, level 1: probabilistic or stochastic models and level 2: agent-based and object-oriented models. The advantage of stochastic occupant modelling approaches, compared to deterministic approaches, is that they are capable of reflecting the variability in human behaviour because they possess some inherent randomness. Agent-based models are the most complex approach, since they are mapping group-level behaviour instead of individual-level behaviour. Therefore, they require big amounts of data. Their output is based on stochastic modelling, resulting in a high complexity. Most modelling approaches are limited to a selected type of behaviour; however, a model trying to consider all factors determining behaviour might neither be feasible nor useful. Due to the given stochastic nature of human behaviour, one of the key research challenges is the issue of generalization of behavioural findings.

6. BEHAVIOURAL INTERVENTIONS

In contrast to the preceding chapters which focused on habitual energy behaviour, this chapter is about behavioural change (e.g. energy saving) and the interventions that can trigger or promote it. Behavioural change is included in this fact sheet because we are aware that everyday energy behaviour may be habitual but not static. It is rather dynamic, involving behavioural changes. Furthermore, we include behavioural change in this fact sheet because of its potential to increase energy efficiency. As we learned above, occupants do not predominantly carry out adaptive actions in order to consume energy or act energy efficiently but to achieve comfortable conditions. Hence, often occupants need to be motivated/convinced to take energy efficiency into account when interacting with the building's systems. Different intervention strategies are presented in this chapter, in order to show how a change in energy behaviour (habitual or strategic) can be motivated. This chapter ends with a summary as well.

6.1. Importance of behavioural change to increase energy efficiency

According to Yan and Hong *et al.* (2014) system and technological efficiency improvements received a lot of attention, whereas the human dimension was ignored. That is why, building systems design and energy retrofits only insufficiently consider occupant behaviour (Yan & Hong *et al.,* 2014). According to Hong *et al.* (2017, p.518) "technological solutions and innovations in building materials in the building sector are insufficient because buildings are dynamic systems, and occupants behave in complex ways". Hence, energy efficiency gains in buildings can be increased by occupant behaviour (Paone & Bacher, 2018; Janda, 2011); **energy-aware occupant behaviour has proven to be a low-cost and effective measure to save up to 20% of energy consumption in buildings, depending on the type of behavioural intervention (Hong *et al., 2017*)**. Also, the impact of occupant behaviour on energy efficiency becomes more important with optimized building envelopes and systems, increased technical energy standards and the spread of low-energy systems (Gaetani, Hoes & Hensen, 2016; Hong *et al*., 2017). Psychology can contribute to emphasizing that occupant behaviour has potential to increase residential energy conservation (Beth *et al*., 2012).

6.2. Factors influencing behavioural change

Abrahamse and Steg (2009) explain that energy use and changes in energy use are determined by different primary factors: **energy use is rather determined by socio-demographic variables, while changes in energy use are in need of some form of cognitive effort and seem to be more dependent on psychological variables**. Psychological variables may play a predominant role for energy conservation (understood as a type of behavioural change) because the decision to (try to) reduce energy consumption requires conscious decision making and/or necessitates conscious efforts to actually save energy (Abrahamse & Steg, 2009; cf. strategic energy behaviour). The considered psychological variables comprise attitude, perceived behavioural control, and personal norm, awareness of consequences and ascription of responsibility (Ibid.). The finding that energy savings are related to psychological variables may be important from a policy perspective, as interventions or policy measures aimed at promoting energy savings may want to target specific (psychological) variables (such as enhancing levels of perceived behavioural control; Abrahamse & Steg, 2009).

6.3. Categorization of behavioural interventions

This section provides two categorizations of intervention strategies. The first one distinguishes interventions into structural and psychological strategies, while the second one makes a distinction between antecedent and consequence strategies.

6.3.1. Structural and psychological strategies

Steg (2008) distinguishes two types of strategies to foster energy conservation in households: on the one hand, there are psychological strategies, which are focused on changing residents' knowledge, perceptions, motivation, cognition and norms related to energy use and conservation. Examples of such strategies are the provision of information (cf. EPC), education and modelling. On the other hand, structural strategies exist, focused on changing the context in which decisions are made such that energy conservation becomes more attractive. Exemplary interventions are new/better products and services, changes in infrastructure, pricing policies and legal measures (Steg, 2008).

6.3.2. Antecedent and consequence strategies

Abrahamse *et al.* (2015) suggest that behavioural interventions can be distinguished into antecedent strategies and consequence strategies. Antecedent interventions have an influence on one or more determinants before the performance of energy-related occupant behaviour. Antecedent strategies are e.g. commitment, goals setting, information and modelling. For instance, the fact that people acquire more knowledge because they receive information about energy-saving options may lead to energy savings (Abrahamse *et al.,* 2005). Hence, antecedent interventions aim to influence behavioural determinants which are assumed to be factors influencing behaviour. By contrast, a consequence is understood to have an influence on determinants after the performance of energy-related occupant behaviour through the provision of a consequence which depends on the outcome of behaviour. **For instance, providing households with feedback about energy savings probably motivates them to further reduce their energy consumption because their perceived self-efficacy to save energy has increased (cf. new EPC).** Consequence strategies are formed on the belief that positive or negative consequences will influence behaviour (Ibid.).

6.4. Selection of adequate intervention strategies

Looking at what constitutes "energy conservation**",** Beth *et al.* (2012, p.2) mention "a diverse set of specific behaviours, including those related to lighting, laundry, heating/cooling and use of electronic devices". Even for a subset of actions such as the use of lighting one can differentiate between different interactions like turning off the light, when not needed, using energy-efficient lighting or time-witches. These specific actions are associated with financial costs, required effort and knowledge in order to implement them. **In order to make behavioural interventions effective, they should target the specific behaviour (Beth *et al*., 2012).** In view of the different possible behaviours, it is obvious that intervention strategies may vary considerably (Janda, 2011; Beth *et al*., 2012).

The behaviour change wheel (BCW) is based on a theoretical model of behaviour which aims to integrate commonly used models of behaviour (e.g. the TPB) and considers other key conceptual variables, reported as important within behaviour change literature (e.g. impulsivity and emotional processing; Staddon *et al.,* 2016). At its core, the BCW comprises the source of behaviour (i.e. opportunity, motivation and capability). In the inner ring the model considers intervention functions, while in the outer ring it refers to policy categories. The model should be read from the inside out.

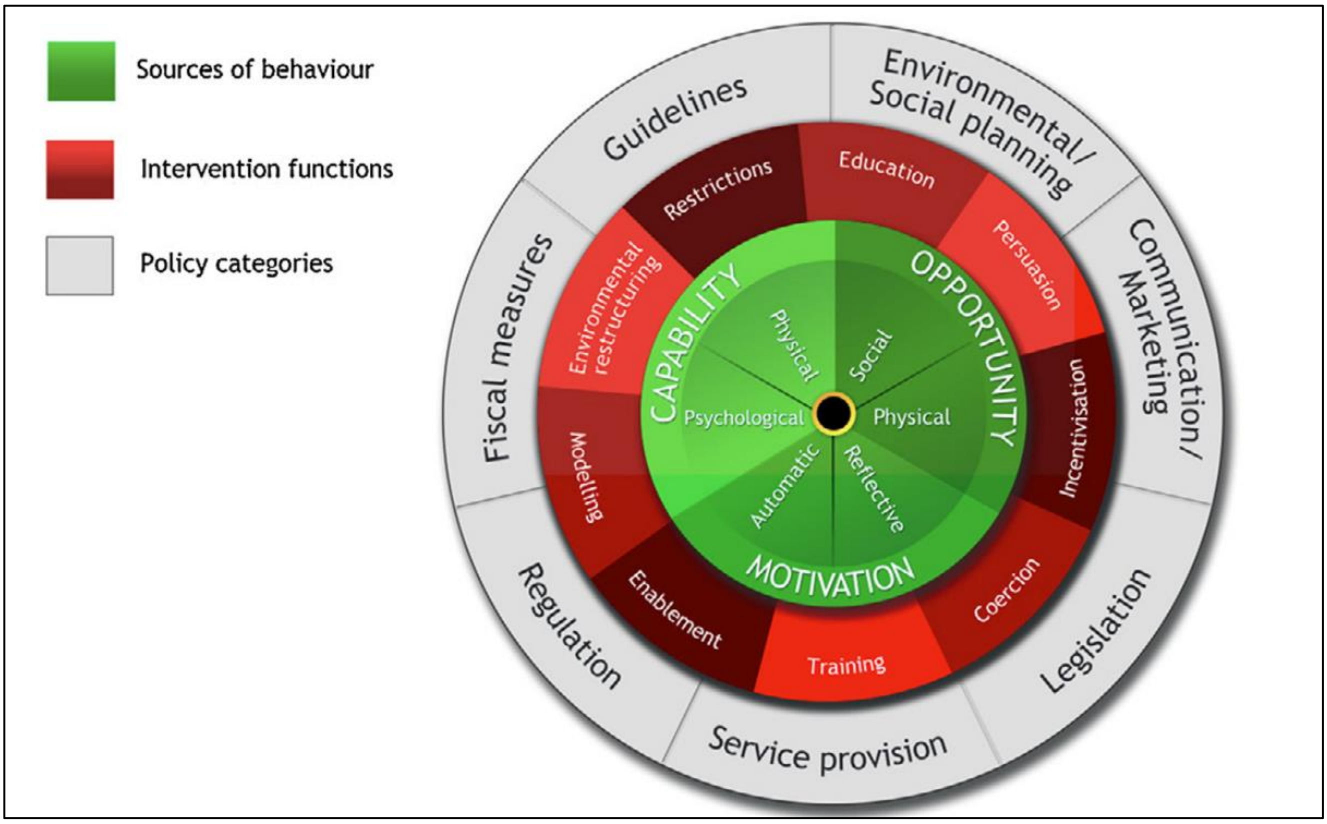

Figure 12: The Behaviour Change Wheel (BCW) (Staddon et al., 2016)

It becomes apparent that multiple intervention functions are associated with each type of source of behaviour (i.e. there is no such thing as one correct intervention; Staddon *et al.,* 2016). According to Abrahamse *et al.* (2005) it is important to contemplate household energy conservation from a multidisciplinary perspective (i.e. using a combination of structural and psychological strategies). Next to the consideration of variables concerning the individual level (e.g. attitudes, abilities) it is important to target macro-level factors contributing to household energy use (such as demographic or societal developments). They shape the physical infrastructure and technical devices that influence material engagement with energy (Abrahamse *et al.,* 2005).

6.5. Potential intervention strategies

This section presents different intervention strategies, which can be ranged into structural/psychological and antecedent/consequence strategies. More precisely, financial rewards, information and feedback are presented as intervention strategies. In addition, the new EPC is presented as potential intervention, influencing energy behaviour.

6.5.1. Financial rewards

Financial rewards can be regarded as a consequence strategy. There is evidence that behavioural changes induced by financial incentives are in general short-term in nature. Changes in behaviour due to financial incentives usually do not prevail and are discontinued as soon as the reward is not received. Also, the provision of financial resources favours the occurrence of the rebound effect, i.e. that people who received or saved money by using less energy, spend money on other, possibly unsustainable and/or energy-intensive actions. This effect would counteract the aim of reducing GHG emissions. An alternative might be to provide delayed rewards, after energy was saved during a period of one year, assuming that energy-saving behaviour would have become habitual and non-reversible by then (Huebner, Cooper & Jones, 2013).

6.5.2. Informational strategies

The provision of information can be regarded as a psychological and antecedent strategy. Some informational strategies seem to be effective in fostering household energy conservation. A list of effective information strategies includes: prompts, information tailored to needs, wants and perceived barriers, commitment strategies, motivating people to indicate how they plan to reduce their energy consumption, and modelling and providing information about the behaviour of others. Informational strategies are especially effective in situations where pro-environmental behaviour is convenient and inexpensive, requires relatively little time and effort and individuals do not experience high social disapproval (Steg, 2008). Thus, information on how to save energy through adapted everyday energy behaviour could be effective. Informational strategies may be an important supplement to structural strategies which aim to change individuals' behaviour. For instance, considering domestic energy consumption, knowing about the operation of the heating system is important because space heating is the largest contributor to domestic energy consumption (Huebner, Cooper & Jones, 2013). **We can consider the EPC as an information tool, currently providing information which can influence strategic energy behaviour (decision-making before purchase/rent and the uptake of renovation measures).**

6.5.3. Feedback

In a broader sense, feedback can be regarded as information. Furthermore, it can be ranged into psychological and antecedent strategies**.** Janda (2011) compares the current use of energy to going shopping in the supermarket without seeing prices of the individual products and receiving an invoice for the value of the purchases at the end of the month. That explains why energy consumption is not tangible for consumers (cf. not speaking of energy behaviour but of performing tasks that require energy). Consequently, with missing information, it is difficult - if not impossible - for residents to evaluate the costs and benefits of their actions. This indicates why it is helpful for residents to receive real-time feedback about their energy consumption instead of a bill at the end of the month. Feedback about the real energy consumption pattern can e.g. be provided via in-home-displays.

Referring to feedback intervention in commercial buildings Paone and Bacher (2018) state that occupants are not necessarily motivated by individual energy feedback. Energy savings can rather be achieved when occupants receive feedback about the energy consumption of their organizational network (Paone & Bacher, 2018).

6.5.4. Potential intervention strategies in (or related to) the next generation of EPC

The impact of the EPC on energy behaviour could e.g. be increased through improved (understandable, binding and individual) information about the energy performance of the building, additional information about behavioural measures to reduce energy consumption in everyday life (e.g. based on the user profile) and improved information about renovation measures. Also, these improvements would meet the needs of improved information and more recommendations, expressed by end users (cf. *Insights on user perceptions and needs regarding the Energy Performance Certificate (EPC)*; DOI: https://zenodo.org/record/4569465#.YKJqp6FCQ2w). For instance, the use of adequate language to communicate technical information could lead to e.g. an increased consideration of the EPC during decision making regarding the rent/purchase of a dwelling/building. Also, the provision of more detailed, individual recommendations could increase end users' motivation to initiate EEMs and/or to change their adaptive behaviours. Referring back to the distinction between strategic and everyday energy behaviour, we can conclude that improved information can address both – strategic and everyday energy behaviour. For instance, tailored information can refer to one-off investments in a new heating system or to everyday energy behaviour when information on the setting of the thermostats is provided.

Moreover, the possibility to create user profiles in the new EPC could increase end users' perceived usefulness of the EPC. End users could probably identify themselves better with the EPC in which their user profile is considered because it would be less standardized. **Other than that, with the possibility to adjust user profiles, end users could "observe" the effect of changing occupant-related factors on the energy consumption of their building. This could raise their awareness about the impact of their energy behaviour on the energy consumption of the building.** Also, this could make visible what changes in behaviour would have a reducing effect on energy consumption. This will be simple to realize in a digital EPC.

Regarding the potential integration of real time feedback on energy consumption in the EPC we must consider that this could likely go beyond the scope of an EPC, distracting from the original purpose of the EPC that was created as an obligatory instrument, for the comparison of the energy efficiency of buildings. For instance, if end users were forced to pay for consumption monitoring as part of the obligatory EPC, this could create resistance (assuming that any new functionalities in the EPC will increase the price of it). However, we can consider that the EPC is one of several information opportunities and other intervention strategies (e.g. real-time feedback tools and financial incentives) related to energy efficiency in buildings. Hence, one could e.g. indicate in the EPC where additional information related to energy efficiency in buildings can be obtained. For instance, one could motivate end users in the EPC to compare the real energy consumption (measured with other tools) of the building to the indicated energy demand in the EPC.

6.6. Negative behavioural consequences of efficiency gains

Intervention strategies may not always be effective in the sense that they increase energy efficiency and therefore reduce the total energy consumption. This is due to e.g. the single-action bias and the rebound-effect.

- **Single-action bias**: "Single action bias" means that people perceive that a single action (e.g. in response to climate change) will make a great deal of impact. This perception prevents them from becoming active in other areas to reduce their climate impact (Bet *et al*., 2012). In the context of the impact of the EPC, this can mean that e.g. end users initiate EEMs and raise their comfort level and therefore adapt their everyday energy behaviour. Or that end users consider the energy efficiency as an important criterion when buying a house, but raise their comfort standard because they can live in a warmer place without paying a higher energy price.
- **Rebound-effect:** The rebound effect can be described as the increased use of services for which energy efficiency measures reduce the energy costs (Guerra-Santin *et al.,* 2018). Hence, people compensate for efficiency improvement by increasing the use of the service and the associated costs (Ibid.). The statement "when we were less efficient we used less energy" (Janda, 2011, n.p.) describes that merely through the increase of energy efficiency we may not attain a reduction in energy consumption. Besides, one should be aware that the rebound effect is in some cases not the result of conscious behavioural change but a result of new technology (Guerra-Santin *et al*., 2018).

We need to be aware of the possible occurrence of the rebound-effect, as well, when making assumptions about the impact of the new EPC on e.g. the total energy consumption. We may assume that improved communication of technical information to end users may result in better understanding. Likewise, we may assume that more accurate and valid information may increase end users' trust and use of the EPC for decision making. However, from this, we cannot anticipate that overall end users will consume less energy.

6.7. Summary of behavioural interventions

Behavioural change is included in this fact sheet because energy behaviour may be habitual but is also subject to change. Besides that, next to the building components' and systems' efficiency, behavioural change has also the potential to increase energy efficiency. By contrast to the factors influencing energy use, psychological factors have a bigger influence on behavioural change. Behavioural change can be stimulated by intervention strategies which can be divided into structural and psychological strategies and/or antecedent and consequence strategies. Intervention strategies encompass e.g. financial rewards, informational strategies and feedback. Behavioural interventions should target the specific behaviour in order to be effective. However, there is no such thing as one correct intervention, hence multiple intervention functions can be associated with each type of source of behaviour. The envisaged improvements of the new EPC (e.g. more accurate, tangible and understandable information on the EPB) could motivate end users to take EPB more into consideration before buying/renting a dwelling /building. Individual and more detailed recommendations could contribute in motivating the end user to initiate EEMs, therefore affecting the strategic energy behaviour. Besides this, the influence of the EPC on everyday energy behaviour could be increased through the inclusion of user profiles in the EPC and individual advice on everyday energy behaviour. Despite the positive behavioural consequences which may be expected as a consequence of, like in this case, improved information, we need to anticipate the occurrence of the rebound effect, counteracting the savings made elsewhere.

7. SYNTHESIS FOR THE DEVELOPMENT OF USER PROFILES FOR THE EPANACEA METHODOLOGY

The development of user profiles, to be integrated in the ePANACEA methodology, can be inspired by the above-described factors that influence energy consumption, models for energy-related occupant behaviour and the developed user profiles by Guerra-Santin & Silvester (2017). This chapter provides guidelines for the development and integration of user profiles in the ePANACEA methodology. This includes considerations about the implementation of user profiles within the context of EPC and a summary of the variable categories constituting a user profile. Besides that, this chapter contains a draft of a user profile interface and presents remaining concerns and questions related to the implementation of user profiles in the outlook section.

7.1. Implementation of user-profiles within the context of EPC

- **User profiles are a possibility to take user behavioural patterns for the energy assessment of buildings into account. In addition, the integration of user profiles also meets end users' needs to make the EPC customizable (cf. *Insights on user perceptions and needs regarding the Energy Performance Certificate (EPC)*; DOI: https://zenodo.org/record/4569465#.YKJqp6FCQ2w).** However, the aim of taking the user characteristics into account is not only to enable end users to interpret the indicators on the EPC based on their user profile; but, the aim is also to better estimate user behaviour during the planning phase, so that the house and the facilities are appropriately designed and selected. Hence, the consideration of user profiles is already important during the planning phase of a building, and should not only be taken into account after the EPC was issued.
- **We need to consider how data about the user dimension that influences energy consumption in buildings can be gathered:** For instance, users (e.g. prospective owner/tenants) could fill in a user profile interface during the design phase of a building. **Furthermore, it should be possible that user profiles can be updated (in the event of changed user behaviour or new tenants/owners). This places demands on the user profiles to be dynamic, at least adjustable.** In case the building is transferred to another person the energy efficiency could be evaluated based on the new user profile, similar to how the energy efficiency is recalculated after major renovations. Moreover, with the possibility to adjust user profiles, end users could "observe" the effect of changing occupant-related factors on the energy consumption of their building. This could raise their awareness about the impact of their energy behaviour on the energy consumption of the building. This raises the question as to how one can guarantee that user profiles remain up-to-date, e.g. if conditions change even though no new tenant has moved in. **For instance, one could send a reminder to end users at least every two years with the request to check and (if necessary) update the information in the user profile interface.** With the update, changes in the household are taken into account and thus any changes in energy consumption can be put back into context (i.e. fluctuations can be explained or expected).
- Moreover, with the inclusion of energy use in the energy assessment that is rather occupant-related than building-related (e.g. electricity use) one should be aware that it is not feasible to indicate electricity use (only) *per area* (because it is less dependent on the building characteristics, more on the user-related characteristics). **It would be more adequate to indicate electricity consumption *per person*.** For the estimation of the total electricity consumption, the query of the number of people living in the household becomes important. Moreover, if the energy consumption was set into relation with the number of persons this could demonstrate if people live in an adequately sized dwelling/house; it could indicate if people live in very big energy efficient houses and consume in total more energy per person (but less per area) compared to a person living in a small dwelling with several other persons.
- The user profiles could be developed according to the approach by Guerra-Santin & Silvester (2017): taking the household typology AND the occupancy (presence & building operation) into account. **But, we need to consider that for the different pilot countries of ePANACEA (as well as for different MS of the EU), different energy**

behaviours may be more/less dominant and therefore important for the energy assessment of buildings. In countries with a cooler climate, heating and DHW is more important than in countries with warmer climates where ventilation and cooling are more relevant to attain comfort levels. Moreover, as we know, different energy behaviour is determined by different factors. **Hence, ideally, user-profiles should be country-specific.**

- Because of practical reasons, there should be one user profile per household. The indication of different individual preferences and characteristics per person might be more exact but will make the calculations of the impact of the user dimension on energy consumption more complex.
- In any case, the user profiles should have a modular structure, consisting of different categories which can be filled in with user-related information. The information which should be taken into account in a user profile are suggested hereafter.

7.2. Information in user-profiles

Based on literature research conducted for this fact sheet, we can conclude that socio-demographic variables, as well as occupancy of the building and comfort preferences which are reflected in the building operation (heating, cooling and ventilation behaviour and the use of lighting) as well as other energy uses such as the use of electrical devices shape occupants' energy use in buildings. This list provides parameters, related to the mentioned categories, which outline the user dimension in relation to energy use in buildings.

- A realistic representation **of occupancy** is important in order to take into account the user dimension in BES. Therefore, the determination **of occupancy profiles** is important. The determination of occupancy profiles requires knowledge about socio-demographic variables such as: **household composition (presence of children/seniors)** and **employment (shaping occupant's schedules throughout the week).** However, regarding employment we need to increasingly consider whether people work from home or not. The point behind collecting this data is to find out when people are regularly at home and when they are not.
- Other socio-demographic variables, not necessarily influencing occupancy but energy consumption, are **income** and **the household size** (number of people living in a household). Both correlate positively with energy consumption. Especially, in relation to the uptake of energy use that is occupant-related rather than building-related, these two variables should be included in user profiles.
- Based on literature review, we can assume that psychological variables are rather <u>not</u> significant in explaining energy use. **Energy use is rather determined by socio-demographic variables**. This suggests that psychological variables do not necessarily have to be taken into account in user profiles. Moreover, it might be harder for end users to provide information on psychological factors since their self-assessment does not happen in comparison to others (they are missing a reference). A self-assessment is not objective either. However, with this we do not mean to say that psychological factors do not play any role regarding every-day energy use.
- **Comfort preferences** should be considered. Thermal comfort preferences could be queried using parameters such as preferred indoor temperature. However, this will likely be difficult to answer for citizens. Habits on building operation and DHW use, which reflect comfort preferences, might be easier to indicate.
- **Building operation and the use of devices should be included in the user profile.** The building operation embraces different energy uses. For instance, it includes heating behaviour which can be characterized by the **presence at home, thermostat setting, use of radiators (heating hours) and ventilation while heating** (cf. Guerra-Santin & Silvester, 2017). Other building-related energy uses encompass ventilation, for which **ventilation settings and window opening behaviour** can be used as parameters. Regarding building-related electricity consumption such as artificial lighting, the **hours lights are turned on** can be considered as parameters, taking the occupant dimension into account.

- Concerning the use of devices/appliances, **the hours of using devices** could be used as a parameter for user behaviour. Furthermore, energy consumption in buildings encompasses the use of DHW. Regarding this, Csoknyai *et al.* (2019) recommend to take operation habits on bathing/showering frequencies (e.g. **duration of showers per week**) into account. Another user-related energy use constitutes 'cooking' which can e.g. be taken into account in user profiles by considering **the number of cooked meals per week**.

7.3. Draft of a user profile interface

This section presents an exemplary user profile interface (Figure 14) which contains the following categories: building type, socio-demographics, occupancy, building operation and other energy uses in the building, whereby the requested information under 'building operation' is relevant with regard to the heating behaviour. Similar information (ventilation settings, duration of use of the air conditioning system, ventilation behaviour during cooling) could be requested regarding cooling behaviour (more important in warmer countries; however, probably increase in importance as persistent heat also increases in more northerly countries. The information used for this figure is based on literature review, conducted for this fact sheet. Necessary information in order to estimate the impact of heating behaviour on energy consumption is retrieved from Guerra-Santin & Silvester (2017). The given values are fictitious.

The first category 'building' type is not considered in current EPC schemes (i.e. one does not distinguish between building and dwelling; EPC is always issued for the complete building). However, the location of a dwelling in a building can significantly influence energy consumption and therefore should be considered. One can discuss whether the user profile is the right place for it.

Furthermore, occupancy is likely to be approximately the same throughout the year with a few exceptions such as vacation. However, the listed parameters under 'building operation' are dependent on the season. In other words, it only makes sense to collect this data for the winter/heating season. Also, the duration of showers/baths and therefore the use of DHW and the use of fans to move air (and therefore to achieve a cooling effect) depends on the season (outdoor temperature, and other meteorological factors such as wind, solar yield) (Csoknyai *et al.,* 2019). One could collect the data for the winter months and then take into account that there is no heating in summer and develop an annual weekly mean, unless user profiles are so dynamic that fluctuations from month to month are taken into account. The question remains whether end users are capable to specify the required data or how inputs are obtained for new constructions (cf. outlook). Concluding, thinking about the draft of a user profile made evident again that there are other influential factors such as the climate of a country (determining the most influential energy use regarding a building's energy consumption, e.g. cooling or heating) and the seasons, which need to be taken into account when developing a user profile that is supposed to contribute to a more accurate indication of the energy demand in the EPC.

User profile interface for residential building

Please enter your information!

Building type	Household information
Detached house	✓
Dwelling (ground floor)	
Dwelling (top floor)	
Dwelling (sandwich)	

Socio-demographics	Household information
Household size [n]	3
Household composition [adults/children/seniors]	2 adults, 1 child
Netto household income [€]	4000

Occupancy (presence)	Household information
Time slots	Days at home/week
• 06:00–09:00	7
• 09:00–12:00	3
• 12:00–15:00	4
• 15:00–18:00	5
• 18:00–23:00	6
• 23:00–06:00	7

Building operation	Household information
Thermostat temperature [°C]	
• 9:00–15:00	17
• 15:00–18:00	18
• 18:00–23:00	19
Setback Temperature [°C]	
• 06:00–09:00	12
• 23:00–06:00	10
• When nobody	14
Use of radiators	1 = always, 2 = sometimes, 3 = never
• Kitchen heating	2
• Bathroom heating	1
• Main bedroom heating	3
• Other bedroom heating	2
• Living room	1
Natural ventilation while heating	1 = regularly, 2 = sometimes, 3 = never
• Living room	2
• Other rooms	2
Lighting [hrs/week]	35

Other energy uses	Household information
Cooked meals [n/week]	6
Showers [mins/week]	140
Baths [mins/week]	30
Electrical devices [mins/week]	
• Dryer	100
• Washing machine	140
• Dish washer	120
• TV	360
• Computer/ laptop	840
• Vacuum cleaner	50
• Fans	0
Kitchen devices	
• Coffee machine	40
• Water heater	20

Figure 14: Exemplary user profile interface (focus on heating behaviour)

7.4. Outlook on user profiles

For the development of user profiles privacy issues need to be considered. Users might not feel comfortable giving lots of information about their household and habits. Users may be particularly uncomfortable about the fact that based on the occupancy data one knows when the home is likely to be vacant. Almost all of the bullet points for user profiles listed in 7.2 and 7.3 are subject to privacy consideration in terms of GDPR. On the one hand, for the sake of reliability and quality of the end result, profiles deserve to be accurate and transparent. On the other hand, EPC is not (entirely) confidential, and it is stored in some repositories and accessible by different actors. Therefore, the privacy aspect needs to be given due consideration.

Moreover, the question remains where the data that is entered in the user profile comes from. Whether, for example, inputs can be assessed and entered by the users themselves. Because in the case of new constructions, it will be impossible to enter measured or observed data on the one hand, and on the other hand it will be difficult for prospective occupants to estimate data (e.g. thermostat settings and window opening behaviour) before occupancy. In these case one would probably have to rely on statistics and make assumption about the energy intensiveness of a household based on socio-demographic variables (cf. approach by Guerra-Santin & Silvester, 2017). This approach could also be an alternative, if it turns out that end users are not capable of providing sufficiently accurate information on building operation and occupancy.

Also, for the sake of simplicity, it might be practical to develop a few main user profiles (cf. Guerra-Santin & Silvester, 2017) which can be assigned to households, depending on the inputs. It might be good if all main user types are visible to end users so that they can compare the impacts of different user types on energy consumption (scenarios of the impact on energy consumption by different user profiles).

Finally, we need to consider what time frequency for data gathering should be used in order to take up-to-date data into account (with regard to changing socio-demographics), and to consider changing energy behaviours throughout the year (depending on changing external factors related to the seasons). These questions are related to the implementation of ‘dynamic user profiles’.

8. CONCLUSION

This fact sheet aimed to inform about energy-related occupant behaviour, focusing on everyday energy behaviour, taking all building uses (predetermining energy consumption) into account and considering building related (e.g. space heating) as well as occupant-related (e.g. DHW; appliances) energy use in buildings. Regarding factors influencing energy behaviour, the focus was on occupant-related factors. The presentation of factors did not include the quantification of their impact on energy consumption.

The energy consumption of buildings is influenced by various factors, one of which is occupant behaviour. However, its consideration in the energy assessment of buildings is insufficient, contributing to the emergence of the performance gap regarding energy efficiency of buildings. The current consideration of the user dimension in energy assessment is insufficient because only 'standard user profiles' are used, disregarding the variety of energy behaviours and their impact on energy consumption. Therefore, the objective of this fact sheet was to increase the understanding about energy-related occupant behaviour and the factors influencing it. Furthermore, the fact sheet aimed at providing us with information about different methods of occupant behaviour modelling and on the development of user profiles for a more accurate integration of the user dimension into the ePANACEA methodology.

Based on the literature review that was conducted in order to compose this fact sheet, we can summarize that there are different types of energy-related occupant behaviour, such as adaptive and non-adaptive behaviours. The former is motivated by the occupant's will to improve or maintain the IEQ. Whereas non-adaptive behaviour comprises e.g. the use of electrical appliances and presence/absence and therefore is not primarily motivated by the will to meet (thermal) comfort needs. Presence in a space is a prerequisite for occupants to interact with building systems or to make changes to adapt themselves to the environment.

The factors influencing energy-related behaviour can be roughly divided into external and internal factors. To our understanding, occupant-related factors, which we focused on, comprise internal and socio-demographic factors. A dominant internal factor influencing adaptive energy behaviour represents the individually perceived comfort. Interestingly, psychological variables seem to be negligibly little influential in explaining energy use. By contrast, socio-demographic factors (income, household size, and household composition) which shape the opportunities and constraints for energy use, appear to be more influential. Energy use in NRBs (on the example of offices) compared to residential buildings is influenced by different, additional factors, such as the presence of various agents and the fact that there are actions for which all share responsibility. The presented DNAs framework provides a systemic representation of energy-related occupant behaviour in buildings, relating drivers, needs, actions and systems with each other and therefore covering and relating the previously mentioned factors and types of energy-related occupant behaviour.

User profiles represent a possibility to take user behavioural patterns for the energy assessment of buildings into account. The development of user profiles, representative for the Netherlands, was presented in this fact sheet. In the described study user profiles were developed based on household types with corresponding occupancy patterns. In regard to the development of user profiles for the ePANACEA methodology we could choose the same approach to develop user profiles. However, ideally, country-specific databases should be available for this.

Regarding occupant behaviour modelling there is a paradigm shift; moving away from considering occupants as passive sources of heat, moisture and emissions, to understanding occupants as active decision-making agents, who are responding to IEQ through adaptive actions to meet their comfort needs. However, the new approach faces various challenges that are related to the nature of occupant behaviour, which is stochastic, diverse, complex, and interdisciplinary. In addition, occupant behaviour is changing over time, placing the demand on occupant modelling to be dynamic. Large amounts of data are needed for occupant behaviour modelling. Occupant monitoring approaches can be divided into observational studies, surveys and interviews and laboratory studies. Based on the resolution, complexity and size of the models three levels of occupant behaviour modelling can be identified: level 0: non-probabilistic models, level 1: probabilistic or stochastic models and level 2: agent-based and object-oriented models. The advantage of stochastic occupant modelling approaches, compared to deterministic approaches, is that they are capable of reflecting the variability in human behaviour because they possess some inherent randomness. Agent-based models are the most complex approach, since they are mapping group-level behaviour instead of individual-level behaviour. Due to the given stochastic nature of human behaviour, one of the key research challenges is the issue of generalization of behavioural findings. Also, the demand on occupant behaviour modelling to be dynamic involves a higher level of model complexity with probably higher uncertainties.

Besides that, next to the building components' and systems' efficiency, also behavioural change has the potential to increase energy efficiency. In contrast to the factors influencing energy use, psychological factors play a bigger role than socio-demographics regarding behavioural change. Different intervention strategies, tailored to behaviours, can motivate behavioural change. For instance, potential improvements coming with the new EPC (e.g. more accurate, tangible and understandable information on the EPB) could motivate end users to take the EPB more into consideration before and after buying/renting a dwelling /building, therefore addressing strategic behaviour. Other than that, the inclusion of user profiles in the EPC makes the impact of occupant-related variables on energy consumption more visible and therefore has the potential to show end users through what changes in adaptive behaviour (e.g. thermostat settings etc.) they can reduce energy consumption. Therefore, envisaged improvements of the EPC also have the potential to address occupants' everyday energy behaviour.

Regarding the integration of user profiles in the ePANACEA methodology we can recognize that this also meets end users' needs to make the EPC customizable. As mentioned before, it should be possible that user profiles can be updated (in case socio-demographics or habits of a household change or new tenants/owners move into the building). Also, we need to consider that for the different pilot countries of ePANACEA (as well as for different MS of the EU), different energy behaviours (that are influenced by different factors) may be more/less dominant and therefore important for the energy assessment of buildings. Therefore, ideally, user-profiles should be country-specific.

The information that could be considered in a user profile within the context of EPC could be the following: a realistic representation of occupancy, which requires the determination of occupancy profiles that are in turn determined by socio-demographic variables like household composition (e.g. presence of children/seniors). Other socio-demographic variables, not necessarily influencing occupancy but energy consumption nevertheless, are income and size of the household. Next to the household characteristics and occupancy profile, information about the operation of building components and systems (reflecting comfort preferences) and the use of appliances should be included in the user profile. Using the example of heating behaviour, information on the following parameters could be taken into account: thermostat settings, use of radiators (heating hours) and ventilation while heating. The information constituting a user profile was visualized in a draft user profile interface. Moreover, remaining concerns and questions related to the implementation of user profiles such as data availability and data protection were mentioned in the outlook.

9. REFERENCES

Abrahamse, W. *et al*. (2005) A review of intervention studies aimed at household energy conservation, *Journal of Environmental Psychology, 25,* pp. 273 - 291.

Abrahamse, W. *et al.* (2007) The effect of tailored information, goal setting, and tailored feedback on household energy use, energy-related behaviours, and behavioural antecedents, *Journal of Environmental Psychology, 27*, pp. 265-276.

Abrahamse, W., Steg, L. (2009), *Journal of Economic Psychology, 30,* pp. 711-720.

Adjei, A., Hamilton, L., Roys, M. (n.d.) *Deliverable 5.2, A study of homeowners' energy efficiency improvements and the impact of the Energy Performance Certificate,* IDEAL EPBD.

Ahmad, J. *et al*. (2018) Occupancy detection in non-residential buildings – A survey and novel privacy preserved occupancy monitoring solution, *Applied Computing and Informatics.*

ASHRAE (n.d.) STANDARD 90.1 Document history, available from https://www.ashrae.org/technical-resources/bookstore/standard-90-1-document-history [Accessed 9th July 2021].

Aune, M., Berker, T., Bye, R. (2009) The missing link which was already there Building operators and energy management in non-residential buildings, *Facilities, 27(1/2),* pp. 44-55.

Beth, K. *et al.* (2012) Dimensions of Conservation: Exploring Differences among Energy Behaviours, *Environment and Behaviour, 46(4),* pp.1-30.

Brounen, D., Kok, N., Quigley, J.M. (2013) Energy literacy, awareness, and conservation behaviour of residential households, *Energy Economics, 38*, pp. 42-50.

Cibinskiene, A., Dumciuviene, D., Andrijauskiene, M. (2020) Energy Consumption in Public Buildings: The Determinants of Occupants' Behaviour, *energies, 13(14)*:3586.

Csoknyai, T. *et al*. (2019) Analysis of energy consumption profiles in residential buildings and impact assessment of a serious game on occupants' behaviour, *Energy and Buildings, 196(1),* pp. 1-20.

De Simone, M. *et al*. (2018) *Reference procedures for obtaining occupancy profiles in residential buildings,* IEA EBC Annex 66 – Subtask A Deliverable.

De Wilde, P. (2014) The gap between predicted and measured energy performance of buildings: A framework for investigation, *Automation in Construction, 41,* pp. 40-49.

Delzendeh, E., Wu, S., Lee, A. & Zhou, Y. (2017). The impact of occupants' behaviours on building energy analysis: A research review. *Renewable and Sustainable Energy Reviews, 80*, 1061-1071.

Dixon, G. N. *et al.* (2015) Using Comparative Feedback to Influence Workplace Energy Conservation: A Case Study of a University Campaign, *Environment and Behaviour, 47(6),* pp. 667 –693.

Fabi, V. *et al*. (2011) *Effect of occupant behaviour related influencing factors on final energy end uses in buildings*, Conference Paper.

Gaetani, I., Hoes, P.-J., Hensen, J. (2016) Occupant behaviour in building energy simulation: Towards a fit-for-purpose modelling strategy, *Energy and Buildings, 121(1),* pp. 188-204.

Gram-Hanssen, K., Georg, S. (2018) Energy performance gaps: promises, people, practices, *Building Research & Information, 46(1),* pp.1–9.

Guerra Santin, O. *et al.* (2018) Considering user profiles and occupants' behaviour on a zero energy renovation strategy for multi-family housing in the Netherlands, *Energy Efficiency, 11,* pp.1847-1870.

Guerra Santin, O., Silvester, S. (2017) Development of Dutch occupancy and heating profiles for building simulation, *Building Research & Information, 45(4),* pp. 396-413.

Guerra-Santin, O., Itard, L., Visscher, H. (2009) The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock, *Energy and Buildings, 41(11),* pp. 1223-1232.

Hong, T. *et al.* (2016) Advances in research and applications of energy-related occupant behaviour in buildings, *Energy and Buildings, 116,* pp. 694-702.

Hong, T. *et al*. (2017) Ten questions concerning occupant behaviour in buildings: The big picture, *Building and Environment, 114,* pp. 518-530.

Hong, T., Lin, H.-W. (2013) *Occupant Behaviour: Impact on Energy Use of Private Offices.*

Hong, T. *et al.,* (2015) *An Ontology to Represent Energy related Occupant Behaviour in Buildings Part I: Introduction to the DNAs Framework.*

Huebner, G. M., Cooper, J. & Jones, K. (2013) Domestic energy consumption - what role do comfort, habit, and knowledge about the heating system play? *Energy Buildings, 66*, pp. 626-636.

Huebner, G. M., *et al*. (2015) Explaining domestic energy consumption – The comparative contribution of building factors, socio-demographics, behaviours and attitudes, *Applied Energy, 159*, pp. 589-600.

Janda, K.B. (2011) Buildings don't use energy: People do, *Architectural Science Review*, *54(1),* pp. 15-22.

Kwok, S.S.K., E.W.M. Lee (2011) A study of the importance of occupancy to building cooling load in prediction by intelligent approach*, Energy conversions and management, 52(7),* pp. 2555-2564.

Laaroussi, Y. *et al.* (2019) *Occupant behaviour: a major issue for building energy performance,* IOP Conf. Series: Materials Science and Engineering.

Li, P., Froese, T. M., Brager, G. (2018) Post-occupancy evaluation: State-of-the-art analysis and state-of-the-practice review, *Building and Environment*, pp. 187-202.

Matthies, E. *et al*. (2011) High reduction potentials for energy user behaviour in public buildings: how much can psychology-based interventions achieve?, *Journal of Environmental Studies and Sciences, 1(3),* pp. 241-255.

Menezes, A.C. *et al.* (2012) Predicted vs. Actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap, *Applied Energy, 97,* pp. 355-364.

Mora, D., Carpino, C., de Simone, M., (2015) Behavioural and physical factors influencing energy building performances in Mediterranean climate, *Energy Procedia, 78*, pp. 603–608.

Paone, A., Bacher, J.-P. (2018) The Impact of Building Occupant Behaviour on Energy Efficiency and Methods to Influence It: A Review of the State of the Art, *energies*, *11(953)*, pp.1-19.

Russell, S.V. *et al.* (2016) Turn it off: An Action Research Study of Top Management Influence on Energy Conservation in the Workplace, *Frontiers in Psychology, 7(389),* pp. 1-10.

Schuitema, G., Aravena, C., Denny, E. (2019) The psychology of energy efficiency labels: Trust, involvement, and attitudes towards energy performance certificates in Ireland, *Energy Research & Social Science, 59.*

Schwartz, T. *et al.* (2010) *Sustainable Energy Practices at Work: Understanding the Role of Workers in Energy Conservation,* NordiCHI '10: Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries, pp. 452 – 462.

Serrano Guerrero, X., Escrivá-Escrivá, G., Roldán-Blay, C. (2018) Statistical Methodology to assess changes in the electrical consumption profile of buildings, *Energy and Buildings, 164(1),* pp. 99-108.

Simanic, B. *et al*. (2020) Influence of User-Related Parameters on Calculated Energy Use in Low-Energy School Buildings, *energies, 13 (2985)*, pp. 1-14.

Staddon, S.C. *et al*. (2016) Intervening to change behaviour and save energy in the workplace: A systematic review of available evidence, *Energy Research & Social Science, 17,* pp. 30-51.

Steg, L. (2008) Promoting household energy conservation, *Energy Policy, 36(12),* pp. 4449–4453.

Sürmeli-Anac, N. & Hermelink, A. H. (2018) *The Smart Readiness Indicator: A potential, forward-looking Energy Performance Certificate complement?* Discussion Paper.

Tam, V. W. Y., Almeida, L., Le, K. (2018) Energy-Related Occupant Behaviour and Its Implications in Energy Use: A Chronological Review, *sustainability, 10 (2635),* pp. 1-20.

Tetlow, R.M. *et al*. (2015) Identifying behavioural predictors of small power electricity consumption in office buildings, *Building and Environment, 92,* pp. 75-85.

Tigchelaar, C, Backhaus, J., de Best-Waldhober, M. (n.d.) *Consumer response to energy labels in buildings, Recommendations to improve the Energy Performance Certificate and the Energy Performance of Buildings Directive based on research findings in 10 EU countries.*

Trotta, G. (2018) Factors affecting energy-saving behaviours and energy efficiency investments in British households, *Energy Policy, 114,* pp. 529-539.

Tuomaala, P. *et al*. (2013) *Impact of individual characteristics – such a sage, gender, BMI, and fitness – on human thermal sensation*, Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28.

Umweltbundesamt (2020) *Energieverbrauch privater Haushalte*, available from https://www.umweltbundesamt.de/daten/private-haushalte-konsum/wohnen/energieverbrauch-privater-haushalte#endenergieverbrauch-der-privaten-haushalte [Accessed 11th May, 2021].

Verbong, G.P., Beemsterboer, S., Sengers, F. (2013) Smart Grids or Smart Users? Involving Users in Developing a Low Carbon Electricity Economy. Energy Policy, 52, pp. 117-125.

Wagner, A., O'Brien, L. (2018) *Occupant behaviour-centric building design and operation EBC Annex 79.*

Yan, D. *et al.* (2015) Occupant behaviour modelling for building performance simulation: Current state and future challenge, *Energy and Buildings, 107,* pp. 264-278.

Yan, D., Hong, T. (2018) Definition and Simulation of Occupant Behaviour in Buildings, Annex 66 Final Report.

Yan, D., Hong, T. Eds. (2014) *EBC Annex 66 Text, Definition and Simulation of Occupant Behaviour in Buildings.*

Yoshino, H., Chen, S. Eds. (2016) *Total Energy Use in Buildings: Analysis and Evaluation Methods (Annex 53), Project Summary Report.*

9.1. List of Figures

9.2. List of Tables

APPENDIX

Table A,5: Data needed to complete basic occupant behaviour studies in window opening/closing, occupancy, shading, lighting, thermal comfort, plug loads and HVAC. (Hong et al., 2016)

	Variables\behaviors	Units	Window opening	Occupancy	Shading	Lighting	Thermal comfort	Plug loads	HVAC	Occupancy survey	Device/system
Weather data	Outdoor air temperature	°C	✓✓				✓✓		✓✓		Weather station
	Outdoor air humidity	%	✓✓				✓✓		✓✓		Weather station
	Wind speed	m/s	✓✓				✓✓				Weather station
	Wind direction	N, E, S, W	✓				✓				Weather station
	Solar irradiance	W	✓		✓✓	✓✓	✓		✓		Weather station
	Illuminance	Lux	✓		✓✓	✓✓	✓				LMS
	Rain (event)	Y, N	✓				✓		✓		Weather station
Space data	Indoor air temperature	°C	✓✓		✓✓		✓✓	✓	✓✓		BMS
	Indoor air humidity	%	✓				✓✓	✓	✓✓		BMS
	CO_2	ppm	✓✓	✓✓			✓✓		✓✓		BMS
	Occupancy	0–1	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓		BMS/custom sensor
	Light level	On-off, dimming		✓	✓✓	✓✓	✓	✓			BMS/LMS
	Window state	Open, closed	✓✓	✓	✓		✓✓		✓		BMS/LMS
	Shading state	Up-down, partial		✓	✓✓	✓✓	✓		✓		EMS
	Plug loads	On-off		✓		✓		✓✓	✓		EMS
	Thermostat settings (cooling & heating)	°C		✓			✓✓	✓	✓✓		BMS
	Heating/cooling state	On-off		✓			✓	✓	✓✓		EMS
Energy data	Total energy use	kW h	✓	✓	✓	✓	✓	✓	✓✓	✓✓	EMS/survey
	Submetering (lighting, HVAC, plug-loads, etc)	kW h				✓	✓	✓	✓		EMS
	Energy production (renewable)	kW h				✓	✓	✓	✓		EMS
Occupants data	Age	Number	✓	✓	✓	✓	✓	✓	✓	✓✓	Management/survey
	Gender	F, M	✓	✓	✓	✓	✓	✓	✓	✓✓	Management/survey
	Working profiles	Working, non-working	✓	✓	✓	✓	✓	✓	✓	✓✓	Management/survey
										BMS = building management system	
							✓✓	Mandatory		EMS = energy management system	
							✓	Optional		LMS = lighting management system	